



Research Repository UCD

Title	Supercongruences for sporadic sequences
Authors(s)	Sahu, Brundaban, Osburn, Robert, Straub, Armin
Publication date	2016-05
Publication information	Sahu, Brundaban, Robert Osburn, and Armin Straub. "Supercongruences for Sporadic Sequences." Cambridge University Press, May 2016. https://doi.org/10.1017/S0013091515000255 .
Publisher	Cambridge University Press
Item record/more information	http://hdl.handle.net/10197/7821
Publisher's version (DOI)	10.1017/S0013091515000255

Downloaded 2025-05-23 04:46:50

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

SUPERCONGRUENCES FOR SPORADIC SEQUENCES

ROBERT OSBURN, BRUNDABAN SAHU AND ARMIN STRAUB

Dedicated to Frits Beukers on the occasion of his 60th birthday

ABSTRACT. We prove two-term supercongruences for generalizations of recently discovered sporadic sequences of Cooper. We also discuss recent progress and future directions concerning other types of supercongruences.

1. INTRODUCTION

The term *supercongruence* first appeared in Beukers' work [4] and was the subject of the Ph.D. thesis of Coster [13]. It refers to the fact that congruences of a certain type are stronger than those suggested by formal group theory. A motivating example in [4] and [13] is the Apéry numbers

$$(1) \quad A(n) = \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{k}^2$$

which not only satisfy [17]

$$(2) \quad A(mp) \equiv A(m) \pmod{p^3},$$

but the *two-term supercongruence* [13]

$$(3) \quad A(mp^r) \equiv A(mp^{r-1}) \pmod{p^{3r}}$$

for primes $p \geq 5$ and integers $m, r \geq 1$. In 1985, Beukers related these numbers to the p -th Fourier coefficient $a(p)$ of $\eta^4(2z)\eta^4(4z)$, where

$$\eta(z) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n)$$

is the Dedekind eta function and $q = e^{2\pi iz}$, with z in the upper half-plane. He proved that [5]

$$(4) \quad A\left(\frac{p-1}{2}\right) \equiv a(p) \pmod{p}$$

and then conjectured that (4) holds modulo p^2 . In [2], Ahlgren and Ono proved this *modular supercongruence* using Gaussian hypergeometric series [21]. The techniques in [2] have been the basis for several recent results of this type (see [16], [25], [27], [29]–[32], [36]). Other types of supercongruences are

Date: June 17, 2014.

2010 Mathematics Subject Classification. Primary: 11A07, 11B83.

also of considerable interest. *Ramanujan-type supercongruences* are p -adic versions of formulas of Ramanujan which relate binomial sums to special values of the gamma function (or $1/\pi^a$, $a \geq 1$). For example, van Hamme [39] conjectured that for Ramanujan's formula

$$\sum_{k=0}^{\infty} (4k+1) \binom{-1/2}{k}^5 = \frac{2}{\Gamma(3/4)^4},$$

we have the p -adic analogue

$$(5) \quad \sum_{k=0}^{(p-1)/2} (4k+1) \binom{-1/2}{k}^5 \equiv \begin{cases} -\frac{p}{\Gamma_p(3/4)^4} & (\text{mod } p^3), \text{ if } p \equiv 1 \pmod{4}, \\ 0 & (\text{mod } p^3), \text{ if } p \equiv 3 \pmod{4}, \end{cases}$$

where $\Gamma_p(\cdot)$ is the p -adic gamma function. For a proof of (5), see [28]. For recent progress in this direction, see [11], [16], [22], [23], [26], [33] or [41]. Finally, *Atkin–Swinnerton-Dyer* supercongruences have been recently studied in [14], [15], [24] and [37].

In this paper, we consider the sequences of numbers given by

$$(6) \quad s_7(n) = \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{k} \binom{2k}{n}$$

as well as

$$(7) \quad s_{18}(n) = \sum_{k=0}^{\lfloor n/3 \rfloor} (-1)^k \binom{n}{k} \binom{2k}{k} \binom{2(n-k)}{n-k} \left[\binom{2n-3k-1}{n} + \binom{2n-3k}{n} \right],$$

with $s_{18}(0) = 1$. These “sporadic” sequences were recently discovered by Cooper [12] while performing a numerical search for sequences which appear as coefficients of series for $1/\pi$ and of series expansions in t of modular forms where t is a modular function. Here, the subscripts 7 and 18 are used in (6) and (7) as the associated modular function is of level 7 and 18, respectively (see Theorem 3.1 in [12]). In [12], Cooper searched for parameters (a, b, c, d) such that the recurrence relation

$$(8) \quad (n+1)^3 s(n+1) = (2n+1)(an^2 + an + b)s(n) - n(cn^2 + d)s(n-1),$$

with initial conditions $s(-1) = 0$, $s(0) = 1$, produces only integer values $s(n)$ for all $n \geq 0$. The tuple $(17, 5, 1, 0)$ corresponds to the Apéry numbers (1), while the tuples $(13, 4, -27, 3)$ and $(14, 6, -192, 12)$ correspond to the sequences $s_7(n)$ and $s_{18}(n)$, respectively. See [3] for the case $d = 0$. This search was motivated by Beukers' [6] and Zagier's [40] work on sequences $t(n)$ defined by

$$(9) \quad (n+1)^2 t(n+1) = (an^2 + an + b)t(n) - cn^2 t(n-1),$$

with initial conditions $t(-1) = 0$, $t(0) = 1$, such that $t(n) \in \mathbb{Z}$ for all $n \geq 0$. Zagier's search yielded six sequences that are not either terminating,

polynomial, hypergeometric or Legendrian. These six sequences were called *sporadic*.

