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MOCK THETA FUNCTIONS**

JEREMY LOVEJOY AND ROBERT OSBURN

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q -HYPERGEOMETRIC DOUBLE SUMS AS MOCK THETA FUNCTIONS

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In memory of Basil Gordon

Recently, Bringmann and Kane established two new Bailey pairs and used them to relate certain q -hypergeometric series to real quadratic fields. We show how these pairs give rise to new mock theta functions in the form of q -hypergeometric double sums. We also prove an identity between one of these sums and two classical mock theta functions introduced by Gordon and McIntosh.

1. Introduction

A *Bailey pair* relative to a is a pair of sequences $(\alpha_n, \beta_n)_{n \geq 0}$ satisfying

$$(1-1) \quad \beta_n = \sum_{k=0}^n \frac{\alpha_k}{(q)_{n-k}(aq)_{n+k}}.$$

Here we have used the standard q -hypergeometric notation,

$$(1-2) \quad (a)_n = (a; q)_n = \prod_{k=1}^n (1 - aq^{k-1}),$$

valid for $n \in \mathbb{N} \cup \{\infty\}$. The *Bailey lemma* states that if (α_n, β_n) is a Bailey pair relative to a , then so is (α'_n, β'_n) , where

$$(1-3) \quad \alpha'_n = \frac{(b)_n(c)_n(aq/bc)^n}{(aq/b)_n(aq/c)_n} \alpha_n, \quad \beta'_n = \sum_{k=0}^n \frac{(b)_k(c)_k(aq/bc)_{n-k}(aq/bc)^k}{(aq/b)_n(aq/c)_n(q)_{n-k}} \beta_k.$$

Inserting (1-3) into (1-1) with $n \rightarrow \infty$ gives

$$(1-4) \quad \sum_{n \geq 0} (b)_n(c)_n(aq/bc)^n \beta_n = \frac{(aq/b)_\infty(aq/c)_\infty}{(aq)_\infty(aq/bc)_\infty} \sum_{n \geq 0} \frac{(b)_n(c)_n(aq/bc)^n}{(aq/b)_n(aq/c)_n} \alpha_n,$$

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valid whenever both sides converge. For more on Bailey pairs, including historical perspectives and recent advances, see [Andrews 1986b, Chapter 3; 2001], or [Warnaar 2001].

In a recent study of multiplicative q -series, Bringmann and Kane [2011] established two new and interesting Bailey pairs. They showed that (a_n, b_n) is a Bailey pair relative to 1, where

$$(1-5) \quad a_{2n} = (1 - q^{4n})q^{2n^2-2n} \sum_{j=-n}^{n-1} q^{-2j^2-2j},$$

$$(1-6) \quad a_{2n+1} = -(1 - q^{4n+2})q^{2n^2} \sum_{j=-n}^n q^{-2j^2},$$

$$(1-7) \quad b_n = \frac{(-1)^n (q; q^2)_{n-1}}{(q)_{2n-1}} \chi(n \neq 0),$$

and (α_n, β_n) is a Bailey pair relative to q , where

$$(1-8) \quad \alpha_{2n} = \frac{1}{1-q} \left(q^{2n^2+2n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} + q^{2n^2} \sum_{j=-n}^n q^{-2j^2} \right),$$

$$(1-9) \quad \alpha_{2n+1} = -\frac{1}{1-q} \left(q^{2n^2+4n+2} \sum_{j=-n}^n q^{-2j^2} + q^{2n^2+2n} \sum_{j=-n-1}^n q^{-2j^2-2j} \right),$$

$$(1-10) \quad \beta_n = \frac{(-1)^n (q; q^2)_n}{(q)_{2n+1}}.$$

These closely resemble Bailey pairs related to seventh order mock theta functions [Andrews 1986a], but surprisingly no q -series obtained by a direct substitution of either (1-5)–(1-7) or (1-8)–(1-10) in (1-4) is a genuine mock theta function. For example, it turns out that substituting (1-5)–(1-7) in (1-4) with $b, c \rightarrow \infty$ yields

$$\frac{-q}{(-q)_\infty} \omega(q)$$

where $\omega(q)$ is one of the third order mock theta functions. The presence of the infinite product means that this is not a mock theta function but a *mixed mock modular form*.

