ON SOME CONGRUENCES FOR ANDREWS’ SINGULAR OVERPARTITIONS

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Received: 3/9/17, Revised: 10/26/17, Accepted: 1/14/18, Published: 2/5/18

Abstract

Andrews’ singular overpartitions can be enumerated by \( \overline{C}_{k,i}(n) \), the number of overpartitions of \( n \) where only parts congruent to \( \pm i \) (mod \( k \)) may be overlined, and no part is divisible by \( k \). A number of authors have studied congruences satisfied by singular overpartitions. In particular, congruences for \( \overline{C}_{3,1}(n) \) modulo 3, 8, 9, 18, 32, 36, 64, 72 and 144 have been proved. In this article, we prove new congruences modulo 108, 192, 288 and 432 for \( \overline{C}_{3,1}(n) \).

1. Introduction

Recently, Andrews [2] defined and studied combinatorial objects associated with parameters \( k \) and \( i \), which he termed as singular overpartitions. He proved that the number of such singular overpartitions is enumerated by \( \overline{C}_{k,i}(n) \), the number of overpartitions of \( n \) in which no part is divisible by \( k \) and only parts \( \equiv \pm i \) (mod \( k \)) may be overlined. For \( k \geq 3 \) and \( 1 \leq i \leq \lfloor k/2 \rfloor \), the generating function for \( \overline{C}_{k,i}(n) \) is given by

\[
\sum_{n=0}^{\infty} \overline{C}_{k,i}(n)q^n = \frac{(q^k; q^k)_\infty (-q^i; q^k)_\infty (q^k; q^k)_{\infty}}{(q; q)_\infty},
\]

(1)

¹Uha Isnaini was supported by the National Institute of Education (Singapore) PhD scholarship
²Pee Choon Toh was supported by the National Institute of Education (Singapore) Academic Research Fund (RI 3/12 TPC) and the Ministry of Education (Singapore) Academic Research Fund (MOE2014-T2-1-051)
where \((a; q)_\infty := \prod_{j=0}^{\infty} (1 - aq^j)\). To simplify notation, we shall use \(f_n\) to denote \((q^n; q^n)_\infty\).

Andrews paid particular interest to the case \((k, i) = (3, 1)\), with the generating function
\[
\sum_{n=0}^{\infty} \overline{C}_{3,1}(n)q^n = \frac{(q^3; q^3)_\infty (-q; q^3)_\infty (-q^2; q^3)_\infty}{(q; q)_\infty} = \frac{f_2f_3^2}{f_1f_6}.
\]

He noted that this is equivalent to \(\overline{A}_3(n)\), the number of overpartitions of \(n\) into parts not divisible by 3. (See [10] and [15] for more information on overpartitions.) Andrews further proved two congruences satisfied by \(\overline{C}_{3,1}(n)\).

**Theorem 1 (Andrews [2]).** For every nonnegative integer \(n\),
\[
\overline{C}_{3,1}(9n + 3) \equiv \overline{C}_{3,1}(9n + 6) \equiv 0 \pmod{3}.
\]

Andrews’ work attracted much interest and many articles proving new congruences satisfied by \(\overline{C}_{k,1}(n)\) appeared in quick succession. In the following, we recall selected results for \(\overline{C}_{3,1}(n)\). Chen, Hirschhorn and Sellers found several infinite families of congruences modulo 3 and 8. One of which is the following.

**Theorem 2 (Chen, Hirschhorn and Sellers [7]).** For all nonnegative integers \(\alpha\) and \(n\),
\[
\overline{C}_{3,1}(2^\alpha(6n + 5)) \equiv 0 \pmod{8}.
\]

Ahmed and Baruah [1] found several congruences modulo 18 and 36.

**Theorem 3 (Ahmed and Baruah [1]).** For every nonnegative integer \(n\),
\[
\begin{align*}
\overline{C}_{3,1}(48n + 12) & \equiv 0 \pmod{18}, \\
\overline{C}_{3,1}(12n + 7) & \equiv 0 \pmod{36}, \\
\overline{C}_{3,1}(12n + 11) & \equiv 0 \pmod{36}, \\
\overline{C}_{3,1}(24n + 14) & \equiv 0 \pmod{36}, \\
\overline{C}_{3,1}(24n + 22) & \equiv 0 \pmod{36}.
\end{align*}
\]

Shen [18] studied congruences modulo 9 and two of her results are the following.

**Theorem 4 (Shen [18]).** For every nonnegative integer \(n\),
\[
\begin{align*}
\overline{C}_{3,1}(48n + 28) & \equiv 0 \pmod{9}, \\
\overline{C}_{3,1}(48n + 44) & \equiv 0 \pmod{9}.
\end{align*}
\]
Yao [20] considered congruences modulo 16, 32 and 64 and proved the following.