Interestingly, Cooper conjectured the following congruences (see Conjecture 5.1 in [12]) which are reminiscent of (2).

Conjecture 1.1. *For any prime $p \geq 3$,*

$$(10) \quad s_7(mp) \equiv s_7(m) \pmod{p^3}.$$

Likewise, for any prime p ,

$$(11) \quad s_{18}(mp) \equiv s_{18}(m) \pmod{p^2}.$$

The purpose of this paper is to exhibit that (10) and (11) are special cases of general two-term supercongruences. For integers A, B, C , let

$$(12) \quad \mathcal{S}(n; A, B, C) = \sum_{k=0}^n \binom{n}{k}^A \binom{n+k}{k}^B \binom{2k}{n}^C.$$

Note that this family of sequences includes the Apéry numbers as well as the sequence $s_7(n)$.

Our main results are the following supercongruences, the first of which, in particular, generalizes the supercongruence (3) for the Apéry numbers.

Theorem 1.2. *Let $A \geq 2$ and $B, C \geq 0$ be integers. For any integers $m, r \geq 1$ and primes $p \geq 5$, we have*

$$(13) \quad \mathcal{S}(mp^r; A, B, C) \equiv \mathcal{S}(mp^{r-1}; A, B, C) \pmod{p^{3r}}.$$

Theorem 1.3. *For any integers $m, r \geq 1$ and any primes p , we have*

$$(14) \quad s_{18}(mp^r) \equiv s_{18}(mp^{r-1}) \pmod{p^{2r}}.$$

Note that by taking $(A, B, C) = (2, 1, 1)$ and $r = 1$ in Theorem 1.2, we prove (10) of Conjecture 1.1 for primes $p \geq 5$. Moreover, Theorem 1.2 shows a general supercongruence for the sporadic sequence

$$\sum_{k=0}^n \binom{n}{k}^2 \binom{2k}{n}^2,$$

which is case (ϵ) in [3] (see also Table 2 in Section 4). On the other hand, we remark that Theorem 1.3 is considerably simpler than Theorem 1.2 because it suffices to consider each summand of the sum (7), defining $s_{18}(n)$, individually. In both cases, our proof of the congruences of Conjecture 1.1 relies on the presence of the binomial sums (6) and (7) which were discovered by Zudilin.

Finally, we should mention that Cooper [12] conjectures congruences similar to (10) for $p = 2$, as well as a stronger version of (11) for $p = 2, 3$. These conjectures as well as (10) for $p = 3$ remain open. Based on numerical evidence, we actually conjecture that

$$(15) \quad s_7(m2^r) \equiv s_7(m2^{r-1}) \pmod{2^{3r+2}}$$

for $m \geq 4$ and

$$(16) \quad s_7(m3^r) \equiv s_7(m3^{r-1}) \pmod{3^{3r}}$$

for any positive integer m , as well as

$$(17) \quad s_{18}(m2^r) \equiv s_{18}(m2^{r-1}) \pmod{2^{2r+3}}$$

for $m \geq 2$ and

$$(18) \quad s_{18}(m3^r) \equiv s_{18}(m3^{r-1}) \pmod{3^{3r-1}}$$

for $m \geq 3$ (for $r = 1$ the congruence (18) empirically holds modulo 3^3). Slightly weaker congruences appear to hold in the cases when m is not large enough. We expect that these conjectures, which naturally generalize the ones from [12], can be established using the techniques we use in the case $p \geq 5$ when coupled with a careful and likely very technical analysis of the kind presented at the end of our proof of Theorem 1.3.

The remainder of the paper is organized as follows. Section 2 is devoted to the proofs of Theorems 1.2 and 1.3. We then indicate in Section 3 that these proofs readily generalize to other sequences of interest. In Section 4, we conclude with remarks concerning future directions. In particular, we discuss both proven and conjectural two-term supercongruences for all known sporadic sequences.

2. PROOF OF THEOREMS 1.2 AND 1.3

Throughout this section, following [4], we let \sum' denote the sum over indices not divisible by p .

We first recall the following version of Jacobsthal's binomial congruence [7]. For a proof, when $a, b \geq 0$, we refer to [18], [20], while the extension to negative integers is discussed in [38]. Similar congruences hold [18, 38] in the cases $p = 2$ and $p = 3$.

Lemma 2.1. *For primes $p \geq 5$, integers a, b and integers $r, s \geq 1$,*

$$(19) \quad \binom{p^r a}{p^s b} / \binom{p^{r-1} a}{p^{s-1} b} \equiv 1 \pmod{p^{r+s+\min(r,s)}}.$$

We will also make use, in the case $n = -2$, of the following simple congruences.

Lemma 2.2. *Let p be a prime and n an integer such that $n \not\equiv 0$ modulo $p-1$. Then, for all integers $r \geq 0$,*

$$(20) \quad \sum_{k=1}^{p^r-1} k^n \equiv 0 \pmod{p^r}.$$

If, additionally, n is even, then, for primes $p \geq 5$,

$$(21) \quad \sum_{k=1}^{(p^r-1)/2} \frac{1}{k^n} \equiv 0 \pmod{p^r}.$$

Proof. Since $n \not\equiv 0$ modulo $p-1$, we find an integer λ , not divisible by p , such that $\lambda^n \not\equiv 1$ modulo p . Then,

$$\lambda^n \sum_{k=1}^{p^r-1} k^n = \sum_{k=1}^{p^r-1} (\lambda k)^n \equiv \sum_{k=1}^{p^r-1} k^n \pmod{p^r},$$

since the second and third sum run over the same residues modulo p^r . As λ^n is not divisible by p , the congruence (20) follows.

