

CONGRUENCES CONCERNING LEGENDRE POLYNOMIALS

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ABSTRACT. Let p be an odd prime. In this paper, by using the properties of Legendre polynomials we prove some congruences for $\sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 m^{-k} \pmod{p^2}$. In particular, we confirm several conjectures of Z.W. Sun. We also pose 13 conjectures on supercongruences.

1. INTRODUCTION

Let p be an odd prime. In 2003, Rodriguez-Villegas [11] conjectured the following congruence:

$$(1.1) \quad \sum_{k=0}^{(p-1)/2} \frac{\binom{2k}{k}^2}{16^k} \equiv (-1)^{\frac{p-1}{2}} \pmod{p^2}.$$

This was later confirmed by Mortenson [7] via the Gross-Koblitz formula. See also [9] and [10, p. 204]. Recently the author's twin brother, Zhi-Wei Sun [13], obtained the congruences for $\sum_{k=0}^{p-1} \binom{2k}{k}^2 m^{-k} \pmod{p}$ in the cases $m = 8, -16, 32$ and made several conjectures for $\sum_{k=0}^{p-1} \binom{2k}{k}^2 m^{-k} \pmod{p^2}$. For example, he conjectured

$$(1.2) \quad \sum_{k=0}^{(p-1)/2} \frac{\binom{2k}{k}^2}{32^k} \equiv \begin{cases} 0 \pmod{p^2} & \text{if } 4 \mid p-3, \\ 2a - \frac{p}{2a} \pmod{p^2} & \text{if } 4 \mid p-1 \text{ and } p = a^2 + b^2 \text{ with } 4 \mid a-1. \end{cases}$$

Let $\{P_n(x)\}$ be the Legendre polynomials given by

$$\frac{1}{\sqrt{1-2xt+t^2}} = \sum_{n=0}^{\infty} P_n(x)t^n \quad (|t| < 1).$$

It is well known that (see [6, pp. 228-232], [4, (3.132)-(3.133)])

$$(1.3) \quad P_n(x) = \frac{1}{2^n} \sum_{k=0}^{\lfloor n/2 \rfloor} \frac{(-1)^k (2n-2k)!}{k!(n-k)!(n-2k)!} x^{n-2k} = \frac{1}{2^n \cdot n!} \cdot \frac{d^n}{dx^n} (x^2 - 1)^n$$

and $(n+1)P_{n+1}(x) = (2n+1)xP_n(x) - nP_{n-1}(x)$, where $[x]$ is the greatest integer not exceeding x .

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In the paper, by using the expansions of Legendre polynomials we obtain some congruences for $P_{\frac{p-1}{2}}(x)$ modulo p^2 , where p is an odd prime and x is a rational p -integer. For example, we have

$$(1.4) \quad \sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2}{16^k} (x^k - (-1)^{\frac{p-1}{2}} (1-x)^k) \equiv 0 \pmod{p^2}$$

and

$$(1.5) \quad \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(x^k - \left(\frac{x}{p}\right)x^{-k}\right) \equiv 0 \pmod{p} \quad \text{for } x \not\equiv 0 \pmod{p},$$

where $\left(\frac{x}{p}\right)$ is the Jacobi symbol. Taking $x = 1$ in (1.4) we obtain (1.1) immediately, and taking $x = \frac{1}{2}$ in (1.4) we deduce (1.2) for $p \equiv 3 \pmod{4}$. We also determine $\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} k(k-1) \cdots (k-r+1) \pmod{p^2}$ for $r \in \{1, 2, \dots, \frac{p-1}{2}\}$, $\sum_{k=0}^{\lfloor p/3 \rfloor} \frac{(3k)!}{54^k \cdot k!^3} \pmod{p}$ and pose some conjectures on supercongruences concerning binary quadratic forms.

Throughout this paper we use \mathbb{Z} , \mathbb{N} and \mathbb{Z}_p to denote the sets of integers, positive integers and rational p -integers for a prime p , respectively.

2. MAIN RESULTS

Lemma 2.1. *For $n \in \mathbb{N}$ we have*

$$P_n(x) = \sum_{k=0}^n \binom{n+k}{2k} \binom{2k}{k} \left(\frac{x-1}{2}\right)^k.$$

Proof. From [4, (3.135)] we have the following result due to Murphy:

$$(2.1) \quad P_n(x) = \sum_{k=0}^n \binom{n}{k} \binom{n+k}{k} \left(\frac{x-1}{2}\right)^k.$$

As $\binom{n+k}{2k} \binom{2k}{k} = \binom{n+k}{k} \binom{n}{k}$, we obtain the result. □

Lemma 2.2. *Let p be an odd prime and $k \in \{1, 2, \dots, (p-1)/2\}$. Then*

$$\binom{\frac{p-1}{2} + k}{2k} \equiv \frac{\binom{2k}{k}}{(-16)^k} \left(1 - p^2 \sum_{i=1}^k \frac{1}{(2i-1)^2}\right) \pmod{p^4}.$$

Proof. Clearly

$$\begin{aligned} \binom{\frac{p-1}{2} + k}{2k} &= \frac{(\frac{p-1}{2} + k)(\frac{p-1}{2} + k - 1) \cdots (\frac{p-1}{2} - k + 1)}{(2k)!} \\ &= \frac{(p + 2k - 1)(p + 2k - 3) \cdots (p - (2k - 3))(p - (2k - 1))}{2^{2k} \cdot (2k)!} \\ &= \frac{(p^2 - 1^2)(p^2 - 3^2) \cdots (p^2 - (2k - 1)^2)}{2^{2k} \cdot (2k)!} \\ &\equiv \frac{(-1)^k \cdot 1^2 \cdot 3^2 \cdots (2k - 1)^2}{2^{2k} \cdot (2k)!} \left(1 - p^2 \sum_{i=1}^k \frac{1}{(2i-1)^2}\right) \pmod{p^4}. \end{aligned}$$

To see the result, we note that

$$\frac{1^2 \cdot 3^2 \cdots (2k-1)^2}{2^{2k} \cdot (2k)!} = \frac{(2k)!^2}{(2 \cdot 4 \cdots (2k))^2 \cdot 2^{2k} \cdot (2k)!} = \frac{(2k)!}{2^{4k} \cdot k!^2} = \frac{\binom{2k}{k}}{16^k}. \quad \square$$

Let p be an odd prime, and let $\{A(n)\}$ be the Apéry numbers given by

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

It is well known that (see [1], [10]) $A(\frac{p-1}{2}) \equiv a(p) \pmod{p^2}$, where $a(n)$ is defined by

$$q \prod_{n=1}^{\infty} (1 - q^{2n})^4 (1 - q^{4n})^4 = \sum_{n=1}^{\infty} a(n)q^n.$$