Recall that mock theta functions are q -series which were introduced by Ramanujan in his last letter to G. H. Hardy on January 12, 1920. Until 2002, it was not known how these functions fit into the theory of modular forms. Thanks to work of Zwegers [2002] and Bringmann and Ono [2006; 2010], we now know that each of Ramanujan's examples of mock theta functions is the holomorphic part of a weight $\frac{1}{2}$ harmonic weak Maass form $f(\tau)$ (as usual, $q := e^{2\pi i \tau}$ where $\tau = x + iy \in \mathbb{H}$). Following [Zagier 2009], the holomorphic part of any weight k harmonic weak

Maass form f is called a mock modular form of weight k . If $k = \frac{1}{2}$ and the image of f under the operator $\xi_k := 2iy^k \bar{\partial} / \partial \bar{\tau}$ is a unary theta function, then the holomorphic part of f is called a mock theta function. Specializations of the Appell–Lerch series

$$m(x, q, z) := \frac{1}{j(z, q)} \sum_{r \in \mathbb{Z}} \frac{(-1)^r q^{\binom{r}{2}} z^r}{1 - q^{r-1} xz}$$

are perhaps the most well-known and most important class of mock theta functions [Zagier 2009; Zwegers 2002]. Here $x, z \in \mathbb{C}^* := \mathbb{C} \setminus \{0\}$ with neither z nor xz an integral power of q , and

$$j(x, q) := (x)_\infty (q/x)_\infty (q)_\infty.$$

For more on mock theta functions, their remarkable history and modern developments, see [Ono 2009] and [Zagier 2009].

The goal of this paper is to obtain genuine mock theta functions from the Bailey pairs of Bringmann and Kane by first moving a step along the Bailey chain. Applying (1-3) to (a_n, b_n) with $(b, c) \rightarrow (-1, \infty)$ and to (α_n, β_n) with $(b, c) \rightarrow (-q, \infty)$, we obtain the Bailey pairs recorded in the following two lemmas.

Lemma 1.1. *The pair (a'_n, b'_n) is a Bailey pair relative to 1, where*

$$\begin{aligned} a'_{2n} &= 2(1 - q^{2n})q^{4n^2-n} \sum_{j=-n}^{n-1} q^{-2j^2-2j}, \\ a'_{2n+1} &= -2(1 - q^{2n+1})q^{4n^2+3n+1} \sum_{j=-n}^n q^{-2j^2}, \\ b'_n &= \frac{1}{(-q)_n} \sum_{j=1}^n \frac{(-1)_j (q; q^2)_{j-1} (-1)^j q^{\binom{j+1}{2}}}{(q)_{n-j} (q)_{2j-1}}. \end{aligned}$$

Lemma 1.2. *The pair (α'_n, β'_n) is a Bailey pair relative to q , where*

$$\begin{aligned} \alpha'_{2n} &= \frac{1}{1-q} \left(q^{4n^2+3n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} + q^{4n^2+n} \sum_{j=-n}^n q^{-2j^2} \right), \\ \alpha'_{2n+1} &= -\frac{1}{1-q} \left(q^{4n^2+7n+3} \sum_{j=-n}^n q^{-2j^2} + q^{4n^2+5n+1} \sum_{j=-n-1}^n q^{-2j^2-2j} \right), \\ \beta'_n &= \frac{1}{(-q)_n} \sum_{j=0}^n \frac{(-q)_j (q; q^2)_j (-1)^j q^{\binom{j+1}{2}}}{(q)_{n-j} (q)_{2j+1}}. \end{aligned}$$

