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A GENERATING FUNCTION OF THE SQUARES OF LEGENDRE POLYNOMIALS

WADIM ZUDILIN

ABSTRACT. We relate a one-parametric generating function for the squares of Legendre polynomials to an arithmetic hypergeometric series whose parametrisation by a level 7 modular function was recently given by S. Cooper. By using this modular parametrisation we resolve a subfamily of identities involving $1/\pi$ which was experimentally observed by Z.-W. Sun.

In our joint papers [7] with H. H. Chan and J. Wan and [15] with Wan we made an arithmetic use but also extended the generating functions of Legendre polynomials

$$P_n(y) = {}_2F_1\left(-n, n+1 \mid \frac{1-y}{2}\right),$$

originally due to F. Brafman [3]. Our generalised generating functions have the form $\sum_{n=0}^{\infty} u_n P_n(y) z^n$ where u_n is a so-called Apéry-like sequence as well as

$$\sum_{n=0}^{\infty} \binom{2n}{n}^2 P_{2n}(y) z^n \quad \text{and} \quad \sum_{n=0}^{\infty} \frac{(3n)!}{n!^3} P_{3n}(y) z^n.$$

One motivation for the work was a list of formulae for $1/\pi$ given by Z.-W. Sun [13]. Because the preprint [13] is a dynamic survey of continuous experimental discoveries by its author, a few newer examples for $1/\pi$ involving the Legendre polynomials appeared after acceptance of [7] and [15]. Namely, the two groups of identities (VI1)–(VI3) and (VII1)–(VII7) related to the generating functions

$$\sum_{n=0}^{\infty} P_n(y)^3 z^n \quad \text{and} \quad \sum_{n=0}^{\infty} \binom{2n}{n} P_n(y)^2 z^n \tag{1}$$

are now given on p. 23 of [13]. A search of existing literature on the subject reveals no formula which could be useful in proving Sun's observations. The closest-to-wanted

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identity is Bailey's

$$\sum_{n=0}^{\infty} P_n(x)P_n(y)z^n = \frac{1}{(1+z(z-2\sqrt{(1-x^2)(1-y^2)}-2xy))^{1/2}} \times {}_2F_1\left(\frac{1}{2}, \frac{1}{2} \middle| \frac{-4\sqrt{(1-x^2)(1-y^2)}z}{1+z(z-2\sqrt{(1-x^2)(1-y^2)}-2xy)}\right), \quad (2)$$

which follows from [2, Eqs. (2.1) and (3.1)] and [1, Eq. (7) on p. 81]. The generating function (2) was rediscovered later by Maximon [10]. It admits, in fact, a less radical form

$$\sum_{n=0}^{\infty} P_n(x)P_n(y)z^n = \frac{1}{(1-2xyz+z^2)^{1/2}} {}_2F_1\left(\frac{1}{4}, \frac{3}{4} \middle| \frac{4(1-x^2)(1-y^2)z^2}{(1-2xyz+z^2)^2}\right) \quad (3)$$

which is due to Wan [14]. Unfortunately, no simple generalisation of the result for the terms on the left-hand side twisted by the central binomial coefficients is known, even in the particular case $x = y$.

With the help of Clausen's identity

$$P_n(y)^2 = {}_3F_2\left(\begin{matrix} -n, n+1, \frac{1}{2} \\ 1, 1 \end{matrix} \middle| 1-y^2\right) = \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} \left(-\frac{1-y^2}{4}\right)^k,$$

we find that the second generating function in (1) is equivalent to

$$\sum_{n=0}^{\infty} \binom{2n}{n} z^n \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} x^k. \quad (4)$$

In view of [15, Theorem 1], its Clausen-type specialization [6] and our identities (5), (7) below, it is quite likely that the latter generating function can be written as a product of two arithmetic hypergeometric series, each satisfying a second order linear differential equation. In this note we only recover the special case $z = x/(1+x)^2$ of the expected identity, the case which is suggested by Sun's observations (VII1) and (VII3)–(VII6) from [13].