**Theorem 5 (Yao [20]).** For every nonnegative integer \( n \),
\[
\begin{align*}
\overline{C}_{3,1}(18n + 15) &\equiv 0 \pmod{32}, \\
\overline{C}_{3,1}(24n + 23) &\equiv 0 \pmod{32}, \\
\overline{C}_{3,1}(72n + 69) &\equiv 0 \pmod{64}.
\end{align*}
\]

Mahadeva Naika and Gireesh [16] proved various congruences modulo 4, 6, 12, 24 and 72.

**Theorem 6 (Mahadeva Naika and Gireesh [16]).** For every nonnegative integer \( n \),
\[
\begin{align*}
\overline{C}_{3,1}(24n + 14) &\equiv 0 \pmod{72}, \\
\overline{C}_{3,1}(24n + 22) &\equiv 0 \pmod{72}.
\end{align*}
\]

In their article, Mahadeva Naika and Gireesh also conjectured a congruence modulo 144, which was proved independently by two groups of researchers.

**Theorem 7 (Kathiravan and Fathima [14], Barman and Ray [3]).** For every nonnegative integer \( n \),
\[
\overline{C}_{3,1}(12n + 11) \equiv 0 \pmod{144}.
\]

However, none of the three groups of researchers mentioned the existence of the following congruence.

**Theorem 8.** For every nonnegative integer \( n \),
\[
\overline{C}_{3,1}(24n + 23) \equiv 0 \pmod{288}.
\]

In this article, we shall prove the above mentioned theorem and establish other new congruences for \( \overline{C}_{3,1}(n) \). In fact, we can extend Theorem 8 by inserting an arbitrary number of pairs of primes of a certain type.

**Theorem 9.** Let \( p_1, \ldots, p_k \) be (not necessarily distinct) primes such that each \( p_i \geq 5 \) and has Legendre symbol \( \left( \frac{-2}{p_i} \right) = -1 \). Then for every nonnegative integer \( n \),
\[
\overline{C}_{3,1} \left( 24n + 23 \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{288}.
\]

Our next result is an extension of one of the congruences from Theorem 5.
Theorem 10. Let \( p_1, \ldots, p_k \) be (not necessarily distinct) primes such that each \( p_i \geq 5 \) and has Legendre symbol \( \left( \frac{-2}{p_i} \right) \) = \(-1\). Then for every nonnegative integer \( n \),

\[
\overline{C}_{3,1}\left( (72n + 69) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{192}.
\]

The final results of this article are the following generalizations of Theorem 4.

Theorem 11. For every nonnegative integer \( n \),

\[
\overline{C}_{3,1}(48n + 28) \equiv 0 \pmod{108}, \quad (15)
\]

\[
\overline{C}_{3,1}(48n + 44) \equiv 0 \pmod{432}. \quad (16)
\]

Both of the above congruences can also be extended.

Theorem 12. Let \( p_1, \ldots, p_k \) be (not necessarily distinct) primes such that each \( p_i \geq 5 \) and has Legendre symbol \( \left( \frac{-1}{p_i} \right) \) = \(-1\). Then for every nonnegative integer \( n \),

\[
\overline{C}_{3,1}\left( (48n + 28) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{108}, \quad (17)
\]

\[
\overline{C}_{3,1}\left( (48n + 44) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{108}. \quad (18)
\]

Our article is structured as follows. In the next section, we recall some preliminary results. In Section 3, we prove Theorem 8 and its generalization. In Section 4, we prove Theorem 10. The final section is devoted to establishing Theorem 11 and its corresponding generalization.

2. Preliminary Results

In this section, we first recall some results from the literature. The following is a 2-dissection due to Ramanujan.

Lemma 1.

\[
\frac{1}{f_1^4} = \frac{f_4^{14}}{f_2^{14} f_8^{14}} + 4 q \frac{f_2^4 f_8^4}{f_2^{14}}.
\]

This identity can be obtained by summing Entries 25(v) and 25(vi) in Chapter 16 of Ramanujan’s notebooks [5, p. 40]. An alternative proof is given in [19, Cor. 2.4].

Our next lemma is essentially the 2-dissection of one of the cubic theta functions and was proved in [12, Eq. (1.36)].
Lemma 2.  

\[ \frac{f_3^3}{f_1} = \frac{f_4^3 f_6^2}{f_2^2 f_1^2} + q \frac{f_2^3}{f_4}. \]

We also require the 3-dissection of the overpartition generating function that was proved by Hirschhorn and Sellers [13].

Lemma 3.  

\[ \frac{f_2}{f_1^2} = \frac{f_6^6 f_9^3}{f_3^3 f_1 f_8} + 2q \frac{f_3^3 f_3^3}{f_3^3} + 4q^2 \frac{f_2^2 f_1^1}{f_3^3}. \]

The following identities were proved by Baruah and Ojah, and appeared respectively as equation (4.37), Theorem 4.17 and Theorem 4.3 in [4].