By the fact $\binom{n+k}{k} \binom{n}{k} = \binom{n+k}{2k} \binom{2k}{k}$ and Lemma 2.2 we have

$$A\left(\frac{p-1}{2}\right) = \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2} + k}{2k}^2 \binom{2k}{k}^2 \equiv \sum_{k=0}^{\frac{p-1}{2}} \left(\frac{\binom{2k}{k}}{(-16)^k}\right)^2 \binom{2k}{k}^2 \pmod{p^2}.$$

Hence

$$(2.2) \quad a(p) \equiv A\left(\frac{p-1}{2}\right) \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^4}{4^{3k}} \pmod{p^2}.$$

Let $b(n)$ be given by $q \prod_{n=1}^{\infty} (1 - q^{4n})^6 = \sum_{n=1}^{\infty} b(n)q^n$. Then Mortenson [8] proved the following conjecture of Rodriguez-Villegas:

$$(2.3) \quad \sum_{k=1}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^3}{4^{3k}} \equiv b(p) \pmod{p^2}.$$

Theorem 2.1. *Let p be an odd prime and let x be a variable. Then*

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2}{16^k} (x^k - (-1)^{\frac{p-1}{2}} (1-x)^k) \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} (x^k - (-1)^{\frac{p-1}{2}} (1-x)^k) \equiv 0 \pmod{p^2}.$$

Proof. For a variable t , by Lemmas 2.1 and 2.2 we have

$$(2.4) \quad P_{\frac{p-1}{2}}(t) = \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2} + k}{2k} \binom{2k}{k} \left(\frac{t-1}{2}\right)^k \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\frac{1-t}{2}\right)^k \pmod{p^2}.$$

It is known that (see [6]) $P_n(t) = (-1)^n P_n(-t)$. Thus, by (2.4),

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\frac{1-t}{2}\right)^k \equiv (-1)^{\frac{p-1}{2}} \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\frac{1+t}{2}\right)^k \pmod{p^2}.$$

Now taking $t = 1 - 2x$ in the congruence we deduce that

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} (x^k - (-1)^{\frac{p-1}{2}} (1-x)^k) \equiv 0 \pmod{p^2}.$$

To complete the proof, we note that for $k \in \{\frac{p+1}{2}, \frac{p+3}{2}, \dots, p-1\}$, $\binom{2k}{k} = 2k(2k-1) \cdots (k+1)/k! \equiv 0 \pmod{p}$. \square

Theorem 2.2. *Let p be an odd prime. Then*

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} \equiv \begin{cases} 0 \pmod{p^2} & \text{if } 4 \mid p-3, \\ 2a - \frac{p}{2a} \pmod{p^2} & \text{if } 4 \mid p-1 \text{ and } p = a^2 + b^2 \text{ with } 4 \mid a-1. \end{cases}$$

Proof. When $p \equiv 3 \pmod{4}$, taking $x = \frac{1}{2}$ in Theorem 2.1 we obtain the result. Now suppose $p \equiv 1 \pmod{4}$ and so $p = a^2 + b^2$ with $a, b \in \mathbb{Z}$ and $a \equiv 1 \pmod{4}$. It is well known that ([6])

$$(2.5) \quad P_{2n+1}(0) = 0 \quad \text{and} \quad P_{2n}(0) = \frac{(-1)^n}{2^{2n}} \binom{2n}{n}.$$

Thus, by (2.4) and (2.5) we have

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} \equiv P_{\frac{p-1}{2}}(0) = \frac{(-1)^{\frac{p-1}{4}}}{2^{\frac{p-1}{2}}} \binom{\frac{p-1}{2}}{\frac{p-1}{4}} \pmod{p^2}.$$

According to the result due to Chowla, Dwork and Evans (see [2] or [3]), we have

$$\binom{\frac{p-1}{2}}{\frac{p-1}{4}} \equiv \frac{2^{p-1} + 1}{2} \left(2a - \frac{p}{2a}\right) \pmod{p^2}.$$

Set $q = (2^{\frac{p-1}{2}} - (-1)^{\frac{p-1}{4}})/p$. Then $2^{p-1} \equiv 1 + 2(-1)^{\frac{p-1}{4}}qp \pmod{p^2}$. Thus

$$\frac{2^{p-1} + 1}{2 \cdot 2^{\frac{p-1}{2}}} \equiv \frac{2 + 2(-1)^{\frac{p-1}{4}}qp}{2((-1)^{\frac{p-1}{4}} + qp)} = (-1)^{\frac{p-1}{4}} \pmod{p^2}.$$

Hence

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} \equiv \frac{(-1)^{\frac{p-1}{4}}}{2^{\frac{p-1}{2}}} \binom{\frac{p-1}{2}}{\frac{p-1}{4}} \equiv \frac{(-1)^{\frac{p-1}{4}}}{2^{\frac{p-1}{2}}} \cdot \frac{2^{p-1} + 1}{2} \left(2a - \frac{p}{2a}\right) \equiv 2a - \frac{p}{2a} \pmod{p^2}.$$

The proof is now complete. □

Remark 2.1. Theorem 2.2 was conjectured by Zhi-Wei Sun ([13]), and the congruence for $\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} \pmod{p}$ was also proved by Zhi-Wei Sun in [13].

Theorem 2.3. *Let p be an odd prime and $r \in \{1, 2, \dots, (p-1)/2\}$. Then*

$$\begin{aligned} & \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} k(k-1) \cdots (k-r+1) \\ & \equiv \begin{cases} 0 \pmod{p^2} & \text{if } 4 \mid (p+1-2r), \\ (-1)^{\frac{p-1+2r}{4}} 2^{-\frac{p-1}{2}} \frac{(\frac{p-1}{2}+r)!}{\frac{p-1-2r}{4}! \frac{p-1+2r}{4}!} \pmod{p^2} & \text{if } 4 \mid (p-1-2r). \end{cases} \end{aligned}$$

Proof. By (2.4) we have

$$(2.6) \quad \begin{aligned} \frac{d^r P_{\frac{p-1}{2}}(t)}{dt^r} & \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-32)^k} \cdot \frac{d^r (t-1)^k}{dt^r} \\ & = \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-32)^k} k(k-1) \cdots (k-r+1) (t-1)^{k-r} \pmod{p^2}. \end{aligned}$$

Hence

$$\left. \frac{d^r P_{\frac{p-1}{2}}(t)}{dt^r} \right|_{t=0} = (-1)^r \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{32^k} k(k-1) \cdots (k-r+1).$$