Theorem 1. *For v from a small neighbourhood of the origin, take*

$$x(v) = \frac{v}{1+5v+8v^2} \quad \text{and} \quad z(v) = \frac{x(v)}{(1+x(v))^2} = \frac{v(1+5v+8v^2)}{(1+2v)^2(1+4v)^2}.$$

Then

$$\sum_{n=0}^{\infty} \binom{2n}{n} z(v)^n \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} x(v)^k = \frac{1+2v}{1+4v} \sum_{n=0}^{\infty} u_n \left(\frac{v}{(1+4v)^3}\right)^n, \quad (5)$$

where the sequence [12, A183204]

$$u_n = \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{n} \binom{2k}{n} = \sum_{k=0}^n (-1)^{n-k} \binom{3n+1}{n-k} \binom{n+k}{n}^3$$

satisfies the Apéry-like recurrence equation

$$(n+1)^3 u_{n+1} = (2n+1)(13n^2 + 13n + 4)u_n + 3n(3n-1)(3n+1)u_{n-1}$$

for $n = 0, 1, 2, \dots$, $u_{-1} = 0$, $u_0 = 1$.

Because $y^2 = 1 + 4x$ for the second generating function in (1), the equivalent form of (5) is the identity

$$\begin{aligned} \sum_{n=0}^{\infty} \binom{2n}{n} P_n \left(\frac{\sqrt{(1+v)(1+8v)}}{\sqrt{1+5v+8v^2}} \right)^2 \left(\frac{v(1+5v+8v^2)}{(1+2v)^2(1+4v)^2} \right)^n \\ = \frac{1+2v}{1+4v} \sum_{n=0}^{\infty} u_n \left(\frac{v}{(1+4v)^3} \right)^n, \end{aligned}$$

Remark 1. S. Cooper constructs in [9, Theorem 3.1] a modular parametrisation of the generating function $\sum_{n=0}^{\infty} u_n w^n$. Namely, he proves that the substitution

$$w(\tau) = \frac{\eta(\tau)^4 \eta(7\tau)^4}{\eta(\tau)^8 + 13\eta(\tau)^4 \eta(7\tau)^4 + 49\eta(7\tau)^8} \quad (6)$$

translates the function into the Eisenstein series $(7E_2(7\tau) - E_2(\tau))/6$. Here $\eta(\tau) = q^{1/24} \prod_{m=1}^{\infty} (1 - q^m)$ is Dedekind's eta function, $q = e^{2\pi i \tau}$, and

$$E_2(\tau) = \frac{12}{\pi i} \frac{d \log \eta}{d\tau} = 1 - 24 \sum_{n=1}^{\infty} \frac{q^n}{1 - q^n}.$$

Using this, Cooper derives a general family [9, Eqs. (37), (39)] of the related Ramanujan-type identities for $1/\pi$. It is this result and the 'translation' method [16] which allow us to prove Sun's observations (VII1) and (VII3)–(VII6) from [13]. Note that this modular parametrisation and results of Chan and Cooper [4, Lemmas 4.1 and 4.3] lead to the following hypergeometric forms of the generating function:

$$\begin{aligned} \frac{1}{\sqrt{1+13h+49h^2}} \sum_{n=0}^{\infty} u_n \left(\frac{h}{1+13h+49h^2} \right)^n \\ = \frac{1}{\sqrt{1+245h+2401h^2}} {}_3F_2 \left(\begin{matrix} \frac{1}{6}, \frac{1}{2}, \frac{5}{6} \\ 1, 1 \end{matrix} \middle| \frac{1728h}{(1+13h+49h^2)(1+245h+2401h^2)^3} \right) \\ = \frac{1}{\sqrt{1+5h+h^2}} {}_3F_2 \left(\begin{matrix} \frac{1}{6}, \frac{1}{2}, \frac{5}{6} \\ 1, 1 \end{matrix} \middle| \frac{1728h^7}{(1+13h+49h^2)(1+5h+h^2)^3} \right) \end{aligned}$$

which are valid near $h = 0$.

Theorem 2 (Satellite identity). *The identity*

$$\begin{aligned} \sum_{n=0}^{\infty} \binom{2n}{n} \left(\frac{x}{(1+x)^2} \right)^n \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} x^k \\ \times (2x(3+4x) - n(1-x)(3+5x) + 4k(1+x)(1+4x)) = 0 \end{aligned} \quad (7)$$

is valid whenever the left-hand side makes sense.