Lemma 4.

\[ \frac{f_3^3}{f_1} = \frac{f_4^4 f_6^2 f_1^2}{f_2^2 f_8 f_2} + 2q \frac{f_3^3 f_8 f_2}{f_2^2 f_1}, \quad (19) \]

\[ \frac{f_3}{f_1} = \frac{f_6^6 f_9^3}{f_3^3 f_1} + 3q^2 \frac{f_3^3 f_1^1}{f_2^2}, \quad (20) \]

\[ \frac{1}{f_1 f_3} = \frac{f_2^2 f_5^5}{f_2^2 f_4 f_6 f_2} + q \frac{f_3^3 f_2^2}{f_2^2 f_6 f_8 f_1}. \quad (21) \]

We will use the following consequence of the binomial theorem throughout our article. For any positive integer \( k \) and prime \( p \),

\[ f_k^p \equiv f_{pk} \pmod{p}. \]

We now recall the special case of a result due to Newman [17].

Lemma 5. Let \( p \) be a prime satisfying \( p \equiv 3 \pmod{4} \). If

\[ \sum_{n=0}^{\infty} H(n) q^n = f_3^9, \]

then for every nonnegative integer \( n \),

\[ H \left( p^2 n + \frac{3(p^2 - 1)}{4} \right) = p^2 H(n). \]

An elementary proof of this result, depending on only the series expansion of \( f_1^3 \) can be found in [9]. We also require another two analogues of Newman’s result.

Lemma 6. Let \( p \) be a prime satisfying, \( p > 3 \) and \( p \equiv 3 \pmod{4} \). If

\[ \sum_{n=0}^{\infty} G(n) q^n = \left( \frac{f_6^6}{f_3^3} \right), \]
then for every nonnegative integer $n$,

\[ G \left( p^2 n + \frac{3(p^2 - 1)}{4} \right) = G(n). \]

Proof. Using the series expansion for $\frac{\mathcal{L}_3}{f_3}$ [5, p. 36], we have

\[
\sum_{n=0}^{\infty} G(n)q^n = \left( \sum_{j=-\infty}^{\infty} q^{\frac{3(4j+1)^2-3}{8}} \right)^2 = \sum_{\substack{j \equiv 1 \pmod{4} \atop k \equiv 1 \pmod{4}}} q^{(3j)^2 + (3k)^2 - 18}/24. \tag{22}
\]

Suppose $p > 3$ is a prime satisfying $p \equiv 3 \pmod{4}$, and

\[
p^2m + \frac{3(p^2 - 1)}{4} = \frac{(3j)^2 + (3k)^2 - 18}{24},
\]

which simplifies to

\[
(3j)^2 + (3k)^2 = 24pm + 18p^2 \equiv 0 \pmod{p}. \tag{23}
\]

Since $p$ cannot be represented as a sum of two squares, we conclude that $p \mid j$ and $p \mid k$. We can thus find $j'$ and $k'$ such that

\[
j = -j'p \quad \text{and} \quad k = -k'p.
\]

Now equation (23) becomes

\[
(3j')^2 + (3k')^2 = \frac{24m}{p} + 18.
\]

Thus

\[
G \left( pm + \frac{3(p^2 - 1)}{4} \right) = \sum_{\substack{j' \equiv 1 \pmod{4} \atop k' \equiv 1 \pmod{4} \atop (3j')^2 + (3k')^2 = \frac{24m}{p} + 18}} 1
\]

\[= G \left( \frac{m}{p} \right). \tag{24}\]

Our second analogue of Lemma 5 is the following.
Lemma 7. Let $p$ be a prime satisfying $p \geq 5$ and with Legendre symbol $\left( \frac{-2}{p} \right) = -1$. If

$$\sum_{n=0}^{\infty} F(n)q^n = f_4f_6^3,$$

then for every nonnegative integer $n$,

$$F\left( p^2n + \frac{11(p^2 - 1)}{12} \right) = \epsilon p F(n),$$

where

$$\epsilon = \begin{cases} 1 & \text{if } p \equiv 7, 13 \pmod{24}, \\ -1 & \text{if } p \equiv 5, 23 \pmod{24}. \end{cases}$$

Proof. Using the series expansions for $f_4$ and $f_6^3$ [5, p. 36 and p. 39], we have

$$\sum_{n=0}^{\infty} F(n)q^n = \left( \sum_{i=-\infty}^{\infty} (-1)^i q^{\frac{(4i+1)^2-1}{6}} \right) \left( \sum_{i=-\infty}^{\infty} (4i + 1)q^{\frac{2(4i+1)^2-1}{4}} \right)$$

$$= \sum_{\substack{j \equiv 1 \pmod{4} \atop k \equiv 1 \pmod{6}}} (-1)^{(k-1)/6} j q^{(3j)^2 + 2k^2 - 11}/12. \quad (25)$$