By (1.3) we have

$$\begin{aligned} \frac{d^r}{dt^r} P_{\frac{p-1}{2}}(t) &= \frac{1}{2^{(p-1)/2}} \cdot \frac{d^r}{dt^r} \sum_{m=0}^{\lfloor \frac{p-1}{4} \rfloor} \frac{(-1)^m (p-1-2m)!}{m! (\frac{p-1}{2}-m)! (\frac{p-1}{2}-2m)!} t^{\frac{p-1}{2}-2m} \\ &= \frac{1}{2^{(p-1)/2}} \sum_{m=0}^{\lfloor \frac{p-1-2r}{4} \rfloor} \frac{(-1)^m (p-1-2m)!}{m! (\frac{p-1}{2}-m)! (\frac{p-1}{2}-2m)!} \\ &\quad \times \left(\frac{p-1}{2}-2m\right) \left(\frac{p-1}{2}-2m-1\right) \cdots \left(\frac{p-1}{2}-2m-r+1\right) t^{\frac{p-1}{2}-2m-r}. \end{aligned}$$

Thus,

$$\left. \frac{d^r P_{\frac{p-1}{2}}(t)}{dt^r} \right|_{t=0} = \begin{cases} 0 & \text{if } r \not\equiv \frac{p-1}{2} \pmod{2}, \\ \frac{(-1)^m (p-1-2m)!}{2^{(p-1)/2} \cdot m! (\frac{p-1}{2}-m)!} & \text{if } r = \frac{p-1}{2} - 2m. \end{cases}$$

Now combining all the above we obtain the result. □

Corollary 2.1. *Let p be an odd prime. Then*

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{k^2 \binom{2k}{k}^2}{32^k} \equiv \begin{cases} (-1)^{\frac{p+3}{4}} 2^{-\frac{p-1}{2}} \frac{\frac{p+3}{2}!}{\frac{p-5}{4}! \frac{p+3}{4}!} \pmod{p^2} & \text{if } p \equiv 1 \pmod{4}, \\ (-1)^{\frac{p+1}{4}} 2^{-\frac{p-1}{2}} \frac{\frac{p+1}{2}!}{\frac{p-3}{4}! \frac{p+1}{4}!} \pmod{p^2} & \text{if } p \equiv 3 \pmod{4}. \end{cases}$$

Proof. By Theorem 2.3 we have

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{k \binom{2k}{k}^2}{32^k} \equiv \begin{cases} 0 \pmod{p^2} & \text{if } p \equiv 1 \pmod{4}, \\ (-1)^{\frac{p+1}{4}} 2^{-\frac{p-1}{2}} \frac{\frac{p+1}{2}!}{\frac{p-3}{4}! \frac{p+1}{4}!} \pmod{p^2} & \text{if } p \equiv 3 \pmod{4} \end{cases}$$

and

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{k(k-1) \binom{2k}{k}^2}{32^k} \equiv \begin{cases} (-1)^{\frac{p+3}{4}} 2^{-\frac{p-1}{2}} \frac{\frac{p+3}{2}!}{\frac{p-5}{4}! \frac{p+3}{4}!} \pmod{p^2} & \text{if } p \equiv 1 \pmod{4}, \\ 0 \pmod{p^2} & \text{if } p \equiv 3 \pmod{4}. \end{cases}$$

Observe that $k^2 = k(k-1) + k$. From the above we deduce the result. □

Lemma 2.3. *Let p be a prime greater than 3 and let t be a variable. Then*

$$P_{\lfloor \frac{p}{3} \rfloor}(t) \equiv \sum_{k=0}^{\lfloor \frac{p}{3} \rfloor} \frac{(3k)!}{k! 3^k} \left(\frac{1-t}{54}\right)^k \pmod{p}.$$

Proof. Suppose $r = 1$ or 2 according to whether $3 \mid p - 1$ or $3 \mid p - 2$. Then clearly

$$\begin{aligned} \binom{\frac{p-r}{3} + k}{2k} &= \frac{(\frac{p-r}{3} + k)(\frac{p-r}{3} + k - 1) \cdots (\frac{p-r}{3} - k + 1)}{(2k)!} \\ &= \frac{(p + 3k - r)(p + 3k - r - 3) \cdots (p - (3k + r - 3))}{3^{2k} \cdot (2k)!} \\ &\equiv (-1)^k \frac{(3k - r)(3k - r - 3) \cdots (3 - r) \cdot r(r + 3) \cdots (3k + r - 3)}{3^{2k} \cdot (2k)!} \\ &= \frac{(-1)^k \cdot (3k)!}{3 \cdot 6 \cdots 3k \cdot 3^{2k} \cdot (2k)!} = \frac{(-1)^k \cdot (3k)!}{3^k \cdot k! \cdot 3^{2k} \cdot (2k)!} \pmod{p}. \end{aligned}$$

Hence, by Lemma 2.1 we have

$$\begin{aligned} P_{[\frac{p}{3}]}(t) &= \sum_{k=0}^{[p/3]} \binom{[\frac{p}{3}] + k}{2k} \binom{2k}{k} \left(\frac{t-1}{2}\right)^k \equiv \sum_{k=0}^{[p/3]} \frac{(-1)^k \cdot (3k)!}{3^{3k} \cdot k! (2k)!} \cdot \frac{(2k)!}{k!^2} \left(\frac{t-1}{2}\right)^k \\ &= \sum_{k=0}^{[p/3]} \frac{(3k)!}{27^k \cdot k!^3} \left(\frac{1-t}{2}\right)^k \pmod{p}. \end{aligned}$$

This proves the lemma. □

Theorem 2.4. *Let p be a prime greater than 3 and let x be a variable. Then*

$$\sum_{k=0}^{[p/3]} \frac{(3k)!}{27^k \cdot k!^3} (x^k - (-1)^{[\frac{p}{3}]} (1-x)^k) \equiv 0 \pmod{p}.$$

Proof. As $P_n(t) = (-1)^n P_n(-t)$, using Lemma 2.3 we deduce that

$$\sum_{k=0}^{[p/3]} \frac{(3k)!}{27^k \cdot k!^3} \left(\left(\frac{1-t}{2}\right)^k - (-1)^{[p/3]} \left(\frac{1+t}{2}\right)^k \right) \equiv 0 \pmod{p}.$$

Now putting $t = 1 - 2x$ in the congruence we obtain the result. □

Corollary 2.2. *Let p be a prime greater than 3. Then*

$$\sum_{k=0}^{[p/3]} \frac{(3k)!}{27^k \cdot k!^3} \equiv \left(\frac{p}{3}\right) \pmod{p}.$$

Proof. Taking $x = 1$ in Theorem 2.4 and noting that $(-1)^{[p/3]} = \left(\frac{p}{3}\right)$ we deduce the result. □

Remark 2.2. By [8] or [10, p. 204] we have the stronger supercongruence $\sum_{k=0}^{p-1} \frac{(3k)!}{27^k \cdot k!^3} \equiv \left(\frac{p}{3}\right) \pmod{p^2}$.