Congruence (21) follows since the sum in (21), modulo p^r , is exactly half of the sum in (20) if n is even. \square

Lemma 2.3. *For integers $n, k \geq 1$ and $A, B, C \geq 0$, define*

$$\mathcal{B}(n, k) = \mathcal{B}(n, k; A, B, C) = \binom{n}{k}^A \binom{n+k}{k}^B \binom{2k}{n}^C.$$

Then, for primes $p \geq 5$ and integers $A \geq 2, r, s \geq 1$ and $k \geq 0$ such that $p \nmid k$,

$$(22) \quad \mathcal{B}(np^r, kp^s) \equiv \mathcal{B}(np^{r-1}, kp^{s-1}) \pmod{p^{3r}}.$$

Proof. By Jacobsthal's congruence (19), we have

$$\binom{np^r}{kp^s} / \binom{np^{r-1}}{kp^{s-1}} \equiv 1 \pmod{p^{r+s+\min(r,s)}}$$

as well as

$$\binom{np^r + kp^s}{np^r} / \binom{np^{r-1} + kp^{s-1}}{np^{r-1}} \equiv 1 \pmod{p^{r+2\min(r,s)}}$$

and

$$\binom{2kp^s}{np^r} / \binom{2kp^{s-1}}{np^{r-1}} \equiv 1 \pmod{p^{r+s+\min(r,s)}}.$$

Thus, if $s \geq r$ then congruence (22) follows immediately upon applying Jacobsthal's congruence to each binomial coefficient. On the other hand, suppose $s \leq r$. Then the same approach yields

$$(23) \quad \mathcal{B}(np^r, kp^s) = \lambda \mathcal{B}(np^{r-1}, kp^{s-1})$$

with $\lambda \equiv 1$ modulo p^{r+2s} . Moreover, since $p \nmid k$, we have

$$\binom{np^r}{kp^s} \equiv \binom{np^{r-1}}{kp^{s-1}} \equiv 0 \pmod{p^{r-s}}.$$

As $A \geq 2$, it follows that $p^{2(r-s)}$ divides $\mathcal{B}(np^r, kp^s)$. Since $r+2s+2(r-s) = 3r$, congruence (22) follows from (23). \square

In the following, $[x]$ denotes the largest integer m such that $m \leq x$.

Lemma 2.4. *For primes p , integers m and integers $k \geq 0, r \geq 1$,*

$$(24) \quad \binom{mp^r - 1}{k} (-1)^k \equiv \binom{mp^{r-1} - 1}{[k/p]} (-1)^{[k/p]} \pmod{p^r}.$$

Proof. Following [4, Lemma 2], we split the defining product of the binomial coefficient, according to whether the index is divisible by p or not, to obtain

$$\begin{aligned} \binom{mp^r - 1}{k} &= \prod_{j=1}^k \frac{mp^r - j}{j} \\ &= \prod_{\substack{j=1 \\ p \nmid j}}^k \frac{mp^r - j}{j} \prod_{\lambda=1}^{[k/p]} \frac{mp^{r-1} - \lambda}{\lambda} \\ &= \binom{mp^{r-1} - 1}{[k/p]} \prod_{\substack{j=1 \\ p \nmid j}}^k \frac{mp^r - j}{j}. \end{aligned}$$

The claim follows upon reducing modulo p^r . \square

Lemma 2.5. *For integers n, k, j and $A, B, C \geq 0$, define*

$$(25) \quad \mathcal{C}(n, k, j) = \mathcal{C}(n, k, j; A, B, C) = \binom{n-1}{k}^A \binom{n+k}{k}^B \binom{j}{n}^C.$$

Then, for primes p and integers $n, k, j \geq 0$, $r \geq 1$,

$$\mathcal{C}(np^r, k, j) \equiv (-1)^{(k+[k/p])A} \mathcal{C}(np^{r-1}, [k/p], [j/p]) \pmod{p^r}.$$

Proof. Note that

$$(26) \quad \binom{n+k}{k} = (-1)^k \binom{-n-1}{k}.$$

Using Lemma 2.4, we find that

$$(-1)^k \binom{-np^r - 1}{k} \equiv (-1)^{[k/p]} \binom{-np^{r-1} - 1}{[k/p]} \pmod{p^r}$$

or, equivalently,

$$(27) \quad \binom{np^r + k}{k} \equiv \binom{np^{r-1} + [k/p]}{[k/p]} \pmod{p^r}.$$

In particular,

$$\binom{np^r + (j - np^r)}{j - np^r} \equiv \binom{np^{r-1} + [j/p] - np^{r-1}}{[j/p] - np^{r-1}} \pmod{p^r},$$

which is equivalent to

$$(28) \quad \binom{j}{np^r} \equiv \binom{[j/p]}{np^{r-1}} \pmod{p^r}.$$

The proof thus follows upon combining (24), (27), (28). \square

Proof of Theorem 1.2. Adapting the original approaches of [4] and [17], we split the binomial sum (12) as

$$\mathcal{S}(mp^r; A, B, C) = \sum_{s \geq 0} G_s(mp^r),$$

where

$$G_s(n) = \sum_k' \mathcal{B}(n, kp^s).$$

It follows from Lemma 2.3 that, for $s \geq 1$,

$$G_s(mp^r) \equiv G_{s-1}(mp^{r-1}) \pmod{p^{3r}}.$$

It therefore remains to show that

$$(29) \quad G_0(mp^r) = \sum_k' \mathcal{B}(mp^r, k) \equiv 0 \pmod{p^{3r}}.$$

Note that

$$(30) \quad \binom{mp^r}{k} = \frac{mp^r}{k} \binom{mp^r - 1}{k - 1}$$

is divisible by p^r if $p \nmid k$. Hence, if $A \geq 3$ then (29) is obviously true and (13) follows.