Suppose $p \geq 5$ is a prime such that

$$pm + 11(p^2 - 1) = \frac{(3j)^2 + 2k^2 - 11}{12},$$

which simplifies to

$$(3j)^2 + 2k^2 = 12pm + 11p^2 \equiv 0 \pmod{p}. \quad (26)$$

However, since $-2$ is a quadratic non-residue modulo $p$, we conclude that $p \mid j$ and $p \mid k$. We can thus find $j'$ and $k'$ such that

$$j = \epsilon_j j'p \quad \text{and} \quad k = \epsilon_k k'p$$

where

$$\epsilon_j = \begin{cases} 1 & \text{if } p \equiv 1 \pmod{4}, \\ -1 & \text{if } p \equiv 3 \pmod{4}; \end{cases} \quad \text{and} \quad \epsilon_k = \begin{cases} 1 & \text{if } p \equiv 1 \pmod{6}, \\ -1 & \text{if } p \equiv 5 \pmod{6}. \end{cases}$$

Furthermore equation (26) becomes

$$(3j')^2 + 2(k')^2 = \frac{12m}{p} + 11.$$
Thus
\[
F \left( pm + \frac{11(p^2 - 1)}{12} \right) = \sum_{\substack{j' \equiv 1 \\ (3j')^2 + 2(k')^2 = \frac{12p}{p+1} + 11 \atop k' \equiv 1 \pmod{6} \atop j' \equiv 1 \pmod{4}}} (-1)^{(s,j'p-1)/6} \epsilon_j j' p
\]
\[
= \epsilon pF \left( \frac{m}{p} \right),
\]
where \( \epsilon \) is defined in the statement of the Lemma.

3. Proofs of Theorems 8 and 9

As mentioned in the introduction, Theorem 7 was proved by Kathiravan and Fathima, and also independently by Barman and Ray. The two proofs are almost identical and begin with the following result [16, Eq. (3.19)],

\[
\sum_{n=0}^{\infty} C_{3,1}(4n + 3)q^n = 6\frac{f_2^3 f_6^3}{f_3^2} = 6f_6^3 \left( \frac{f_2}{f_3^2} \right)^3.
\]

Substituting Lemma 3 gives

\[
\sum_{n=0}^{\infty} C_{3,1}(4n + 3)q^n = 6\frac{f_2^3 f_6^3}{f_3^2} + 36q\frac{f_6^2 f_9^2}{f_3^3 f_9^2} + 144q^2\frac{f_6^2 f_9^2}{f_3^3 f_9} + 336q^3\frac{f_6^2 f_9^3}{f_3^3 f_9^3} + 576q^4\frac{f_6^2 f_9^3}{f_3^3 f_9^3} + 384q^5\frac{f_6^2 f_9^3}{f_3^3 f_9^3}.
\]

Extracting coefficients of \( q^{3n+2} \), we get

\[
\sum_{n=0}^{\infty} C_{3,1}(12n + 11)q^n = 144\frac{f_2^3 f_3^2}{f_3^2 f_6} + 576q\frac{f_2^3 f_3^2}{f_3^2 f_6}.
\]

which appeared in both [14] and [3]. Next using the binomial theorem, the above equation can be written as

\[
\sum_{n=0}^{\infty} C_{3,1}(12n + 11)q^n \equiv 144f_4f_6^3 \pmod{288},
\]

We first observe that extracting coefficients of \( q^{2n+1} \) completes the proof of Theorem 8. In fact, if we are only interested in proving Theorem 8, we can simply combine the two congruences (5) and (11). However, Lemma 7 allows us to generalize equation (31). We have

\[
\sum_{n=0}^{\infty} C_{3,1}(12n + 11)q^n \equiv 144\sum_{n=0}^{\infty} F(n)q^n \pmod{288}.
\]
Now let \( p \) be any prime satisfying the conditions in Lemma 7, then
\[
C_{3,1}(12p^2n + 11p^2) \equiv 144epF(n) \equiv 144F(n) \pmod{288}.
\] (33)

Continuing the process by induction, we can insert any number of copies of \( p^2 \) into the congruence. Finally extracting terms involving \( p^{2n+1} \) completes the proof of
Theorem 9.

4. Proof of Theorem 10

We first observe that combining the second congruence from Theorem 1 with con-
gruences (10) and (12) respectively proves the following.