Lemma 2.4. *Let p be an odd prime and $k \in \{1, 2, \dots, \frac{p-1}{2}\}$. Then*

$$\binom{(p-1)/2}{k} \equiv \frac{1}{(-4)^k} \binom{2k}{k} \left(1 - p \sum_{i=1}^k \frac{1}{2i-1}\right) \pmod{p^2}.$$

Proof. It is clear that

$$\begin{aligned} \binom{\frac{p-1}{2}}{k} &= \frac{\frac{p-1}{2}(\frac{p-1}{2}-1)\cdots(\frac{p-1}{2}-k+1)}{k!} = \frac{(p-1)(p-3)\cdots(p-(2k-1))}{2^k \cdot k!} \\ &\equiv \frac{(-1)(-3)\cdots(-(2k-1))}{2^k \cdot k!} \left(1 - p \sum_{i=1}^k \frac{1}{2i-1}\right) \\ &= \frac{(-1)^k \cdot (2k)!}{(2^k \cdot k!)^2} \left(1 - p \sum_{i=1}^k \frac{1}{2i-1}\right) \pmod{p^2}. \end{aligned}$$

This yields the result. □

Theorem 2.5. *Let p be a prime greater than 5. Then*

$$\sum_{k=0}^{\lfloor p/3 \rfloor} \frac{(3k)!}{54^k \cdot k!^3} \equiv \begin{cases} 0 \pmod{p} & \text{if } 6 \mid p-5, \\ 2A \pmod{p} & \text{if } 6 \mid p-1 \text{ and } p = A^2 + 3B^2 \text{ with } 3 \mid A-1 \end{cases}$$

and

$$\sum_{k=0}^{\lfloor p/3 \rfloor} \frac{k \cdot (3k)!}{54^k \cdot k!^3} \equiv \begin{cases} 0 \pmod{p} & \text{if } 6 \mid p-1, \\ \frac{1}{3}(-1)^{\frac{p+1}{6}} 2^{-\frac{p+1}{3}} \binom{(p+1)/3}{(p+1)/6} \pmod{p} & \text{if } 6 \mid p-5. \end{cases}$$

Proof. Taking $t = 0$ in Lemma 2.3 and applying (2.5) and Lemma 2.4 we deduce that

$$\sum_{k=0}^{\lfloor p/3 \rfloor} \frac{(3k)!}{54^k \cdot k!^3} \equiv \begin{cases} 0 \pmod{p} & \text{if } p \equiv 5 \pmod{6}, \\ \frac{(-1)^{(p-1)/6}}{2^{(p-1)/3}} \binom{(p-1)/3}{(p-1)/6} \equiv \binom{(p-1)/2}{(p-1)/6} \pmod{p} & \text{if } p \equiv 1 \pmod{6}. \end{cases}$$

Now suppose $p \equiv 1 \pmod{6}$, and so $p = A^2 + 3B^2$ with $A, B \in \mathbb{Z}$ and $A \equiv 1 \pmod{3}$. By [2, Theorem 9.4.4] we have $\binom{(p-1)/2}{(p-1)/6} \equiv 2A \pmod{p}$. Thus the first part follows.

By Lemma 2.3 we have

$$\frac{d}{dt} P_{\lfloor \frac{p}{3} \rfloor}(t) \equiv - \sum_{k=0}^{\lfloor p/3 \rfloor} \frac{(3k)!}{54^k \cdot k!^3} \cdot k(1-t)^{k-1} \pmod{p}.$$

Thus, $\frac{d}{dt} P_{\lfloor \frac{p}{3} \rfloor}(t)|_{t=0} \equiv - \sum_{k=0}^{\lfloor p/3 \rfloor} \frac{k \cdot (3k)!}{54^k \cdot k!^3} \pmod{p}$. From (1.3) we know that

$$\frac{d}{dt} P_{\lfloor \frac{p}{3} \rfloor}(t)|_{t=0} = \begin{cases} 0 & \text{if } p \equiv 1 \pmod{6}, \\ 2^{-\frac{p-2}{3}} \cdot (-1)^{\frac{p-5}{6}} \frac{\frac{p+1}{3}!}{\frac{p-5}{6}! \frac{p+1}{6}!} & \text{if } p \equiv 5 \pmod{6}. \end{cases}$$

Thus the second part is true. □

Lemma 2.5. *Let p be an odd prime and $k \in \{1, 2, \dots, \frac{p-1}{2}\}$. Then*

$$\frac{(-1)^k \binom{(p-1)/2+k}{k}}{\binom{(p-1)/2}{k}} \equiv 1 + 2p \sum_{i=1}^k \frac{1}{2i-1} \equiv 3 - 2(-4)^k \frac{\binom{(p-1)/2}{k}}{\binom{2k}{k}} \pmod{p^2}.$$

Proof. It is clear that

$$\begin{aligned} \frac{(-1)^k \binom{(p-1)/2+k}{k}}{\binom{(p-1)/2}{k}} &= \frac{\left(\frac{p-1}{2} + k\right)\left(\frac{p-1}{2} + k - 1\right) \cdots \left(\frac{p-1}{2} + 1\right)}{(-1)^k \frac{p-1}{2} \left(\frac{p-1}{2} - 1\right) \cdots \left(\frac{p-1}{2} - k + 1\right)} \\ &= \frac{(p + 2k - 1)(p + 2k - 3) \cdots (p + 1)}{(-1)^k (p - 1)(p - 3) \cdots (p - (2k - 1))} \\ &\equiv \frac{1 \cdot 3 \cdots (2k - 1)(1 + p \sum_{i=1}^k \frac{1}{2i-1})}{1 \cdot 3 \cdots (2k - 1)(1 - p \sum_{i=1}^k \frac{1}{2i-1})} \\ &\equiv \left(1 + p \sum_{i=1}^k \frac{1}{2i - 1}\right)^2 \equiv 1 + 2p \sum_{i=1}^k \frac{1}{2i - 1} \pmod{p^2}. \end{aligned}$$

This together with Lemma 2.4 yields the result. □

Theorem 2.6. *Let p be an odd prime, $x \in \mathbb{Z}_p$ and $x \not\equiv -1 \pmod{p}$. Then*

$$P_{\frac{p-1}{2}}(x) \equiv \left(\frac{2(x+1)}{p}\right) P_{\frac{p-1}{2}}\left(\frac{3-x}{1+x}\right) \pmod{p}.$$

Proof. It is known that (see [4, (3.134)])

$$P_n(x) = \sum_{k=0}^n \binom{n}{k}^2 \left(\frac{x+1}{2}\right)^{n-k} \left(\frac{x-1}{2}\right)^k.$$