In the remainder, we consider the case $A = 2$. With (30) substituted into (29), we find that we need to show that

$$(31) \quad \sum_k' \frac{1}{k^2} \binom{mp^r - 1}{k - 1}^2 \binom{mp^r + k}{k}^B \binom{2k}{mp^r}^C \equiv 0 \pmod{p^r}.$$

If $p \nmid k$ then $[(k - 1)/p] = [k/p]$ so that, by Lemma 2.4,

$$(32) \quad \binom{mp^r - 1}{k - 1}^2 \equiv \binom{mp^{r-1} - 1}{[k/p]}^2 \pmod{p^r}.$$

By (32) and Lemma 2.5 with $A = 0$, the left-hand side of (31) is congruent modulo p^r to

$$(33) \quad \sum_k' \frac{1}{k^2} \binom{mp^{r-1} - 1}{[k/p]}^2 \binom{mp^{r-1} + [k/p]}{[k/p]}^B \binom{[2k/p]}{mp^{r-1}}^C.$$

Using the notation of (25) and (33), congruence (31) is equivalent to

$$(34) \quad \sum_k' \frac{1}{k^2} \mathcal{C}(mp^{r-1}, [k/p], [2k/p]) \equiv 0 \pmod{p^r}.$$

In order to establish (34), we now show that

$$(35) \quad \sum_k' \frac{1}{k^2} \mathcal{C}(mp^r, k, 2k) \equiv \sum_k' \frac{1}{k^2} \mathcal{C}(mp^{r-s}, [k/p^s], [2k/p^s]) \pmod{p^r}$$

for $s = 0, 1, \dots, r$. The case $s = 0$ is trivial, while the case $s = 1$ follows from Lemma 2.5. If we now let $\{k : p^s\} := k - p^s[k/p^s]$, the remainder of k divided by p^s , then observe that

$$[2k/p^s] = 2[k/p^s] + \begin{cases} 1, & \text{if } \{k : p^s\} > p^s/2, \\ 0, & \text{otherwise.} \end{cases}$$

Hence,

$$\begin{aligned} \sum_k' \frac{1}{k^2} \mathcal{C}(mp^{r-s}, [k/p^s], [2k/p^s]) &= \sum_n \sum_{[k/p^s]=n}' \frac{1}{k^2} \mathcal{C}(mp^{r-s}, [k/p^s], [2k/p^s]) \\ &= \sum_n \mathcal{C}(mp^{r-s}, n, 2n) \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} < p^s/2}}' \frac{1}{k^2} \\ (36) \quad &+ \sum_n \mathcal{C}(mp^{r-s}, n, 2n+1) \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} > p^s/2}}' \frac{1}{k^2}. \end{aligned}$$

It follows from (21) of Lemma 2.2 that each of the inner sums in the last expression of (36) is divisible by p^s . Suppose that $s < r$. Thus, by (36) and Lemma 2.5, we now have

$$\begin{aligned} &\sum_k' \frac{1}{k^2} \mathcal{C}(mp^{r-s}, [k/p^s], [2k/p^s]) \\ &\equiv \sum_n \mathcal{C}(mp^{r-s-1}, [n/p], [2n/p]) \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} < p^s/2}}' \frac{1}{k^2} \\ &+ \sum_n \mathcal{C}(mp^{r-s-1}, [n/p], [(2n+1)/p]) \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} > p^s/2}}' \frac{1}{k^2} \pmod{p^r} \\ &\equiv \sum_n \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} < p^s/2}}' \frac{1}{k^2} \mathcal{C}(mp^{r-s-1}, [[k/p^s]/p], [[2k/p^s]/p]) \\ &+ \sum_n \sum_{\substack{[k/p^s]=n \\ \{k:p^s\} > p^s/2}}' \frac{1}{k^2} \mathcal{C}(mp^{r-s-1}, [[k/p^s]/p], [[2k/p^s]/p]) \pmod{p^r} \\ &\equiv \sum_k' \frac{1}{k^2} \mathcal{C}(mp^{r-s-1}, [k/p^{s+1}], [2k/p^{s+1}]) \pmod{p^r}. \end{aligned}$$

Hence (35) follows by induction on s . Moreover, the case $s = r$ in (36) shows that, for $s = r$ and hence all $s = 0, 1, \dots, r$, the sums in (35) are divisible by p^r . In particular, the case $s = 1$ proves (34) and thus (13). \square

Proof of Theorem 1.3. As in [35], we use the identity

$$\binom{a-b}{c-d} \binom{b}{d} = \frac{\binom{a}{c} \binom{c}{d} \binom{a-c}{b-d}}{\binom{a}{b}},$$

to obtain that

$$\binom{2k}{k} \binom{2(n-k)}{n-k} = \frac{\binom{2n}{n} \binom{n}{k}^2}{\binom{2n}{2k}} = \binom{n}{k} \frac{(2k)!(2(n-k))!}{n!k!(n-k)!} = \binom{n}{k} S(n-k, k),$$

where $S(m, n)$ are the *super Catalan numbers*

$$S(m, n) = \frac{(2m)!(2n)!}{m!n!(m+n)!}.$$

We refer to [19] and the references therein for the history and properties of these numbers. Here, we only need that $S(n-k, k)$ is an integer; in fact, it is an even integer if $n \geq 1$.