With our main result, we present four mock theta functions arising from the Bailey pairs in Lemmas 1.1 and 1.2. Define

$$\begin{aligned} \theta_{n,p}(x, y, q) &:= \frac{1}{\bar{J}_{0,np(2n+p)}} \sum_{r^*=0}^{p-1} \sum_{s^*=0}^{p-1} q^{n\binom{r-(n-1)/2}{2} + (n+p)(r-(n-1)/2)(s+(n+1)/2) + n\binom{s+(n+1)/2}{2}} \\ &\quad \times \frac{(-x)^{r-(n-1)/2} (-y)^{s+(n+1)/2} J_{p^2(2n+p)}^3 j(-q^{np(s-r)} x^n / y^n, q^{np^2})}{j(q^{p(2n+p)r+p(n+p)/2} (-y)^{n+p} / (-x)^n, q^{p^2(2n+p)})} \\ &\quad \times \frac{j(q^{p(2n+p)(r+s)+p(n+p)} x^p y^p, q^{p^2(2n+p)})}{j(q^{p(2n+p)s+p(n+p)/2} (-x)^{n+p} / (-y)^n, q^{p^2(2n+p)})}, \end{aligned}$$

where $r := r^* + \{(n-1)/2\}$ and $s := s^* + \{(n-1)/2\}$ with $0 \leq \{\alpha\} < 1$ denoting the fractional part of α . Also, $J_m := J_{m,3m}$ with $J_{a,m} := j(q^a, q^m)$, and $\bar{J}_{a,m} := j(-q^a, q^m)$.

Theorem 1.3. *The following are mock theta functions:*

$$\begin{aligned} (1-11) \quad \mathcal{W}_1(q) &:= \sum_{n \geq j \geq 1} \frac{(-1)_j (q; q^2)_{j-1} (-1)^j q^{n^2 + \binom{j+1}{2}}}{(-q)_n (q)_{n-j} (q)_{2j-1}} \\ &= 4m(-q^{17}, q^{48}, -1) - 4q^{-5} m(-q, q^{48}, -1) - \frac{2q^2 \theta_{3,2}(q^5, q^5, q)}{j(q, q^3)}, \end{aligned}$$

$$\begin{aligned} (1-12) \quad \mathcal{W}_2(q) &:= \sum_{n \geq j \geq 1} \frac{(q; q^2)_n (-1)_j (q; q^2)_{j-1} (-1)^{n+j} q^{\binom{j+1}{2}}}{(-q)_n (q)_{n-j} (q)_{2j-1}} \\ &= 4m(-q, q^8, -1) + \frac{2q \theta_{1,2}(-q^2, -q^2, q)}{j(-1, q)}, \end{aligned}$$

$$\begin{aligned} (1-13) \quad \mathcal{W}_3(q) &:= \sum_{n \geq j \geq 1} \frac{(q; q^2)_n (-1)_j (q^2; q^4)_{j-1} (-1)^{n+j} q^{n^2 + j^2 + j}}{(-q^2; q^2)_n (q^2; q^2)_{n-j} (q^2; q^2)_{2j-1}} \\ &= 4m(-q, q^{12}, -1) + \frac{2q^3 \theta_{1,1}(-q^7, -q^7, q^4)}{j(-q, q^4)}, \end{aligned}$$

$$\begin{aligned} (1-14) \quad \mathcal{W}_4(q) &:= \sum_{n \geq j \geq 0} \frac{(-q)_j (q; q^2)_j (-1)^j q^{n^2 + n + \binom{j+1}{2}}}{(-q)_n (q)_{n-j} (q)_{2j+1}} \\ &= -2q^{-4} m(-q^5, q^{48}, -1) - 2q^{-2} m(-q^{11}, q^{48}, -1) + \frac{\theta_{3,2}(q^3, q^3, q)}{j(q, q^3)}. \end{aligned}$$

It should be noted that the series defining $\mathcal{W}_2(q)$ does not converge. However, similar to the sixth order mock theta function $\mu(q)$ [Andrews and Hickerson 1991],

the sequence of even partial sums and the sequence of odd partial sums both converge. We define ${}^{\circ}W_2(q)$ as the average of these two values.