Thus, using Lemma 2.5 and (2.1) we see that

$$\begin{aligned} P_{\frac{p-1}{2}}(x) &= \left(\frac{x+1}{2}\right)^{\frac{p-1}{2}} \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2}}{k}^2 \left(\frac{x-1}{x+1}\right)^k \\ &\equiv \left(\frac{2(x+1)}{p}\right) \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2}}{k} \binom{\frac{p-1}{2} + k}{k} (-1)^k \left(\frac{x-1}{x+1}\right)^k \\ &= \left(\frac{2(x+1)}{p}\right) P_{\frac{p-1}{2}}\left(1 + 2 \cdot \frac{1-x}{1+x}\right) = \left(\frac{2(x+1)}{p}\right) P_{\frac{p-1}{2}}\left(\frac{3-x}{1+x}\right) \pmod{p}. \end{aligned}$$

This proves the theorem. □

Corollary 2.3. *Let p be a prime of the form $4k + 3$. Then $P_{\frac{p-1}{2}}(3) \equiv 0 \pmod{p}$.*

Proof. By Theorem 2.6 and (2.5) we have $P_{\frac{p-1}{2}}(3) \equiv \binom{2}{p} P_{\frac{p-1}{2}}(0) = 0 \pmod{p}$. □

Theorem 2.7. *Let p be an odd prime, $x \in \mathbb{Z}_p$ and $x \not\equiv 0 \pmod{p}$. Then*

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(x^k - \left(\frac{x}{p}\right)x^{-k}\right) \equiv 0 \pmod{p}.$$

Proof. Clearly the result is true for $x \equiv 1 \pmod{p}$. Now assume $x \not\equiv 1 \pmod{p}$. As $P_n(t) = (-1)^n P_n(-t)$ (see [6]), using Theorem 2.6 we see that for $t \in \mathbb{Z}_p$ with $t \not\equiv \pm 1 \pmod{p}$,

$$\left(\frac{2(t+1)}{p}\right) P_{\frac{p-1}{2}}\left(\frac{3-t}{1+t}\right) \equiv (-1)^{\frac{p-1}{2}} \left(\frac{2(-t+1)}{p}\right) P_{\frac{p-1}{2}}\left(\frac{3+t}{1-t}\right) \pmod{p}.$$

Thus,

$$P_{\frac{p-1}{2}}\left(\frac{3-t}{1+t}\right) \equiv \left(\frac{t^2-1}{p}\right)P_{\frac{p-1}{2}}\left(\frac{3+t}{1-t}\right) \pmod{p}.$$

Now applying (2.4) we deduce that

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\frac{1-\frac{3-t}{1+t}}{2}\right)^k \equiv \left(\frac{t^2-1}{p}\right) \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\frac{1-\frac{3+t}{1-t}}{2}\right)^k \pmod{p}$$

and so

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{16^k} \left(\left(\frac{t-1}{t+1}\right)^k - \left(\frac{(t-1)/(t+1)}{p}\right) \left(\frac{t+1}{t-1}\right)^k \right) \equiv 0 \pmod{p}.$$

Set $t = (1+x)/(1-x)$. Then $t \not\equiv \pm 1 \pmod{p}$ and $x = (t-1)/(t+1)$. Hence the result follows. □

Let p be an odd prime, and let $x \in \mathbb{Z}_p$ with $x \not\equiv 0, 1 \pmod{p}$. By Theorems 2.1 and 2.7 we have

$$(2.7) \quad \sum_{k=0}^{(p-1)/2} \frac{\binom{2k}{k}^2}{(16x)^k} \equiv \left(\frac{x(x-1)}{p}\right) \sum_{k=0}^{(p-1)/2} \frac{\binom{2k}{k}^2}{(16(1-x))^k} \pmod{p}.$$

Theorem 2.8. *Let p be an odd prime, $x \in \mathbb{Z}_p$ and $x \not\equiv 0 \pmod{p}$. Then*

$$\sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 \left(\frac{x}{4}\right)^{2k} \equiv \left(\frac{-x}{p}\right)P_{\frac{p-1}{2}}\left(\frac{x+x^{-1}}{2}\right) \pmod{p}.$$

Proof. From [4, (3.138)] we have the following result due to Kelisky:

$$(2.8) \quad \sum_{k=0}^n \binom{2n-2k}{n-k} \binom{2k}{k} x^{2k} = 2^{2n} x^n P_n\left(\frac{x+x^{-1}}{2}\right).$$

Taking $n = (p-1)/2$ in (2.8) we have

$$\sum_{k=0}^{\frac{p-1}{2}} \binom{p-1-2k}{\frac{p-1}{2}-k} \binom{2k}{k} x^{2k} = 2^{p-1} x^{\frac{p-1}{2}} P_{\frac{p-1}{2}}\left(\frac{x+x^{-1}}{2}\right) \equiv \left(\frac{x}{p}\right)P_{\frac{p-1}{2}}\left(\frac{x+x^{-1}}{2}\right) \pmod{p}.$$

To see the result, using Lemma 2.2 we note that for $0 \leq k \leq \frac{p-1}{2}$,

$$(2.9) \quad \begin{aligned} \binom{p-1-2k}{\frac{p-1}{2}-k} &= \frac{(p-1-2k)(p-2-2k)\cdots(p-(\frac{p-1}{2}+k))}{(\frac{p-1}{2}-k)!} \\ &\equiv (-1)^{\frac{p-1}{2}-k} \frac{(2k+1)(2k+2)\cdots(\frac{p-1}{2}+k)}{(\frac{p-1}{2}-k)!} \\ &= (-1)^{\frac{p-1}{2}-k} \binom{\frac{p-1}{2}+k}{2k} \equiv (-1)^{\frac{p-1}{2}-k} \frac{\binom{2k}{k}}{16^k} \pmod{p}. \end{aligned}$$

□

Theorem 2.9. *Let p be a prime of the form $4k + 1$ and $p = a^2 + b^2$ with $a, b \in \mathbb{Z}$ and $a \equiv 1 \pmod{4}$. Then*

$$\sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{8^k} \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-16)^k} \equiv P_{\frac{p-1}{2}}(3) \equiv (-1)^{\frac{p-1}{4}} \left(2a - \frac{p}{2a}\right) \pmod{p^2}.$$

Proof. By Theorem 2.1 and (2.4) we have $\sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 8^{-k} \equiv \sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 (-16)^{-k} \equiv P_{\frac{p-1}{2}}(3) \pmod{p^2}$. From Theorem 2.6, (2.5) and Gauss' congruence $\binom{(p-1)/2}{(p-1)/4} \equiv 2a \pmod{p}$ (see [2]) we have

$$P_{\frac{p-1}{2}}(3) \equiv \left(\frac{2}{p}\right) P_{\frac{p-1}{2}}(0) = \left(\frac{2}{p}\right) \frac{(-1)^{(p-1)/4}}{2^{(p-1)/2}} \binom{(p-1)/2}{(p-1)/4} \equiv (-1)^{\frac{p-1}{4}} \cdot 2a \pmod{p}.$$

Write $P_{\frac{p-1}{2}}(3) = (-1)^{\frac{p-1}{4}} \cdot 2a + qp$. Then $P_{\frac{p-1}{2}}(3)^2 \equiv 4a^2 + (-1)^{\frac{p-1}{4}} \cdot 4aqp \pmod{p^2}$.