Denote the summand of (7) by $\mathcal{D}(n, k)$, that is

$$\mathcal{D}(n, k) = (-1)^k \binom{n}{k}^2 S(n-k, k) \left[\binom{2n-3k-1}{n} + \binom{2n-3k}{n} \right],$$

so that

$$s_{18}(mp^r) = \sum_{s \geq 0} \sum_k' \mathcal{D}(mp^r, kp^s).$$

In analogy with Lemma 2.3, we claim that, for primes $p \geq 5$ and integers $r, s \geq 1$,

$$(37) \quad \mathcal{D}(mp^r, kp^s) \equiv \mathcal{D}(mp^{r-1}, kp^{s-1}) \pmod{p^{3r}}.$$

A direct application of Lemma 2.1 shows that

$$\binom{2mp^r - 3kp^s}{mp^r} / \binom{2mp^{r-1} - 3kp^{s-1}}{mp^{r-1}} \equiv 1 \pmod{p^{r+2\min(r,s)}}$$

as well as

$$S(mp^r - kp^s, kp^s) / S(mp^{r-1} - kp^{s-1}, kp^{s-1}) \equiv 1 \pmod{p^{r+2\min(r,s)}}.$$

On the other hand, for all integers a and integers $b \geq 0$,

$$(38) \quad \binom{a+b}{b} = (-1)^b \binom{-a-1}{b},$$

so that

$$\binom{2n-3k-1}{n} = (-1)^n \binom{3k-n}{n}.$$

Hence, Lemma 2.1 implies that

$$\binom{2mp^r - 3kp^s - 1}{mp^r} / \binom{2mp^{r-1} - 3kp^{s-1} - 1}{mp^{r-1}} \equiv 1 \pmod{p^{r+2\min(r,s)}}.$$

Proceeding as in the proof of Lemma 2.3, we therefore obtain (37). The congruence (14) then follows if we can prove that, for integers k such that $p \nmid k$,

$$\mathcal{D}(mp^r, k) \equiv 0 \pmod{p^{2r}}.$$

This is an immediate consequence of the fact that $\mathcal{D}(n, k)$ is divisible by $\binom{n}{k}^2$.

Finally, let us briefly indicate how to obtain the corresponding congruences in the case that $p = 2$ or $p = 3$. For $p = 3$, congruence (19) of Lemma 2.1 only holds modulo $p^{r+s+\min(r,s)-1}$. The same arguments as above then show that congruence (37) holds modulo p^{3r-1} , and hence modulo p^{2r} , for $p = 3$. The case $p = 2$ requires some more attention. In that case, the counterpart of congruence (19) is

$$\binom{2^r a}{2^s b} / \binom{2^{r-1} a}{2^{s-1} b} \equiv \varepsilon \pmod{2^{r+s+\min(r,s)-2}}$$

with $\varepsilon = -1$, if $2^{r-1}a \equiv 0$, $2^{s-1}b \equiv 1$ modulo 2, and $\varepsilon = 1$ otherwise. Hence, applying the same arguments as for $p > 2$ shows that

$$\mathcal{D}(2^r m, 2^s k) = \lambda \mathcal{D}(2^{r-1} m, 2^{s-1} k)$$

with $\lambda \equiv \pm 1$ modulo $2^{r+2\min(r,s)-2}$ and, hence, $\lambda \equiv 1$ modulo 2. Moreover, both sides are divisible by $2^{2\max(r-s,0)+1}$ because $\binom{2^r m}{2^s k}$ is divisible by 2^{r-s} , if $r \geq s$, and the super Catalan numbers $S(n-k, k)$ are even when $n \geq 1$. In the cases $r = 1$ or $s = 1$, this suffices to conclude that (37) holds modulo p^{2r} for $p = 2$. On the other hand, if $r \geq 2$ and $s \geq 2$, then going through the above computations reveals that $\lambda \equiv 1$ modulo $2^{r+2\min(r,s)-2}$, and hence modulo $2^{r+\min(r,s)}$. Together with the divisibility of $\mathcal{D}(2^r m, 2^s k)$ by 2^{r-s} , if $r \geq s$, we again find that (37) holds modulo p^{2r} for $p = 2$. \square

3. COMMENTS ON DIRECT GENERALIZATIONS

The approaches of the proof of Theorems 1.2 and 1.3, which are based on [17] and [4], generalize easily to other sequences.

Example 3.1. For instance, consider the sequence

$$(39) \quad Z(n) = \sum_{k=0}^n (-1)^k \binom{n}{k}^3 \left(\binom{4n-5k-1}{3n} + \binom{4n-5k}{3n} \right),$$

which is case (η) in [3] (see also Table 2 in Section 4). We claim that the proof of Theorem 1.3 naturally extends to show that, for primes $p \geq 5$,

$$(40) \quad Z(mp^r) \equiv Z(mp^{r-1}) \pmod{p^{3r}}.$$

Similar to the proof of Theorem 1.3, write

$$Z(mp^r) = \sum_{s \geq 0} \sum_k' \mathcal{A}(mp^r, kp^s),$$

where

$$\mathcal{A}(n, k) = (-1)^k \binom{n}{k}^3 \left(\binom{4n-5k-1}{3n} + \binom{4n-5k}{3n} \right).$$

As in the proof of Theorem 1.3, we find that for primes $p \geq 5$,

$$\mathcal{A}(mp^r, kp^s) \equiv \mathcal{A}(mp^{r-1}, kp^{s-1}) \pmod{p^{3r}}.$$

On the other hand, the presence of $\binom{n}{k}^3$ shows that, for $p \nmid k$,

$$\mathcal{A}(mp^r, k) \equiv 0 \pmod{p^{3r}}.$$

Combining these two congruences, we conclude that the supercongruence (40) indeed holds.