Proof of Theorems 1 and 2. The identity (5) is equivalent to

$$\sum_{n=0}^{\infty} \binom{2n}{n} \frac{v^n (1+5v+8v^2)^n}{(1+2v)^{2n+1} (1+4v)^{2n+1}} \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} \frac{v^k}{(1+5v+8v^2)^k} \\ = \sum_{n=0}^{\infty} u_n \frac{v^n}{(1+4v)^{3n+2}}.$$

It is routine to verify that the both sides are annihilated by the differential operator

$$v^2(1+v)(1+8v)(1+5v+8v^2) \frac{d^3}{dv^3} + 3v(1+21v+122v^2+280v^3+192v^4) \frac{d^2}{dv^2} \\ + (1+50v+454v^2+1408v^3+1216v^4) \frac{d}{dv} + 4(1+22v+108v^2+128v^3),$$

and the proof of Theorem 1 follows. A similar routine shows the vanishing in Theorem 2. \square

# in [13]	x	z	v	$w = v/(1+4v)^3$	τ
(VII1)	$-\frac{1}{14}$	$\frac{14}{225}$	1	$\frac{1}{5^3}$	$\frac{2i}{\sqrt{7}}$
(VII2)	$\frac{9}{20}$	$-\frac{5}{196}$			
(VII3)	$-\frac{1}{21}$	$\frac{21}{484}$	$1 + \frac{\sqrt{14}}{4}$	$\frac{188-42\sqrt{14}}{22^3}$	$\frac{i\sqrt{6}}{\sqrt{7}}$
(VII4)	$-\frac{1}{45}$	$\frac{45}{2116}$	$\frac{5}{2} + \frac{7\sqrt{2}}{4}$	$\left(\frac{8-3\sqrt{2}}{46}\right)^3$	$\frac{i\sqrt{10}}{\sqrt{7}}$
(VII5)	$\frac{1}{7}$	$-\frac{7}{36}$	$-\frac{3}{4} - \frac{\sqrt{7}}{4}$	$\frac{-34+14\sqrt{7}}{6^3}$	$\frac{i\sqrt{3}}{\sqrt{7}}$
(VII6)	$\frac{1}{175}$	$-\frac{175}{30276}$	$-\frac{45}{4} - \frac{17\sqrt{7}}{4}$	$\left(\frac{-13+7\sqrt{7}}{174}\right)^3$	$\frac{i\sqrt{19}}{\sqrt{7}}$
(VII7)	$-\frac{576}{3025}$	$\frac{3025}{188356}$			

TABLE 1. The choice of parameters for Sun's observations in [13, p. 23]. The last column corresponds to the choice of τ such that $w(\tau) = v/(1+4v)^3$ for the modular function $w(\tau)$ defined in (6)

In Table 1 we list the relevant parametrisations of Sun's formulae from [13]. The last column corresponds to the choice of τ in (6) such that $v/(1+4v)^3 = w(\tau)$ there. The general formulae for $1/\pi$ in these cases,

$$\sum_{n=0}^{\infty} (a+bn)u_n w^n = \frac{1}{\pi\sqrt{7}}, \quad (8)$$

are given by Cooper in [9, Eq. (37)]. On using (5) and its v -derivative

$$\begin{aligned} & \sum_{n=0}^{\infty} \binom{2n}{n} z(v)^n \sum_{k=0}^n \binom{n}{k} \binom{n+k}{n} \binom{2k}{k} x(v)^k \\ & \times \left(n \frac{(1-8v^2)(1+4v+8v^2)}{v(1+2v)(1+4v)(1+5v+8v^2)} + k \frac{1-8v^2}{v(1+5v+8v^2)} \right) \\ & = \frac{1+2v}{1+4v} \sum_{n=0}^{\infty} u_n \frac{v^n}{(1+4v)^{3n}} \left(n \frac{1-8v}{v(1+4v)} - \frac{2}{(1+2v)(1+4v)} \right), \end{aligned}$$

the equalities (8) together with the related specialisations of (7) (to eliminate the linear term in k) imply Sun's identities (VIII1), (VII3)–(VII6) by translation [16].

Note that Cooper's [9, Table 1] involves two more examples corresponding to the choices $-1/4^3$ and $-1/22^3$ for $v/(1+4v)^3$; the values of x and z in these cases are zeroes of certain irreducible cubic polynomials though. There are also several examples when x and z are taken from a quadratic field. For instance, taking $\tau = \frac{i\sqrt{11}}{\sqrt{7}}$ one gets

$$x = \frac{23 - 8\sqrt{11}}{175} \quad \text{and} \quad z = \frac{83 - 32\sqrt{11}}{1100}$$

in (5) and (7); the corresponding $v_1 = -6.798\dots$ and $v_2 = -0.018\dots$ solve the quartic equation $64v^4 + 448v^3 + 96v^2 + 56v + 1 = 0$. As such identities are only of theoretical importance, we do not derive them here.