By a result due to Van Hamme [15], we have $(\sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2}}{k} \binom{\frac{p-1}{2}+k}{k})^2 \equiv 4a^2 - 2p \pmod{p^2}$. This together with (2.1) yields $P_{\frac{p-1}{2}}(3)^2 \equiv 4a^2 - 2p \pmod{p^2}$. Hence $(-1)^{\frac{p-1}{4}} \cdot 4aq \equiv -2 \pmod{p}$, and so $P_{\frac{p-1}{2}}(3) \equiv (-1)^{\frac{p-1}{4}} \cdot 2a - \frac{p}{2(-1)^{(p-1)/4}a} \pmod{p^2}$. Now combining all the above we obtain the result. \square

Remark 2.3. For a prime $p = 4k + 1 = a^2 + b^2$ with $a \equiv 1 \pmod{4}$, the congruence $\sum_{k=0}^{(p-1)/2} \binom{2k}{k}^2 8^{-k} \equiv \sum_{k=0}^{(p-1)/2} \binom{2k}{k}^2 (-16)^{-k} \equiv (-1)^{\frac{p-1}{4}} \cdot 2a \pmod{p}$ was proved by Zhi-Wei Sun in [13], and he also conjectured

$$\begin{aligned} \sum_{k=0}^{(p-1)/2} \binom{2k}{k}^2 8^{-k} &\equiv \sum_{k=0}^{(p-1)/2} \binom{2k}{k}^2 (-16)^{-k} \\ &\equiv (-1)^{\frac{p-1}{4}} \left(2a - \frac{p}{2a}\right) \pmod{p^2}. \end{aligned}$$

Theorem 2.10. *Let p be a prime of the form $4k + 1$, and so $p = a^2 + b^2$ with $a, b \in \mathbb{Z}$ and $a \equiv 1 \pmod{4}$. Then*

$$\sum_{k=0}^{\frac{p-1}{4}} \frac{\binom{4k}{2k}^2}{16^{2k}} \equiv \frac{1}{2} + (-1)^{\frac{p-1}{4}} a - (-1)^{\frac{p-1}{4}} \frac{p}{4a} \pmod{p^2}.$$

Proof. Since $\sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 16^{-k} + \sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 (-16)^{-k} = 2 \sum_{k=0}^{\frac{p-1}{4}} \binom{4k}{2k}^2 16^{-2k}$, by (1.1) and Theorem 2.9 we deduce the result. \square

For a prime $p > 3$ and $A, B, C \in \mathbb{Z}_p$, and let $\#E_p(y^2 = x^3 + Ax^2 + Bx + C)$ be the number of points on the curve $E_p : y^2 = x^3 + Ax^2 + Bx + C$ over the field \mathbb{F}_p of p elements.

Lemma 2.6 ([5]). *Let $p > 3$ be a prime and $\lambda \in \mathbb{Z}_p$ with $\lambda \not\equiv 0, 1 \pmod{p}$. Then*

$$p + 1 - \#E_p(y^2 = x(x-1)(x-\lambda)) \equiv (-1)^{\frac{p-1}{2}} \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2} + k}{k} \binom{\frac{p-1}{2}}{k} (-\lambda)^k \pmod{p}.$$

Theorem 2.11. *Let $p > 3$ be a prime and $t \in \mathbb{Z}_p$. Then*

$$P_{\frac{p-1}{2}}(t) \equiv \sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 \left(\frac{1-t}{32}\right)^k \equiv -\left(\frac{-6}{p}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 3(t^2+3)x + 2t(t^2-9)}{p}\right) \pmod{p}.$$

Proof. For $t \equiv \pm 1 \pmod{p}$ we have

$$\begin{aligned} & \sum_{x=0}^{p-1} \left(\frac{x^3 - 3(t^2 + 3)x + 2t(t^2 - 9)}{p} \right) \\ &= \sum_{x=0}^{p-1} \left(\frac{x^3 - 12x \mp 16}{p} \right) = \sum_{x=0}^{p-1} \left(\frac{(2x)^3 - 12(2x) \mp 16}{p} \right) = \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 3x \mp 2}{p} \right) \\ &= \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{(x \pm 1)^2(x \mp 2)}{p} \right) = \left(\frac{2}{p} \right) \left(\sum_{x=0}^{p-1} \left(\frac{x \mp 2}{p} \right) - \left(\frac{\mp 3}{p} \right) \right) = - \left(\frac{\mp 6}{p} \right). \end{aligned}$$

Thus applying (2.4) and the fact $P_n(\pm 1) = (\pm 1)^n$ (see [6]) we deduce the result.

Now assume $t \not\equiv \pm 1 \pmod{p}$. For $A, B, C \in \mathbb{Z}_p$, it is easily seen that (see for example [12, pp. 221-222])

$$\#E_p(y^2 = x^3 + Ax^2 + Bx + C) = p + 1 + \sum_{x=0}^{p-1} \left(\frac{x^3 + Ax^2 + Bx + C}{p} \right).$$

Taking $\lambda = (1 - t)/2$ in Lemma 2.6 and applying the above and (2.1) we see that

$$\begin{aligned} P_{\frac{p-1}{2}}(t) &= \sum_{k=0}^{\frac{p-1}{2}} \binom{\frac{p-1}{2} + k}{k} \binom{\frac{p-1}{2}}{k} \left(\frac{t-1}{2} \right)^k \\ &\equiv (-1)^{\frac{p-1}{2}} (p + 1 - \#E_p(y^2 = x(x-1)(x - (1-t)/2))) \\ &= (-1)^{\frac{p+1}{2}} \sum_{x=0}^{p-1} \left(\frac{x(x-1)(x - (1-t)/2)}{p} \right) \pmod{p}. \end{aligned}$$