**Corollary 1.** For every nonnegative integer \( n \),
\[
C_{3,1}(18n + 15) \equiv 0 \pmod{96},
\] (34)
\[
C_{3,1}(72n + 69) \equiv 0 \pmod{192}.
\] (35)

However, we cannot use the latter congruence as a basis to prove Theorem 10. Our starting point is the following identity that was proved in [20, Equation (3.13)]
\[
\sum_{n=0}^{\infty} C_{3,1}(9n + 6)q^n = 24\frac{f_2^7 f_3^{12}}{f_1^6 f_6^3} + 96q\frac{f_2^4 f_3^3 f_6^6}{f_1^{13}}.
\] (36)

Using Lemma 1 and identity (19), we find that
\[
24\frac{f_2^7}{f_3^3} \left( \frac{f_2^3}{f_1^2} \right)^6 \left( \frac{1}{f_1^4} \right) = 24\frac{f_2^{38} f_3^6 f_6^{12}}{f_2^{32} f_2^{10} f_6^{24}} + 96q\frac{f_2^{26} f_3^6 f_6^{12}}{f_2^3 f_6^{24}} + 96q\frac{f_2^{35} f_6^6}{f_2^2 f_6^{24}} + 96q^2\frac{f_2^{32} f_6^6 f_6^{12}}{f_2 f_6^{24}} (\text{mod } 192),
\] (37)

Likewise expanding with Lemma 2 gives
\[
96q\frac{f_2^4 f_6^6}{f_2 f_6} \left( \frac{f_3}{f_1} \right)^3 \left( \frac{1}{f_1^4} \right)^3 = 96q\frac{f_2^{15} f_6^8}{f_2^{20} f_6^{12}} + 96q^2\frac{f_6^6 f_6^{12}}{f_2^{35} f_6^{24}} (\text{mod } 192).
\] (38)

Combining the two previous equations and simplifying with the binomial theorem, we have
\[
\sum_{n=0}^{\infty} C_{3,1}(18n + 15)q^n \equiv 96 \left( \frac{f_2^{26} f_3^3 f_6^{12}}{f_1^{34} f_2^{12} f_6^{12}} + \frac{f_2^{35} f_3^4 f_6^6}{f_1^{36} f_4^{12} f_6^{12}} + \frac{f_2^{45} f_6^8}{f_2^{40} f_4^{12} f_6^{12}} \right)
\equiv 96 f_2^{22} \left( \frac{f_3}{f_1} \right) \left( \frac{1}{f_1^4} \right)^8 (\text{mod } 192)
\] (39)
which implies congruence (34).

We shall now 2-dissect each of the products of the right side of congruence (39). We use Lemmas 1 and 2 to compute that

\[
f_2^{22} \left( \frac{f_3}{f_1} \right) \left( \frac{1}{f_3} \right)^8 = \frac{f_1^{111} f_6^2}{f_2^{90} f_4^{32}} + q \frac{f_1^{111} f_1^{12}}{f_2^{90} f_4^{32}} \pmod{2}. \tag{40}
\]

This means

\[
\sum_{n=0}^{\infty} C_{3,1}(36n + 33)q^n \equiv 96 \frac{f_1^{111} f_6^2}{f_2^{90} f_4^{32}} \pmod{192} \equiv 96 f_4 f_6^2 \pmod{192} \equiv 96 \sum_{n=0}^{\infty} F(n)q^n \pmod{192}. \tag{41}
\]

As in the previous section, if \( p \) is any prime satisfying the conditions in Lemma 7, then

\[
C_{3,1}(36p^2 n + 33p^2) \equiv 96 F(n) \pmod{192}. \tag{42}
\]

We can continue to insert any number of copies of \( p_i^2 \) before finally extracting coefficients of \( q^{2n+1} \) to prove Theorem 10.

5. Proof of Theorems 11 and 12

The proof of Theorem 11 is more intricate. In order to simplify our proof, we introduce the following three functions defined by their generating functions:

\[
\sum_{n=0}^{\infty} A(n)q^n := \frac{f_2^{19} f_3^6 f_1^{12}}{f_1^{18} f_2 f_6}, \tag{43}
\]

\[
\sum_{n=0}^{\infty} B(n)q^n := \frac{f_2^{13} f_2^2 f_2^2 f_6^3}{f_1^{14} f_4 f_6^2}, \tag{44}
\]

\[
\sum_{n=0}^{\infty} C(n)q^n := \frac{f_2^{13} f_4 f_4 f_2^2 f_1^{12}}{f_1^{12}}. \tag{45}
\]

We now prove several lemmas involving these functions.