Example 3.2. The proof of Theorem 1.3 directly generalizes to supercongruences for the following family of sequences which includes $s_{18}(n)$ as the case $(A, B, C, D, E) = (1, 1, 1, 1, 1)$. For nonnegative integers A, B, C, D, E , define $\mathcal{T}(n; A, B, C, D, E)$ to be the sequence

$$\sum_{k=0}^{\lfloor n/3 \rfloor} (-1)^k \binom{n}{k}^A \binom{2k}{k}^B \binom{2(n-k)}{n-k}^C \left[\binom{2n-3k-1}{n}^D + \binom{2n-3k}{n}^E \right].$$

If $A \geq 1$, $B \geq 1$ and $C \geq 1$, then

$$\mathcal{T}(mp^r; A, B, C, D, E) \equiv \mathcal{T}(mp^{r-1}; A, B, C, D, E) \pmod{p^{2r}}$$

for all primes p . More generally, we have, for instance, that if $A \geq 2$, $B \geq 1$ and $C \geq 1$, then

$$\mathcal{T}(mp^r; A, B, C, D, E) \equiv \mathcal{T}(mp^{r-1}; A, B, C, D, E) \pmod{p^{3r}}$$

for all primes $p \geq 5$.

Example 3.3. In [8] and [9], the sequence

$$u(n) = \sum_{k=0}^n (-1)^k \binom{n}{k} \binom{2n}{k}$$

is studied. In particular, it is proved that $u(mp) \equiv u(m)$ modulo p^3 for all primes $p \geq 5$. Following the approach of Theorem 1.2, we obtain that, more generally,

$$u(mp^r) \equiv u(mp^{r-1}) \pmod{p^{3r}}$$

for all primes $p \geq 5$. Let a, b be nonnegative integers. It is shown in [8] that the more general sequences

$$u_{a,b}^\varepsilon(n) = \sum_{k=0}^n (-1)^{\varepsilon k} \binom{n}{k}^a \binom{2n}{k}^b$$

satisfy, for primes $p \geq 5$, the congruence

$$u_{a,b}^\varepsilon(p) \equiv u_{a,b}^\varepsilon(1) \pmod{p^3}$$

unless $(\varepsilon, a, b) = (0, 0, 1)$ or $(0, 1, 0)$. Again, we can generalize this congruence by using the approach of Theorem 1.2 to show that, for primes $p \geq 5$,

$$u_{a,b}^\varepsilon(mp^r) \equiv u_{a,b}(mp^{r-1}) \pmod{p^{3r}}$$

provided that $a + b \geq 2$.

4. CONCLUDING REMARKS

There are several directions for future work. First, we have numerically checked that each of the six sporadic examples of Zagier (labelled **A**, **B**, **C**, **D**, **E**, **F** in [40]) and the six sporadic examples in [3] (labelled (δ) , (η) , (α) , (ϵ) , (ζ) , (γ)) satisfies a two-term supercongruence. Precisely, cases **A** and **D** are modulo p^{3r} while cases **B**, **C**, **E**, **F** are modulo p^{2r} . All six cases from [3] are modulo p^{3r} . Cases **A** and **D** have been proven by Coster [13] and cases **C** and **E** were settled by the first two authors in [34] and [35]. Cases (α) and (γ) have been proven in [35] and [13], respectively. As mentioned in the introduction, the proof of Theorem 1.2 implies case (ϵ) . On the other hand, case (η) is proven in Example 3.1 of Section 3. For a discussion concerning connections between the six sporadic examples in [3] and [40], see Theorem 4.1 in [3] or Theorem 3.5 and Tables 1 and 2 in [10].

The information on supercongruences for Apéry-like numbers is summarized in Tables 1 and 2. The value for k indicates that the sequence $A(n)$ (at least conjecturally in cases **B**, **F**, (δ) and (ζ)) satisfies the supercongruence

$$A(mp^r) \equiv A(mp^{r-1}) \pmod{p^{kr}}$$

for primes $p \geq 5$. In the cases where this congruence has been proven, a reference is indicated in the final column. It would be of interest to prove cases **B**, **F**, (δ) and (ζ) and, more generally, provide a framework for all two-term supercongruences.

Secondly, for each of the 15 sporadic cases in Tables 1 and 2, one could ask if there exists a modular form $f(z)$ whose p -th Fourier coefficient satisfies a modular supercongruence. This is true for cases **D** [1] and (γ) [2].

Finally, it also appears that all known Ramanujan-type series for $1/\pi^a$, $a \geq 1$, have a p -adic analogue which satisfies a Ramanujan-type supercongruence. Different techniques have been employed as there is currently no general explanation for this occurrence. For example, the first author and McCarthy [28] utilized Gaussian hypergeometric series and Whipple's transformation to prove (5). Zudilin [41] proved several Ramanujan-type supercongruences using the Wilf–Zeilberger method while Long [26] used a combination of combinatorial identities, p -adic analysis and transformations and “strange” evaluations of ordinary hypergeometric series due to Whipple, Gessel and Gosper.