To prove Theorem 1.3 we first use the Bailey machinery to express the ${}^{\circ}W_i$ in terms of Hecke-type double sums $f_{a,b,c}(x, y, q)$, where

$$(1-15) \quad f_{a,b,c}(x, y, q) := \sum_{\text{sg}(r)=\text{sg}(s)} \text{sg}(r)(-1)^{r+s} x^r y^s q^{a\binom{r}{2}+brs+c\binom{s}{2}}.$$

Here $x, y \in \mathbb{C}^*$ and $\text{sg}(r) := 1$ for $r \geq 0$ and $\text{sg}(r) := -1$ for $r < 0$. Then we apply recent results of Hickerson and Mortenson [2012] to express the Hecke-type double sums as Appell–Lerch series $m(x, q, z)$ (up to the addition of weakly holomorphic modular forms).

We highlight one connection to classical mock theta functions. Namely, we express the multisum (1-12) in terms of the “eighth order” mock theta functions $S_1(q)$ and $T_1(q)$, defined by (see [Gordon and McIntosh 2000])

$$S_1(q) := \sum_{n \geq 0} \frac{q^{n(n+2)}(-q; q^2)_n}{(-q^2; q^2)_n} \quad \text{and} \quad T_1(q) := \sum_{n \geq 0} \frac{q^{n(n+1)}(-q^2; q^2)_n}{(-q; q^2)_{n+1}}.$$

Corollary 1.4. *We have the identity*

$${}^{\circ}W_2(q) = 2qT_1(q) - qS_1(q).$$

Similar identities involving mock theta functions and multisums were given in [Andrews 2007, Section 13], and more could be deduced from [Bringmann et al. 2010, Theorem 2.4].

The paper proceeds as follows. Some background material on Hecke-type double sums and Appell–Lerch series is collected in Section 2, and Theorem 1.3 and Corollary 1.4 are established in Section 3.

2. Preliminaries

We recall some relevant preliminaries. The most important is a result which allows us to convert from the Hecke-type double sums (1-15) to Appell–Lerch series. Define

$$(2-1) \quad g_{a,b,c}(x, y, q, z_1, z_0) := \sum_{t=0}^{a-1} (-y)^t q^{c\binom{t}{2}} j(q^{bt}x, q^a) m\left(-q^{a\binom{b+1}{2}-c\binom{a+1}{2}-t(b^2-ac)} \frac{(-y)^a}{(-x)^b}, q^{a(b^2-ac)}, z_0\right) + \sum_{t=0}^{c-1} (-x)^t q^{a\binom{t}{2}} j(q^{bt}y, q^c) m\left(-q^{c\binom{b+1}{2}-a\binom{c+1}{2}-t(b^2-ac)} \frac{(-x)^c}{(-y)^b}, q^{c(b^2-ac)}, z_1\right).$$

Following Hickerson and Mortenson, we use the term “generic” to mean that the parameters do not cause poles in the Appell–Lerch series or in the quotients of theta functions.

Theorem 2.1 [Hickerson and Mortenson 2012, Theorem 0.3]. *Let n and p be positive integers with $(n, p) = 1$. For generic $x, y \in \mathbb{C}^*$,*

$$f_{n,n+p,n}(x, y, q) = g_{n,n+p,n}(x, y, q, -1, -1) + \theta_{n,p}(x, y, q).$$

We shall also require certain facts about $j(x, q)$, $m(x, q, z)$ and $f_{a,b,c}(x, y, q)$. From the definition of $j(x, q)$, we have

$$(2-2) \quad j(q^n x, q) = (-1)^n q^{-\binom{n}{2}} x^{-n} j(x, q)$$

where $n \in \mathbb{Z}$ and

$$(2-3) \quad j(x, q) = j(q/x, q) = -xj(x^{-1}, q).$$

Next, some relevant properties of the sum $m(x, q, z)$ are given in the following (see (2.2b) of Proposition 2.1 and Theorem 2.3 in [Hickerson and Mortenson 2012]).