**Lemma 8.** For every nonnegative integer \( n \),

\[
A(6n + 3) + 9B(6n + 3) \equiv 0 \pmod{27},
\]

\[
A(6n + 5) + 9B(6n + 5) \equiv 0 \pmod{27}.
\]
Proof. We can rewrite
\[ \sum_{n=0}^{\infty} A(n)q^n = \frac{f_2^{19}f_4^2}{f_3^4f_6^3} \left( \frac{f_3}{f_1} \right)^6, \] (46)
\[ \sum_{n=0}^{\infty} B(n)q^n = \frac{f_2^3f_4^3}{f_3^2f_6^1} \left( \frac{f_3}{f_1} \right)^4 \left( \frac{1}{f_1^2f_3^1} \right), \] (47)

Using identities (20) and (21), we can extract the coefficients of \( q^{2n+1} \) to get
\[ \sum_{n=0}^{\infty} A(2n+1)q^n = 9 \sum_{n=0}^{\infty} B(2n+1)q^n = 18 \frac{f_2^{30}f_3^9}{f_1^{33}f_6^7} \equiv (\text{mod } 27). \] (48)

By the binomial theorem, we have
\[ 18 \frac{f_2^{30}f_3^9}{f_1^{33}f_6^7} \equiv 18 \frac{f_4^4}{f_3^2} \equiv (\text{mod } 27). \]

Extracting the coefficients of \( q^{3n+1} \) and \( q^{3n+2} \) separately proves the lemma. \( \square \)

Recall that the theta function \( \varphi(q) \) has the following infinite product representation:
\[ \varphi(q) := 1 + 2 \sum_{n=1}^{\infty} q^{n^2} = \frac{f_2^5}{f_1^2f_4^2}. \] (49)

Ramanujan proved many identities involving combinations of \( \varphi(q)^2 \) and \( \varphi(q^3)^2 \).

Lemma 9. The following hold:
\[ \varphi(q^3)^2 + \varphi(q)^2 = \frac{f_6^{10}}{f_3^4f_1^2} + \frac{f_2^{10}}{f_4^1f_1^4} = 2 \frac{f_2^3f_3^2f_6}{f_1^7f_4f_12}, \] (50)
\[ 3\varphi(q^3)^2 - \varphi(q)^2 = 3 \frac{f_6^{10}}{f_3^4f_1^2} - \frac{f_2^{10}}{f_4^1f_1^4} = 2 \frac{f_1^4f_2^6}{f_3^2f_4f_12}, \] (51)
\[ 3\varphi(q^3)^2 + \varphi(q)^2 = 3 \frac{f_6^{10}}{f_3^4f_1^2} + \frac{f_2^{10}}{f_4^1f_1^4} = 4 \frac{f_2^3f_3^2f_6}{f_1^7f_4f_12}. \] (52)

Identity (50) can be found in [5, p. 351, line 3] while identity (51) is in [5, p. 232, line 20]. Identity (52) can be deduced by combining Entry 44 in Chapter 25 of Ramanujan’s notebooks [6, p. 197] and identity (50). Alternative proofs of Lemma 9 can also be found in Chapter 34 of [11] or derived from [8, Theorem 3.25]. Identity (50) is also equivalent to the following.

Corollary 2. We have
\[ 27q \frac{f_2^{11}f_3^4f_6f_1^2}{f_1^{14}f_4^3} + 27q \frac{f_2^2f_3^6f_6^{11}}{f_1^{30}f_3^4f_1^2} = 54 \sum_{n=0}^{\infty} C(n)q^n. \]
Lemma 10. For every nonnegative integer $n$,

$$A(2n + 1) + 9B(2n + 1) \equiv 0 \pmod{16}.$$  

Proof. We consider the generating functions of $A(n)$ and $B(n)$,

$$
\sum_{n=0}^{\infty} A(n)q^n + 9 \sum_{n=0}^{\infty} B(n)q^n = \frac{f_2^{19}f_3^6f_2^2}{f_1^{18}f_2^4f_6^7} + 9\frac{f_2^{16}f_3^6f_2^4f_6^3}{f_1^{14}f_2^2f_6^5} \\
= (\varphi(q)^2 + 9\varphi(q^3)^2) \frac{f_2^{16}f_3^6f_2^4f_6^3}{f_1^{14}f_6^5} \\
= (6\varphi(q^3)^2 + 2\varphi(q)^2 + 3\varphi(q^3)^2 - \varphi(q)^2) \frac{f_2^{16}f_3^6f_2^4f_6^3}{f_1^{14}f_6^5} \\
= \left(8 \frac{f_2^3f_3^6f_3^2f_2^2}{f_1f_3f_2f_6} + 2 \frac{f_2^3f_4f_6^3}{f_2^3f_4f_6} \right) \frac{f_2^3f_3^6f_2^4f_6^3}{f_1^{14}f_6^5},
$$

(53)

where Lemma 9 was used. Now using the binomial theorem, we have

$$
\sum_{n=0}^{\infty} A(n)q^n + 9 \sum_{n=0}^{\infty} B(n)q^n \equiv 8 \left(\frac{1}{f_1f_3} \right)^3 f_2^{12} + 2 \left(\frac{f_3}{f_1} \right)^4 \frac{f_2^{10}f_4f_6^3}{f_4^6} \pmod{16}.
$$