Acknowledgements. The first author would like to thank Frits Beukers and Matthijs Coster for their continued interest. The second author is partially funded by SERB grant SR/FTP/MS-053/2012. The third author

(a, b, c)	[40]	[3]	$A(n)$	k	
$(7, 2, -8)$	A	(a)	$\sum_k \binom{n}{k}^3$	3	[13]
$(11, 3, -1)$	D	(b)	$\sum_k \binom{n}{k}^2 \binom{n+k}{n}$	3	[13]
$(10, 3, 9)$	C	(c)	$\sum_k \binom{n}{k}^2 \binom{2k}{k}$	2	[34]
$(12, 4, 32)$	E	(d)	$\sum_k \binom{n}{k} \binom{2k}{k} \binom{2(n-k)}{n-k}$	2	[35]
$(9, 3, 27)$	B	(f)	$\sum_k (-1)^k 3^{n-3k} \binom{n}{3k} \frac{(3k)!}{k!^3}$	2	
$(17, 6, 72)$	F	(g)	$\sum_{k,l} (-1)^k 8^{n-k} \binom{n}{k} \binom{k}{l}^3$	2	

TABLE 1. Sporadic sequences from [40] for (9)

(a, b, c, d)	[3], [12]	$A(n)$	k	
$(7, 3, 81, 0)$	(δ)	$\sum_k (-1)^k 3^{n-3k} \binom{n}{3k} \binom{n+k}{n} \frac{(3k)!}{k!^3}$	3	
$(11, 5, 125, 0)$	(η)	defined in (39)	3	(40)
$(10, 4, 64, 0)$	(α)	$\sum_k \binom{n}{k}^2 \binom{2k}{k} \binom{2(n-k)}{n-k}$	3	[35]
$(12, 4, 16, 0)$	(ϵ)	$\sum_k \binom{n}{k}^2 \binom{2k}{n}^2$	3	(13)
$(9, 3, -27, 0)$	(ζ)	$\sum_{k,l} \binom{n}{k}^2 \binom{n}{l} \binom{k}{l} \binom{k+l}{n}$	3	
$(17, 5, 1, 0)$	(γ)	$\sum_k \binom{n}{k}^2 \binom{n+k}{n}^2$	3	[13]
$(6, 2, -64, 4)$	s_{10}	$\sum_k \binom{n}{k}^4$	3	[13]
$(13, 4, -27, 3)$	s_7	$\sum_k \binom{n}{k}^2 \binom{n+k}{k} \binom{2k}{n}$	3	(13)
$(14, 6, -192, 12)$	s_{18}	defined in (7)	2	(14)

TABLE 2. Sporadic sequences from [3] and [12] for (8)

would like to thank the Max-Planck-Institute for Mathematics in Bonn, where he was in residence when this work was completed, for providing

wonderful working conditions. Finally, we thank the referee for their helpful comments and suggestions.

REFERENCES

- [1] S. Ahlgren, *Gaussian hypergeometric series and combinatorial congruences*, Symbolic computation, number theory, special functions, physics and combinatorics (Gainesville, FL, 1999), 1–12, Dev. Math., **4**, Kluwer Acad. Publ., Dordrecht, 2001.
- [2] S. Ahlgren, K. Ono, *A Gaussian hypergeometric series evaluation and Apéry number congruences*, J. reine angew. Math. **518** (2000), 187–212.
- [3] G. Almkvist, D. van Straten and W. Zudilin, *Generalizations of Clausen’s formula and algebraic transformations of Calabi-Yau differential equations*, Proc. Edinb. Math. Soc. (2) **54** (2011), no. 2, 273–295.
- [4] F. Beukers, *Some congruences for the Apéry numbers*, J. Number Theory **21** (1985), no. 2, 141–155.
- [5] F. Beukers, *Another congruence for the Apéry numbers*, J. Number Theory **25** (1987), no. 2, 201–210.
- [6] F. Beukers, *On B. Dwork’s accessory parameter problem*, Math. Z. **241** (2002), no. 2, 425–444.
- [7] V. Brun, J. Stubban, J. Fjeldstad, L. Tambs, K. Aubert, W. Ljunggren, E. Jacobsthal, *On the divisibility of the difference between two binomial coefficients*, Den 11te Skandinaviske Matematikerkongress, Trondheim, 1949, pp. 42–54. Johan Grundt Tanums Forlag, Oslo, 1952.
- [8] M. Chamberland, K. Dilcher, *Divisibility properties of a class of binomial sums*, J. Number Theory **120** (2006), no. 2, 349–371.
- [9] M. Chamberland, K. Dilcher, *A binomial sum related to Wolstenholme’s theorem*, J. Number Theory **129** (2009), no. 11, 2659–2672.
- [10] H. Chan, S. Cooper, *Rational analogues of Ramanujan’s series for $1/\pi$* , Math. Proc. Cambridge Philos. Soc. **153** (2012), no. 2, 361–383.
- [11] S. Chisholm, A. Deines, L. Long, G. Nebe, H. Swisher, *p -adic analogues of Ramanujan type formulas for $1/\pi$* , Mathematics **1** (2013), 9–31.
- [12] S. Cooper, *Sporadic sequences, modular forms and new series for $1/\pi$* , Ramanujan J. **29** (2012), no. 1–3, 163–183.
- [13] M. Coster, *Supercongruences*, Ph.D. thesis, Universiteit Leiden, 1988.
- [14] M. Coster, L. Van Hamme, *Supercongruences of Atkin and Swinnerton-Dyer type for Legendre polynomials*, J. Number Theory **38** (1991), no. 3, 265–286.
- [15] J. Kibelbek, L. Long, K. Moss, B. Sheller and H. Yuan, *Supercongruences and complex multiplication*, J. Number Theory, to appear.
- [16] T. Kilbourn, *An extension of the Apéry number supercongruence*, Acta Arith. **123** (2006), 335–348.
- [17] I. Gessel, *Some congruences for Apéry numbers*, J. Number Theory **14** (1982), no. 3, 362–368.
- [18] I. Gessel, *Some congruences for generalized Euler numbers*, Canad. J. Math. **35** (1983), no. 4, 687–709.
- [19] I. Gessel, *Super ballot numbers*, J. of Symbolic Comput. **14** (1992), no. 2–3, 179–194.
- [20] A. Granville, *Arithmetic properties of binomial coefficients I: Binomial coefficients modulo prime powers*, Organic mathematics (Burnaby, BC, 1995), 253–276, CMS Conf. Proc., **20**, Amer. Math. Soc., Providence, RI, 1997.
- [21] J. Greene, *Hypergeometric functions over finite fields*, Trans. Amer. Math. Soc. **301** (1987), no. 1, 77–101.
- [22] J. Guillera, *Mosaic supercongruences of Ramanujan type*, Exp. Math. **21** (2012), no. 1, 65–68.