Proposition 2.2. *For generic $x, z, z_0 \in \mathbb{C}^*$, we have*

$$(2-4) \quad m(x, q, z) = x^{-1} m(x^{-1}, q, z^{-1}),$$

$$(2-5) \quad m(x, q, z) = m(x, q, z_0) + \frac{z_0 J_1^3 j(z/z_0, q) j(xz z_0, q)}{j(z_0, q) j(z, q) j(xz z_0, q) j(xz, q)}.$$

Finally, two important transformation properties of $f_{a,b,c}(x, y, q)$ are given in the following (see Propositions 5.1 and 5.2 in [Hickerson and Mortenson 2012]).

Proposition 2.3. *For $x, y \in \mathbb{C}^*$, we have*

$$(2-6) \quad \begin{aligned} f_{a,b,c}(x, y, q) &= f_{a,b,c}(-x^2 q^a, -y^2 q^c, q^4) - x f_{a,b,c}(-x^2 q^{3a}, -y^2 q^{c+2b}, q^4) \\ &\quad - y f_{a,b,c}(-x^2 q^{a+2b}, -y^2 q^{3c}, q^4) + x y q^b f_{a,b,c}(-x^2 q^{3a+2b}, -y^2 q^{3c+2b}, q^4), \end{aligned}$$

$$(2-7) \quad f_{a,b,c}(x, y, q) = -\frac{q^{a+b+c}}{xy} f_{a,b,c}(q^{2a+b}/x, q^{2c+b}/y, q).$$

3. Proof of Theorem 1.3

Proof of Theorem 1.3. Recall that the goal is to express each double sum q -series in terms of Appell–Lerch series. For (1-11), apply Lemma 1.1 and let $b, c \rightarrow \infty$ in

(1-4) to obtain

$$\begin{aligned} \mathcal{W}_1(q) &= \sum_{n \geq 0} q^{n^2} b'_n(q) = \frac{1}{(q)_\infty} \sum_{n \geq 0} q^{n^2} a'_n(q) \\ &= \frac{1}{(q)_\infty} \left(\sum_{n \geq 0} q^{4n^2} a'_{2n}(q) + \sum_{n \geq 0} q^{4n^2+4n+1} a'_{2n+1}(q) \right) \\ &= \frac{2}{(q)_\infty} \left(\sum_{n \geq 0} q^{8n^2-n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} - \sum_{n \geq 0} q^{8n^2+n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} \right. \\ &\quad \left. - \sum_{n \geq 0} q^{8n^2+7n+2} \sum_{j=-n}^n q^{-2j^2} - \sum_{n \geq 0} q^{8n^2+9n+3} \sum_{j=-n}^n q^{-2j^2} \right). \end{aligned}$$

After replacing n with $-n$ in the second sum and n with $-n-1$ in the fourth sum, we let $n = (r+s+1)/2$, $j = (r-s-1)/2$ in the first two sums and $n = (r+s)/2$, $j = (r-s)/2$ in the latter two sums to find

$$\begin{aligned} \mathcal{W}_1(q) &= \frac{2q^2}{(q)_\infty} \left(\left(\sum_{\substack{r,s \geq 0 \\ r \not\equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \not\equiv s \pmod{2}}} \right) q^{\frac{3}{2}r^2+5rs+\frac{7}{2}r+\frac{3}{2}s^2+\frac{7}{2}s} \right. \\ &\quad \left. - \left(\sum_{\substack{r,s \geq 0 \\ r \equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \equiv s \pmod{2}}} \right) q^{\frac{3}{2}r^2+5rs+\frac{7}{2}r+\frac{3}{2}s^2+\frac{7}{2}s} \right) \\ &= -\frac{2q^2}{(q)_\infty} \left(\left(\sum_{r,s \geq 0} - \sum_{r,s < 0} \right) q^{\frac{3}{2}r^2+5rs+\frac{7}{2}r+\frac{3}{2}s^2+\frac{7}{2}s} \right) \\ &= -\frac{2q^2}{(q)_\infty} f_{3,5,3}(q^5, q^5, q). \end{aligned}$$