Using identities (20) and (21), we can extract the coefficients of $q^{2n+1}$ to get

$$
\sum_{n=0}^{\infty} A(2n + 1)q^n + 9 \sum_{n=0}^{\infty} B(2n + 1)q^n \\
\equiv 8 \left(3 \frac{f_1^4f_2^3f_2^2f_6^3}{f_3^{10}f_2^{12}} + 9 \frac{f_2^{15}f_3^6}{f_3^3f_4f_6^3} \right) \\
+ 2 \left(12 \frac{f_2^{21}f_3^6}{f_4^{14}f_3^8} + 108q \frac{f_2^{13}f_3^2f_5^5}{f_2^{10}} \right) \pmod{16} \\
\equiv 8 \left(f_1^{18} + qf_6^4f_3^{12} \right) + 8 \left(f_1^{18} + qf_1^{6}f_3^{12} \right) \pmod{16} \\
\equiv 0 \pmod{16}.
$$

(54)

The proof follows.

\[ \square \]

Lemma 11. For every nonnegative integer $n$,

$$C(3n) \equiv 0 \pmod{2},$$

$$C(6n + 5) \equiv 0 \pmod{8}.$$  

(55)\hspace{1cm} (56)

Proof. We write the generating function $C(n)$ as

$$
\sum_{n=0}^{\infty} C(n)q^n = qf_3^4f_6^2f_2^6 \left(\frac{f_2}{f_1^2} \right) \left(\frac{f_4}{f_2^3} \right).
$$

(57)
Applying Lemma 3 and a second time with $q^2$ in place of $q$, we can 3-dissect the above identity. Equating coefficients of $q^{3n}$ proves equation (55). Next, we can extract coefficients of $q^{3n+2}$ to get

\[
\sum_{n=0}^{\infty} C(3n+2)q^n = 4f_2^{17} f_3^{33} f_4^{15} f_6^{0} + 4q f_2^{20} f_3^{36} f_4^{13} f_6^{12} \pmod{8}
\]

\[
\equiv 4f_2^6 f_6^2 \left( \frac{1}{f_1 f_3} \right) + 4q f_2^4 f_6^6 \pmod{8}.
\]

(58)

Using identity (21) and equating coefficients of $q^{2n+1}$, yields

\[
\sum_{n=0}^{\infty} C(6n + 5)q^n \equiv 4f_2^{18} f_6^{0} + 4f_2^{2} f_6^{4} \pmod{8}
\]

\[
\equiv 0 \pmod{8}.
\]

(59)

where the last congruence results from the binomial theorem.

We are now ready for the proof of Theorem 11.

**Proof.** From [16, Eq.(3.14)],

\[
\sum_{n=0}^{\infty} C_{3,1}(2n)q^n = \frac{f_2^{13} f_6^2}{f_2^{10} f_4 f_6} + 4q f_2 f_4 f_6^2 f_8 f_6 f_12
\]

(60)

Equating the coefficients of $q^{2n}$ we have

\[
\sum_{n=0}^{\infty} C_{3,1}(4n)q^n = \frac{f_2^{13} f_6^2}{f_2^{10} f_4 f_6} = \frac{f_2^{13} f_6^2}{f_2^{10} f_4 f_6} \left( \frac{f_4}{f_2} \right)^3 \left( \frac{1}{f_1 f_3} \right).
\]

(61)

Using identities (20) and (21), we can equate coefficients of $q^{2n+1}$ to get

\[
\sum_{n=0}^{\infty} C_{3,1}(8n + 4)q^n = \frac{f_2^{19} f_6^2 f_6}{f_2^{18} f_4 f_6 f_6} + 9 \frac{f_2^{18} f_6^2 f_6}{f_2^{14} f_4 f_6 f_6} + 27q \frac{f_2^{11} f_4^2 f_6 f_6}{f_2^{11} f_4 f_4 f_6} + 27q \frac{f_2 f_2 f_4^2 f_6}{f_2^{11} f_4 f_4 f_6}
\]

\[
= \sum_{n=0}^{\infty} A(n)q^n + 9 \sum_{n=0}^{\infty} B(n)q^n + 54 \sum_{n=0}^{\infty} C(n)q^n,
\]

(62)

where Corollary 2 was used in the final equality. By Lemma 8, we have

\[
\sum_{n=0}^{\infty} C_{3,1}(48n + 28)q^n \equiv \sum_{n=0}^{\infty} A(6n + 3)q^n + 9 \sum_{n=0}^{\infty} B(6n + 3)q^n \pmod{27}
\]

\[
\equiv 0 \pmod{27},
\]

(63)
as well as
\[
\sum_{n=0}^{\infty} C_{3,1}(48n + 44)q^n \equiv \sum_{n=0}^{\infty} A(6n + 5)q^n + 9 \sum_{n=0}^{\infty} B(6n + 5)q^n \pmod{27}
\]
\[
\equiv 0 \pmod{27}. \tag{64}
\]