It is apparent that there is a variety of formulae similar to (5) and (7) designed for generating functions of other polynomials. For example, Sun's list contains five identities involving values of the polynomials

$$A_n(x) = \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{n} x^k, \quad n = 0, 1, 2, \dots$$

By examining the entries (2.1)–(2.3) on p. 3 of [13] one notices that the parameters x and z of the generating function

$$\sum_{n=0}^{\infty} \binom{2n}{n} A_n(x) z^n \tag{9}$$

are related by $z = x/(1-4x)$, while the entries (6.1) and (6.2) on p. 15 there correspond to the relation $z = 1/(x+1)^2$. With some work we find that those specialisations indeed lead to third order arithmetic linear differential equations

which can be then identified with the known examples [5, 8]:

$$\begin{aligned}
& \sum_{n=0}^{\infty} \binom{2n}{n} \frac{v^n(1-v)^n(1-4v)^n}{(1-2v+4v^2)^{2n+1}} \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{n} \frac{v^k(1-v)^k(1-4v)^k}{(1-4v^2)^{2k+1}} \\
&= \sum_{n=0}^{\infty} \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{n}^2 \frac{v^n(1-2v)^n(1-4v)^{2n}}{(1-v)^{n+1}(1+2v)^{n+1}} \\
&= \sum_{n=0}^{\infty} \sum_{k=0}^n \binom{n}{k}^2 \binom{2k}{k} \binom{2n-2k}{n-k} \frac{(-1)^n v^n (1-v)^n (1-4v^2)^n}{(1-4v)^{2n+2}} \\
&= \sum_{n=0}^{\infty} \frac{(3n)!}{n!^3} \binom{2n}{n} \frac{v^n(1-v)^n(1-4v^2)^n(1-4v)^{4n}}{(1+4v-8v^2)^{2n+2}}
\end{aligned}$$

and

$$\begin{aligned}
& \sum_{n=0}^{\infty} \binom{2n}{n} \frac{v^{2n}}{(1+10v+27v^2)^{2n+1}} \sum_{k=0}^n \binom{n}{k}^2 \binom{n+k}{n} \frac{(1+9v+27v^2)^k}{v^k} \\
&= \sum_{n=0}^{\infty} \frac{(3n)!}{n!^3} \binom{2n}{n} \frac{v^n(1+9v+27v^2)^n}{(1+9v)^{6n+2}},
\end{aligned}$$

respectively. Additionally, there are satellite identities for each of the specialisations, both similar to (7). These identities, the known Ramanujan-type formulae for the right-hand sides and the translation technique can be then used to prove Sun's observations.

On the other hand, as already mentioned at the beginning, it is natural to expect the existence of Bailey–Brafman-like identities [7, 15] for the two-variate generating functions (4), (9).

Question. Given an (arithmetic) generating function $\sum_{n=0}^{\infty} A_n z^n$ which satisfies a second order linear differential equation (with regular singularities), is it true that $\sum_{n=0}^{\infty} \binom{2n}{n} A_n z^n$ can be written as the product of two arithmetic series, each satisfying (its own) second order linear differential equation?

Here, of course, we allow A_n depend on some other parameters; the example of such a product decomposition for $A_n = A_n(x) = \sum_k \binom{n}{k}^2 \binom{2k}{n} x^n$ is given recently by M. Rogers and A. Straub [11, Theorem 2.3]. An affirmative answer to the question would give one an arithmetic parametrisation of the generating function $\sum_{n=0}^{\infty} \binom{2n}{n} P_n(x) P_n(y) z^n$ (cf. (2) or (3)).

Note that there are some other generating functions in [13], like the first one in (1), which are not of the form $\sum_{n=0}^{\infty} \binom{2n}{n} A_n z^n$. We believe however that they can be reduced to the latter form by a suitable algebraic transformation.

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SCHOOL OF MATHEMATICAL AND PHYSICAL SCIENCES, THE UNIVERSITY OF NEWCASTLE,
 CALLAGHAN, NSW 2308, AUSTRALIA
E-mail address: wadim.zudilin@newcastle.edu.au