By Theorem 2.1, (2-1), (2-2) and (2-3), we have

$$\begin{aligned} &f_{3,5,3}(q^5, q^5, q) \\ &= -2q^{-2} j(q, q^3) m(-q^{17}, q^{48}, -1) + 2q^{-7} j(q, q^3) m(-q, q^{48}, -1) + \theta_{3,2}(q^5, q^5, q) \end{aligned}$$

and so

$$\mathcal{W}_1(q) = 4m(-q^{17}, q^{48}, -1) - 4q^{-5} m(-q, q^{48}, -1) - \frac{2q^2 \theta_{3,2}(q^5, q^5, q)}{j(q, q^3)}.$$

For (1-12), apply Lemma 1.1 and let $b = -\sqrt{q}$ and $c = \sqrt{q}$ in (1-4) to get

$$\mathcal{W}_2(q) = \sum_{n \geq 0} (-1)^n (q; q^2)_n b'_n(q) = \frac{(q; q^2)_\infty}{2(q^2; q^2)_\infty} \sum_{n \geq 0} (-1)^n a'_n(q)$$

$$\begin{aligned}
 &= \frac{(q; q^2)_\infty}{2(q^2; q^2)_\infty} \left(\sum_{n \geq 0} a'_{2n}(q) - \sum_{n \geq 0} a'_{2n+1}(q) \right) \\
 &= \frac{(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\sum_{n \geq 0} q^{4n^2-n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} - \sum_{n \geq 0} q^{4n^2+n} \sum_{j=-n}^{n-1} q^{-2j^2-2j} \right. \\
 &\quad \left. + \sum_{n \geq 0} q^{4n^2+3n+1} \sum_{j=-n}^n q^{-2j^2} - \sum_{n \geq 0} q^{4n^2+5n+2} \sum_{j=-n}^n q^{-2j^2} \right).
 \end{aligned}$$

As before, we proceed with

$$\begin{aligned}
 \mathfrak{W}_2(q) &= \frac{(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\left(\sum_{\substack{r,s \geq 0 \\ r \not\equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \not\equiv s \pmod{2}}} \right) q^{\frac{1}{2}r^2+3rs+\frac{3}{2}r+\frac{1}{2}s^2+\frac{3}{2}s+1} \right. \\
 &\quad \left. + \left(\sum_{\substack{r,s \geq 0 \\ r \equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \equiv s \pmod{2}}} \right) q^{\frac{1}{2}r^2+3rs+\frac{3}{2}r+\frac{1}{2}s^2+\frac{3}{2}s+1} \right) \\
 &= \frac{(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\left(\sum_{r,s \geq 0} - \sum_{r,s < 0} \right) q^{\frac{1}{2}r^2+3rs+\frac{3}{2}r+\frac{1}{2}s^2+\frac{3}{2}s+1} \right) \\
 &= \frac{q(q; q^2)_\infty}{(q^2; q^2)_\infty} f_{1,3,1}(-q^2, -q^2, q).
 \end{aligned}$$

By Theorem 2.1, (2-1) and (2-2), we have

$$f_{1,3,1}(-q^2, -q^2, q) = 2q^{-1} j(-1, q) m(-q, q^8, -1) + \theta_{1,2}(-q^2, -q^2, q)$$

and so

$$\mathfrak{W}_2(q) = 4m(-q, q^8, -1) + \frac{2q\theta_{1,2}(-q^2, -q^2, q)}{j(-1, q)}.$$

For (1-13), apply Lemma 1.1 and let $b = q, c \rightarrow \infty$ and $q \rightarrow q^2$ in (1-4) to get

$$\begin{aligned}
 \mathfrak{W}_3(q) &= \sum_{n \geq 0} (-1)^n (q; q^2)_n q^{n^2} b'_n(q^2) = \frac{(q; q^2)_\infty}{(q^2; q^2)_\infty} \sum_{n \geq 0} (-1)^n q^{n^2} a'_n(q^2) \\
 &= \frac{(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\sum_{n \geq 0} q^{4n^2} a'_{2n}(q^2) - \sum_{n \geq 0} q^{4n^2+4n+1} a'_{2n+1}(q^2) \right)
 \end{aligned}$$

$$= \frac{2(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\sum_{n \geq 0} q^{12n^2 - 2n} \sum_{j=-n}^{n-1} q^{-4j^2 - 4j} - \sum_{n \geq 0} q^{12n^2 + 2n} \sum_{j=-n}^{n-1} q^{-4j^2 - 4j} \right. \\ \left. + \sum_{n \geq 0} q^{12n^2 + 10n + 3} \sum_{j=-n}^n q^{-4j^2} - \sum_{n \geq 0} q^{12n^2 + 14n + 5} \sum_{j=-n}^n q^{-4j^2} \right).$$