- [23] J. Guillera, W. Zudilin, “Divergent” Ramanujan-type supercongruences, Proc. Amer. Math. Soc. **140** (2012), no. 3, 765–777.
- [24] W.-C. W. Li, L. Long, *Atkin and Swinnerton-Dyer congruences and noncongruence modular forms*, preprint available at <http://arxiv.org/abs/1303.6228v2>
- [25] P. Loh, R. Rhoades, *p-adic and combinatorial properties of modular form coefficients*, Int. J. Number Theory **2** (2006), no. 2, 305–328.
- [26] L. Long, *Hypergeometric evaluation identities and supercongruences*, Pacific J. Math. **249** (2011), no. 2, 405–418.
- [27] D. McCarthy, *On a supercongruence conjecture of Rodriguez-Villegas*, Proc. Amer. Math. Soc. **140** (2012), no. 7, 2241–2254.
- [28] D. McCarthy, R. Osburn, *A p-adic analogue of a formula of Ramanujan*, Arch. Math. (Basel) **91** (2008), no. 6, 492–504.
- [29] E. Mortenson, *Supercongruences between truncated ${}_2F_1$ hypergeometric functions and their Gaussian analogs*, Trans. Amer. Math. Soc. **355** (2003), no. 3, 987–1007.
- [30] E. Mortenson, *A supercongruence conjecture of Rodriguez-Villegas for a certain truncated hypergeometric function*, J. Number Theory **99** (2003), no. 1, 139–147.
- [31] E. Mortenson, *Supercongruences for truncated ${}_{n+1}F_n$ hypergeometric series with applications to certain weight three newforms*, Proc. Amer. Math. Soc. **133** (2005), no. 2, 321–330.
- [32] E. Mortenson, *Modularity of a certain Calabi-Yau threefold and combinatorial congruences*, Ramanujan J. **11** (2006), no. 1, 5–39.
- [33] E. Mortenson, *A p-adic supercongruence conjecture of van Hamme*, Proc. Amer. Math. Soc. **136** (2008), no. 12, 4321–4328.
- [34] R. Osburn, B. Sahu, *Supercongruences for Apéry-like numbers*, Adv. in Appl. Math. **47** (2011), no. 3, 631–638.
- [35] R. Osburn, B. Sahu, *A supercongruence for generalized Domb numbers*, Funct. Approx. Comment. Math. **48** (2013), part 1, 29–36.
- [36] R. Osburn, C. Schneider, *Gaussian hypergeometric series and supercongruences*, Math. Comp. **78** (2009), no. 265, 275–292.
- [37] A. Scholl, *Modular forms and de Rham cohomology; Atkin-Swinnerton-Dyer congruences*, Invent. Math. **79** (1985), no. 1, 49–77.
- [38] A. Straub, *Multivariate Apéry numbers and supercongruences of rational functions*, preprint available at <http://arxiv.org/abs/1401.0854>
- [39] L. Van Hamme, *Some conjectures concerning partial sums of generalized hypergeometric series*, p-adic functional analysis (Nijmegen, 1996), 223–236, Lecture Notes in Pure and Appl. Math., **192**, Dekker, 1997.
- [40] D. Zagier, *Integral solutions of Apéry-like recurrence equations*, Group and Symmetries, 349–366, CRM Proc. Lecture Notes, **47**. Amer. Math. Soc., Providence, RI, 2009.
- [41] W. Zudilin, *Ramanujan-type supercongruences*, J. Number Theory **129** (2009), no. 8, 1848–1857.

SCHOOL OF MATHEMATICAL SCIENCES, UNIVERSITY COLLEGE DUBLIN, BELFIELD,
DUBLIN 4, IRELAND

E-mail address: robert.osburn@ucd.ie

SCHOOL OF MATHEMATICAL SCIENCES, NATIONAL INSTITUTE OF SCIENCE EDUCATION
AND RESEARCH, BHUBANESWAR 751005, INDIA

E-mail address: brundaban.sahu@niser.ac.in

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN,
URBANA, IL 61801, UNITED STATES

Current address: Max-Planck-Institut für Mathematik, 53111 Bonn, Germany

E-mail address: `astraub@illinois.edu`