Since

$$\begin{aligned} & \sum_{x=0}^{p-1} \left(\frac{x(x-1)(x - (1-t)/2)}{p} \right) \\ &= \sum_{x=0}^{p-1} \left(\frac{\frac{x}{2}(\frac{x}{2} - 1)(\frac{x}{2} - \frac{1-t}{2})}{p} \right) = \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{x(x-2)(x+t-1)}{p} \right) \\ &= \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{x^3 + (t-3)x^2 - 2(t-1)x}{p} \right) \\ &= \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{(x - \frac{t-3}{3})^3 + (t-3)(x - \frac{t-3}{3})^2 - 2(t-1)(x - \frac{t-3}{3})}{p} \right) \\ &= \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{x^3 - \frac{t^2+3}{3}x + \frac{2t^3-18t}{27}}{p} \right) = \left(\frac{2}{p} \right) \sum_{x=0}^{p-1} \left(\frac{(\frac{x}{3})^3 - \frac{t^2+3}{3} \cdot \frac{x}{3} + \frac{2t^3-18t}{27}}{p} \right) \\ &= \left(\frac{6}{p} \right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 3(t^2 + 3)x + 2t(t^2 - 9)}{p} \right), \end{aligned}$$

by the above and (2.4) we obtain the result. The proof is now complete. □

Theorem 2.12. *Let $p > 3$ be a prime. Then*

$$\begin{aligned}
 P_{\frac{p-1}{2}}(-31) &\equiv \sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{256^k} \equiv -\left(\frac{p}{3}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 723x - 7378}{p}\right) \pmod{p}, \\
 P_{\frac{p-1}{2}}(33) &\equiv \sum_{k=0}^{\frac{p-1}{2}} (-1)^k \binom{2k}{k}^2 \equiv (-1)^{\frac{p-1}{2}} \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-256)^k} \equiv (-1)^{\frac{p+1}{2}} \sum_{x=0}^{p-1} \left(\frac{x^3 - 91x + 330}{p}\right) \pmod{p}, \\
 P_{\frac{p-1}{2}}(-15) &\equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{2^k} \equiv \left(\frac{2}{p}\right) \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{128^k} \equiv (-1)^{\frac{p+1}{2}} \sum_{x=0}^{p-1} \left(\frac{x^3 - 19x - 30}{p}\right) \pmod{p}, \\
 P_{\frac{p-1}{2}}(9) &\equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-4)^k} \equiv (-1)^{\frac{p-1}{2}} \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-64)^k} \equiv (-1)^{\frac{p+1}{2}} \sum_{x=0}^{p-1} \left(\frac{x^3 - 7x + 6}{p}\right) \pmod{p}, \\
 P_{\frac{p-1}{2}}(5) &\equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-8)^k} \equiv \left(\frac{-2}{p}\right) \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-32)^k} \equiv -\left(\frac{p}{3}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 21x + 20}{p}\right) \pmod{p}.
 \end{aligned}$$

Proof. Taking $t = -31$ in Theorem 2.11 and applying Theorem 2.7 we see that

$$\begin{aligned}
 P_{\frac{p-1}{2}}(-31) &\equiv \sum_{k=0}^{\frac{p-1}{2}} \binom{2k}{k}^2 \equiv \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{256^k} \equiv -\left(\frac{-6}{p}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 3(31^2 + 3)x - 62(31^2 - 9)}{p}\right) \\
 &= -\left(\frac{-6}{p}\right) \sum_{x=0}^{p-1} \left(\frac{(2x)^3 - 4 \cdot 723 \cdot 2x - 8 \cdot 7378}{p}\right) \\
 &= -\left(\frac{-3}{p}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 723x - 7378}{p}\right) \pmod{p}.
 \end{aligned}$$

Taking $t = 33$ in Theorem 2.11 and applying Theorem 2.7 we see that

$$\begin{aligned}
 P_{\frac{p-1}{2}}(33) &\equiv \sum_{k=0}^{\frac{p-1}{2}} (-1)^k \binom{2k}{k}^2 \equiv \left(\frac{-16}{p}\right) \sum_{k=0}^{\frac{p-1}{2}} \frac{\binom{2k}{k}^2}{(-256)^k} \equiv -\left(\frac{-6}{p}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 3276x + 71280}{p}\right) \\
 &= -\left(\frac{-6}{p}\right) \sum_{x=0}^{p-1} \left(\frac{(6x)^3 - 36 \cdot 91 \cdot 6x + 216 \cdot 330}{p}\right) \\
 &= -\left(\frac{-1}{p}\right) \sum_{x=0}^{p-1} \left(\frac{x^3 - 91x + 330}{p}\right) \pmod{p}.
 \end{aligned}$$

The remaining congruences can be proved similarly. □

For $a, b, n \in \mathbb{N}$, if $n = ax^2 + by^2$ for some $x, y \in \mathbb{Z}$, we say that $n = ax^2 + by^2$. In 2003, Rodriguez-Villegas [11] posed many conjectures on supercongruences. In particular, he conjectured that for any prime $p > 3$,

$$\sum_{k=0}^{p-1} \frac{(4k)!}{256^k k!^4} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1, 3 \pmod{8}, \text{ and so } p = x^2 + 2y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 5, 7 \pmod{8} \end{cases}$$

and

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2 \binom{3k}{k}}{108^k} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } 3 \mid p - 1, \text{ and so } p = x^2 + 3y^2, \\ 0 \pmod{p^2} & \text{if } 3 \nmid p - 2. \end{cases}$$

Recently Zhi-Wei Sun ([13, 14]) made a lot of conjectures on supercongruences. In particular, he conjectured that for a prime $p \neq 2, 7$,

$$\sum_{k=0}^{p-1} \binom{2k}{k}^3 \equiv \sum_{k=0}^{p-1} \frac{(4k)!}{81^k k!^4} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = 1 \text{ and so } p = x^2 + 7y^2, \\ 0 \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = -1. \end{cases}$$

Inspired by his work, we pose the following conjectures.

Conjecture 2.1. *Let $p > 3$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(4k)!}{648^k k!^4} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1 \pmod{4} \text{ and } p = x^2 + y^2 \text{ with } 2 \nmid x, \\ 0 \pmod{p^2} & \text{if } p \equiv 3 \pmod{4}. \end{cases}$$

Conjecture 2.2. *Let $p > 3$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(4k)!}{(-144)^k k!^4} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1 \pmod{3}, \text{ and so } p = x^2 + 3y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 2 \pmod{3}. \end{cases}$$

Conjecture 2.3. *Let $p \neq 2, 3, 7$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(4k)!}{(-3969)^k k!^4} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1, 2, 4 \pmod{7}, \text{ and so } p = x^2 + 7y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 3, 5, 6 \pmod{7}. \end{cases}$$

Conjecture 2.4. *Let $p \neq 2, 3, 11$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(6k)!}{66^{3k} (3k)! k!^3} \equiv \begin{cases} \left(\frac{p}{33}\right) (4x^2 - 2p) \pmod{p^2} & \text{if } 4 \mid p - 1 \text{ and } p = x^2 + y^2 \text{ with } 2 \nmid x, \\ 0 \pmod{p^2} & \text{if } 4 \nmid p - 3. \end{cases}$$

Conjecture 2.5. *Let $p > 5$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(6k)!}{20^{3k} (3k)! k!^3} \equiv \begin{cases} \left(\frac{-5}{p}\right) (4x^2 - 2p) \pmod{p^2} & \text{if } p \equiv 1, 3 \pmod{8} \text{ and } p = x^2 + 2y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 5, 7 \pmod{8}. \end{cases}$$