On the other hand, Lemmas 10 and 11 give
\[
\sum_{n=0}^{\infty} C_{3,1}(48n + 28)q^n \equiv \sum_{n=0}^{\infty} A(6n + 3)q^n + 9 \sum_{n=0}^{\infty} B(6n + 3)q^n
\]
\[
+ 2 \sum_{n=0}^{\infty} C(6n + 3)q^n \pmod{4}
\]
\[
\equiv 0 \pmod{4}. \tag{65}
\]

Similarly,
\[
\sum_{n=0}^{\infty} C_{3,1}(48n + 44)q^n \equiv \sum_{n=0}^{\infty} A(6n + 5)q^n + 9 \sum_{n=0}^{\infty} B(6n + 5)q^n
\]
\[
+ 6 \sum_{n=0}^{\infty} C(6n + 5)q^n \pmod{16}
\]
\[
\equiv 0 \pmod{16}. \tag{66}
\]

Since 27 is relatively prime to 4 and 16, this completes the proof of Theorem 11. \qed

Finally, we prove Theorem 12.

Proof. Recall that in the proof of Lemma 8, we have
\[
\sum_{n=0}^{\infty} A(2n + 1)q^n \equiv 9 \sum_{n=0}^{\infty} B(2n + 1)q^n \equiv 18 \frac{f_6^4}{f_3^2} \pmod{27}. \tag{67}
\]

Thus, we can deduce from equation (62) that
\[
\sum_{n=0}^{\infty} C_{3,1}(16n + 12)q^n \equiv \sum_{n=0}^{\infty} A(2n + 1)q^n + 9 \sum_{n=0}^{\infty} B(2n + 1)q^n \pmod{27}
\]
\[
\equiv 9 \left( \frac{f_6^2}{f_3} \right)^2 \pmod{27}, \tag{68}
\]

Lemma 6 allows us to generalize congruence (68). We have
\[
\sum_{n=0}^{\infty} C_{3,1}(16n + 12)q^n \equiv 9 \sum_{n=0}^{\infty} G(n)q^n \pmod{27}. \tag{69}
\]
Now let $p > 3$ be a prime satisfying $p \equiv 3 \pmod{4}$, then
\[ C_{3,1}(16p^2n + 12p^2) \equiv 9G(n) \pmod{27}. \] (70)
Continuing the process by induction, we can insert any number of copies of $p_i^2$ into the congruence. Extracting terms involving $q^{3n+1}$ and $q^{3n+2}$ separately, we get
\[
C_{3,1} \left( (48n + 28) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{27}, \] (71)
\[
C_{3,1} \left( (48n + 44) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{27}. \] (72)
On the other hand, we have
\[
\sum_{n=0}^{\infty} C(n)q^n = q \left( \frac{f_3^2}{f_1^2} \right)^2 \left( \frac{1}{f_1^2} \right)^2 f_2^4 f_4 f_6 f_{12}.
\] (73)
Using Lemma 1 and identity (19), we can extract the coefficients of $q^{2n+1}$ to get
\[
\sum_{n=0}^{\infty} C(2n+1)q^n \equiv \frac{f_3^{37} f_4 f_6^5}{f_1^{34} f_4^{10} f_{12}^3} \pmod{2}
\equiv (f_3^3)^2 \pmod{2}.
\] (74)
From equation (62), Lemma 10 and congruence (74), we have
\[
\sum_{n=0}^{\infty} C_{3,1}(16n + 12)q^n \equiv 2 \sum_{n=0}^{\infty} C(2n+1)q^n \pmod{4}
\equiv 2 (f_3^3)^2 \pmod{4}.
\] (75)
Lemma 5 allows us to generalize congruence (75). We have
\[
\sum_{n=0}^{\infty} C_{3,1}(16n + 12)q^n \equiv 2 \sum_{n=0}^{\infty} H(n)q^n \pmod{4}.
\] Now let $p > 3$ be a prime satisfying $p \equiv 3 \pmod{4}$, then
\[
C_{3,1}(16p^2n + 12p^2) \equiv 2p^2 H(n) \equiv 2H(n) \pmod{4}.
\]
Continuing the process by induction, we can insert the same sequence of primes $p_i^2$ as congruences (71) and (72). Extracting terms involving $q^{3n+1}$ and $q^{3n+2}$ separately, we get
\[
C_{3,1} \left( (48n + 28) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{4}, \] (76)
\[
C_{3,1} \left( (48n + 44) \prod_{i=1}^{k} p_i^2 \right) \equiv 0 \pmod{4}. \] (77)
Since 27 and 4 are relatively prime, this completes the proof of Theorem 12. □

Acknowledgements We thank Mike Hirschhorn and the anonymous referee for their helpful comments.

References