So,

$$\begin{aligned} \mathfrak{W}_3(q) &= \frac{2(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\left(\sum_{\substack{r, s \geq 0 \\ r \not\equiv s \pmod{2}}} - \sum_{\substack{r, s < 0 \\ r \not\equiv s \pmod{2}}} \right) q^{2r^2 + 8rs + 5r + 2s^2 + 5s + 3} \right. \\ &\quad \left. + \left(\sum_{\substack{r, s \geq 0 \\ r \equiv s \pmod{2}}} - \sum_{\substack{r, s < 0 \\ r \equiv s \pmod{2}}} \right) q^{2r^2 + 8rs + 5r + 2s^2 + 5s + 3} \right) \\ &= \frac{2(q; q^2)_\infty}{(q^2; q^2)_\infty} \left(\left(\sum_{r, s \geq 0} - \sum_{r, s < 0} \right) q^{2r^2 + 8rs + 5r + 2s^2 + 5s + 3} \right) \\ &= \frac{2q^3(q; q^2)_\infty}{(q^2; q^2)_\infty} f_{1,2,1}(-q^7, -q^7, q^4). \end{aligned}$$

By Theorem 2.1, (2-1), (2-2) and (2-3), we have

$$f_{1,2,1}(-q^7, -q^7, q^4) = 2q^{-3} j(-q, q^4) m(-q, q^{12}, -1) + \theta_{1,1}(-q^7, -q^7, q^4)$$

and so

$$\mathfrak{W}_3(q) = 4m(-q, q^{12}, -1) + \frac{2q^3 \theta_{1,1}(-q^7, -q^7, q^4)}{j(-q, q^4)}.$$

Finally, for (1-14), apply Lemma 1.2 and let $b, c \rightarrow \infty$ in (1-4) to get

$$\begin{aligned} \mathfrak{W}_4(q) &= \sum_{n \geq 0} q^{n^2 + n} \beta'_n(q) = \frac{(1-q)}{(q)_\infty} \sum_{n \geq 0} q^{n^2 + n} \alpha'_n(q) \\ &= \frac{(1-q)}{(q)_\infty} \left(\sum_{n \geq 0} q^{4n^2 + 2n} \alpha'_{2n}(q) + \sum_{n \geq 0} q^{4n^2 + 6n + 2} \alpha'_{2n+1}(q) \right) \\ &= \frac{1}{(q)_\infty} \left(\sum_{n \geq 0} q^{8n^2 + 5n} \sum_{j=-n}^{n-1} q^{-2j^2 - 2j} + \sum_{n \geq 0} q^{8n^2 + 3n} \sum_{j=-n}^n q^{-2j^2} \right. \\ &\quad \left. - \sum_{n \geq 0} q^{8n^2 + 13n + 5} \sum_{j=-n}^n q^{-2j^2} - \sum_{n \geq 0} q^{8n^2 + 11n + 3} \sum_{j=-n-1}^n q^{-2j^2 - 2j} \right). \end{aligned}$$