Conjecture 2.6. *Let $p > 5$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(6k)!}{54000^k (3k)! k!^3} \equiv \begin{cases} \left(\frac{p}{5}\right) (4x^2 - 2p) \pmod{p^2} & \text{if } 3 \mid p - 1, \text{ and so } p = x^2 + 3y^2, \\ 0 \pmod{p^2} & \text{if } 3 \nmid p - 2. \end{cases}$$

Conjecture 2.7. *Let $p > 5$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(6k)!}{(-12288000)^k (3k)! k!^3} \equiv \begin{cases} \left(\frac{10}{p}\right) (L^2 - 2p) \pmod{p^2} & \text{if } p \equiv 1 \pmod{3}, \text{ and so } 4p = L^2 + 27M^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 2 \pmod{3}. \end{cases}$$

Conjecture 2.8. *Let $p > 7$ be a prime. Then*

$$\sum_{k=0}^{p-1} \frac{(6k)!}{(-15)^{3k} (3k)! k!^3} \equiv \begin{cases} \left(\frac{p}{15}\right) (4x^2 - 2p) \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = 1, \text{ and so } p = x^2 + 7y^2, \\ 0 \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = -1. \end{cases}$$

Conjecture 2.9. Let $p \neq 2, 3, 5, 7, 17$ be a prime. Then

$$\sum_{k=0}^{p-1} \frac{(6k)!}{255^{3k}(3k)!k!^3} \equiv \begin{cases} \left(\frac{p}{255}\right)(4x^2 - 2p) \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = 1, \text{ and so } p = x^2 + 7y^2, \\ 0 \pmod{p^2} & \text{if } \left(\frac{p}{7}\right) = -1. \end{cases}$$

Conjecture 2.10. Let $p > 3$ be a prime. Then

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2 \binom{3k}{k}}{1458^k} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1 \pmod{3}, \text{ and so } p = x^2 + 3y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 2 \pmod{3}. \end{cases}$$

Conjecture 2.11. Let $p > 5$ be a prime. Then

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2 \binom{3k}{k}}{15^{3k}} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } p \equiv 1, 4 \pmod{15}, \text{ and so } p = x^2 + 15y^2, \\ 2p - 12x^2 \pmod{p^2} & \text{if } p \equiv 2, 8 \pmod{15}, \text{ and so } p = 3x^2 + 5y^2, \\ 0 \pmod{p^2} & \text{if } p \equiv 7, 11, 13, 14 \pmod{15}. \end{cases}$$

Conjecture 2.12. Let $p > 5$ be a prime. Then

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2 \binom{3k}{k}}{(-8640)^k} \equiv \begin{cases} 4x^2 - 2p \pmod{p^2} & \text{if } 3 \mid p-1, p = x^2 + 3y^2 \text{ and } 5 \mid xy, \\ p - 2x^2 \pm 6xy \pmod{p^2} & \text{if } 3 \mid p-1, p = x^2 + 3y^2, 5 \nmid xy \\ & \text{and } x \equiv \pm y, \pm 2y \pmod{5}, \\ 0 \pmod{p^2} & \text{if } 3 \mid p-2. \end{cases}$$

Conjecture 2.13. Let $p > 3$ be a prime. Then

$$\sum_{k=0}^{p-1} \frac{(3k)!}{54^k \cdot k!^3} \equiv \begin{cases} \left(\frac{p}{3}\right)(2x - \frac{p}{2x}) \pmod{p^2} & \text{if } 3 \mid p-1, \text{ and so } p = x^2 + 3y^2, \\ 0 \pmod{p^2} & \text{if } 3 \mid p-2. \end{cases}$$

REFERENCES

1. S. Ahlgren and K. Ono, *A Gaussian hypergeometric series evaluation and Apéry number congruences*, J. Reine Angew. Math. **518** (2000), 187-212. MR1739404 (2001c:11057)
2. B.C. Berndt, R.J. Evans and K.S. Williams, *Gauss and Jacobi Sums*, John Wiley & Sons, New York, 1998. MR1625181 (99d:11092)
3. S. Chowla, B. Dwork and R. J. Evans, *On the mod p^2 determination of $\binom{p-1}{(p-1)/4}$* , J. Number Theory **24** (1986), 188-196. MR863654 (88a:11130)
4. H.W. Gould, *Combinatorial Identities, A Standardized Set of Tables Listing 500 Binomial Coefficient Summations*, Morgantown, W. Va., 1972. MR0354401 (50:6879)
5. P.-R. Loh and R.C. Rhoades, *p -adic and combinatorial properties of modular form coefficients*, Int. J. Number Theory **2** (2006), 305-328. MR2240232 (2007f:11047)
6. W. Magnus, F. Oberhettinger and R.P. Soni, *Formulas and Theorems for the Special Functions of Mathematical Physics, 3rd. ed.*, D. Grund. Math. Wissen. Springer, New York, 1966, pp. 228-232. MR0232968 (38:1291)
7. E. Mortenson, *A supercongruence conjecture of Rodriguez-Villegas for a certain truncated hypergeometric function*, J. Number Theory **99** (2003), 139-147. MR1957248 (2004e:11089)
8. E. Mortenson, *Supercongruences between truncated ${}_2F_1$ by hypergeometric functions and their Gaussian analogs*, Trans. Amer. Math. Soc. **355** (2003), 987-1007. MR1938742 (2003i:11119)
9. E. Mortenson, *Supercongruences for truncated ${}_n+1F_n$ hypergeometric series with applications to certain weight three newforms*, Proc. Amer. Math. Soc. **133** (2005), 321-330. MR2093051 (2005f:11080)
10. K. Ono, *The Web of Modularity: Arithmetic of the Coefficients of Modular Forms and q -series*, CBMS Monograph 102, Amer. Math. Soc., Providence, RI, 2004. MR2020489 (2005c:11053)
11. F. Rodriguez-Villegas, *Hypergeometric families of Calabi-Yau manifolds. Calabi-Yau Varieties and Mirror Symmetry* (Yui, Noriko (ed.) et al., Toronto, ON, 2001), 223-231, Fields Inst. Commun., 38, Amer. Math. Soc., Providence, RI, 2003. MR2019156 (2005b:11086)

12. Z.H. Sun, *On the number of incongruent residues of $x^4 + ax^2 + bx$ modulo p* , J. Number Theory **119** (2006), 210-241. MR2250045 (2007f:11003)
13. Z.W. Sun, *On congruences related to central binomial coefficients*, preprint, arXiv:0911.2415, <http://arxiv.org/abs/0911.2415>.
14. Z.W. Sun, *Open conjectures on congruences*, arXiv:0911.5665. <http://arxiv.org/abs/0911.5665>.
15. L. Van Hamme, *Proof of a conjecture of Beukers on Apéry numbers*, Proceedings of the Conference on p-adic Analysis (N. De Grande-De Kimpe and L. Van Hamme, ed., Houthalen, 1987), pp. 189-195, Vrije Univ. Brussel, Brussels, 1986. MR921871 (89b:11007)

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