After replacing n with $-n - 1$ in the third and fourth sums, we let $n = (r + s + 1)/2$, $j = (r - s - 1)/2$ in the first and fourth sums and $n = (r + s)/2$, $j = (r - s)/2$ in

the second and third sums to get

$$\begin{aligned}
\mathcal{W}_4(q) &= \frac{1}{(q)_\infty} \left(\left(\sum_{\substack{r,s \geq 0 \\ r \not\equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \not\equiv s \pmod{2}}} \right) q^{\frac{3}{2}r^2 + 5rs + \frac{13}{2}r + \frac{3}{2}s^2 + \frac{13}{2}s + 5} \right. \\
&\quad \left. + \left(\sum_{\substack{r,s \geq 0 \\ r \equiv s \pmod{2}}} - \sum_{\substack{r,s < 0 \\ r \equiv s \pmod{2}}} \right) q^{\frac{3}{2}r^2 + 5rs + \frac{3}{2}r + \frac{3}{2}s^2 + \frac{3}{2}s} \right) \\
&= \frac{1}{(q)_\infty} (2q^{13} f_{3,5,3}(-q^{25}, -q^{29}, q^4) \\
&\quad + f_{3,5,3}(-q^9, -q^9, q^4) + q^{11} f_{3,5,3}(-q^{25}, -q^{25}, q^4)) \\
&= \frac{1}{(q)_\infty} f_{3,5,3}(q^3, q^3, q),
\end{aligned}$$

where in the last step we have used (2-6) and (2-7). By Theorem 2.1, (2-1), (2-2), (2-3) and (2-4), we have

$$\begin{aligned}
&f_{3,5,3}(q^3, q^3, q) \\
&= -2q^{-4} j(q, q^3) m(-q^5, q^{48}, -1) - 2q^{-2} j(q, q^3) m(-q^{11}, q^{48}, -1) + \theta_{3,2}(q^3, q^3, q)
\end{aligned}$$

and so

$$\mathcal{W}_4(q) = -2q^{-4} m(-q^5, q^{48}, -1) - 2q^{-2} m(-q^{11}, q^{48}, -1) + \frac{\theta_{3,2}(q^3, q^3, q)}{j(q, q^3)}. \quad \square$$

Proof of Corollary 1.4. Equations (4.36) and (4.38) of [Hickerson and Mortenson 2012] state that

$$S_1(q) = -2q^{-1} m(-q, q^8, -1) + \frac{\bar{J}_{3,8} J_{2,8}^2}{q J_{1,8}^2}, \quad T_1(q) = q^{-1} m(-q, q^8, q^6).$$

By (1-12), (2-3) and (2-5), the claim is equivalent to the identity

$$\frac{\bar{J}_{3,8} J_{2,8}^2}{J_{1,8}^2} + \frac{2q \theta_{1,2}(-q^2, -q^2, q)}{j(-1, q)} = \frac{-2j(q^8, q^{24})^3 j(-q^6, q^8)}{j(q^6, q^8) j(-1, q^8) j(-q^7, q^8)}.$$

We have verified this identity using a MAPLE program [Garvan 2010]. □

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JEREMY LOVEJOY
CNRS, LIAFA
UNIVERSITÉ DENIS DIDEROT - PARIS 7
CASE 7014
75205 PARIS CEDEX 13
FRANCE
lovejoy@liafa.univ-paris-diderot.fr

ROBERT OSBURN
SCHOOL OF MATHEMATICAL SCIENCES
UNIVERSITY COLLEGE DUBLIN
BELFIELD
DUBLIN 4
IRELAND
robert.osburn@ucd.ie

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pacific@math.ucla.edu

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Department of Mathematics
University of California
Los Angeles, CA 90095-1555
balmer@math.ucla.edu

Don Blasius
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
blasius@math.ucla.edu

Vyjayanthi Chari
Department of Mathematics
University of California
Riverside, CA 92521-0135
chari@math.ucr.edu

Daryl Cooper
Department of Mathematics
University of California
Santa Barbara, CA 93106-3080
cooper@math.ucsb.edu

Robert Finn
Department of Mathematics
Stanford University
Stanford, CA 94305-2125
finn@math.stanford.edu

Kefeng Liu
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
liu@math.ucla.edu

Jiang-Hua Lu
Department of Mathematics
The University of Hong Kong
Pokfulam Rd., Hong Kong
jhlu@maths.hku.hk

Sorin Popa
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
popa@math.ucla.edu

Jie Qing
Department of Mathematics
University of California
Santa Cruz, CA 95064
qing@cats.ucsc.edu

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Princeton University
Princeton NJ 08544-1000
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