

EXACT FORMULAS FOR COEFFICIENTS OF JACOBI FORMS

KATHRIN BRINGMANN AND OLAV K. RICHTER

ABSTRACT. In previous work, we introduced harmonic Maass-Jacobi forms. The space of such forms includes the classical Jacobi forms and certain Maass-Jacobi-Poincaré series, as well as Zwegers' real-analytic Jacobi forms, which play an important role in the study of mock theta functions and related objects. Harmonic Maass-Jacobi forms decompose naturally into holomorphic and non-holomorphic parts. In this paper, we give exact formulas for the Fourier coefficients of the holomorphic parts of harmonic Maass-Jacobi forms and, in particular, we obtain explicit formulas for the Fourier coefficients of weak Jacobi forms.

1. Introduction and statement of results

In 1985, Eichler and Zagier [5] systematically developed a theory of Jacobi forms. That theory has since grown enormously, establishing deep connections to many other areas of mathematics and physics, such as the theory of Heegner points (see Gross, Kohnen, and Zagier [6]), the theory of elliptic genera (see Zagier [10]), string theory (for example, see Cardy [4]), and more recently, mock theta functions (see Zwegers [11]). In [2], we initiated a theory of harmonic Maass-Jacobi forms, which includes the holomorphic Jacobi forms of [5], the real-analytic Jacobi forms in [11], and certain Maass-Jacobi-Poincaré series as explicit examples. Of particular interest is $\widehat{\mathbb{J}}_{k,m}^{cusp}$, a distinguished subspace of harmonic Maass-Jacobi forms, which we will briefly review in Section 2. If $\phi \in \widehat{\mathbb{J}}_{k,m}^{cusp}$, then $\phi = \phi^+ + \phi^-$, where

$$(1) \quad \phi^+(\tau, z) = \sum_{\substack{n,r \in \mathbb{Z} \\ D \ll \infty}} c^+(n, r) q^n \zeta^r$$

is the holomorphic part of ϕ , while the non-holomorphic part of ϕ is given by

$$(2) \quad \phi^-(\tau, z) = \sum_{\substack{n,r \in \mathbb{Z} \\ D > 0}} c^-(n, r) \Gamma\left(\frac{3}{2} - k, \frac{\pi D y}{m}\right) q^n \zeta^r.$$

Here and throughout the paper, $\tau = x + iy \in \mathbb{H}$ (the usual complex upper half plane), $z = u + iv \in \mathbb{C}$, $q := e^{2\pi i \tau}$, $\zeta := e^{2\pi i z}$, $D := r^2 - 4nm$, and $\Gamma(s, x) := \int_x^\infty e^{-t} t^{s-1} dt$ is the incomplete Gamma-function. In particular, if $\phi \in \widehat{\mathbb{J}}_{k,m}^{cusp}$ is holomorphic, then $\phi = \phi^+$ is a weak Jacobi form. If in addition, the Fourier series in (1) is only over $D \leq 0$, then ϕ is a Jacobi form as in [5] and if the Fourier series in (1) is only over $D < 0$, then ϕ is a Jacobi

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cuspidal form. Note that our notion of weak Jacobi form is slightly more general than the one in [5], where weak Jacobi forms have an expansion as in (1) with the additional condition that $n \geq 0$. If ϕ^+ is as in (1), then we call

$$(3) \quad P_{\phi^+}(\tau, z) := \sum_{\substack{n, r \in \mathbb{Z} \\ D > 0}} c^+(n, r) q^n \zeta^r$$

the principal part of ϕ^+ .

In this paper, we extend ideas of [1] to obtain exact formulas for the coefficients of ϕ^+ in (1). It turns out that the principal part P_{ϕ^+} in (3) dictates the coefficients of ϕ^+ for $D < 0$, as explained in the following theorem, which is the main result of this paper.

Theorem 1. *Let $\phi \in \widehat{\mathbb{J}}_{k, m}^{\text{cusp}}$ with holomorphic part ϕ^+ as in (1). If $k < 0$ is even and $D' := r'^2 - 4mn' < 0$, then*

$$c^+(n', r') = \frac{1}{2\Gamma\left(\frac{5}{2} - k\right)} \sum_{\substack{r \pmod{2m} \\ D > 0}} c^+(n, r) c_{n, r}^{(k)}(n', r'),$$

where $\Gamma(\cdot)$ is the Gamma-function and

$$(4) \quad c_{n, r}^{(k)}(n', r') := b_{n, r}^{(k)}(n', r') + (-1)^k b_{n, r}^{(k)}(n', -r')$$

with

$$b_{n, r}^{(k)}(n', r') := \sqrt{2\pi} i^{-k} m^{-\frac{1}{2}} \left(\frac{|D'|}{D}\right)^{\frac{k}{2} - \frac{3}{4}} \sum_{c > 0} c^{-\frac{3}{2}} K_c(n, r, n', r') I_{k - \frac{3}{2}}\left(\frac{\pi \sqrt{|D'|D}}{mc}\right).$$

Here $I_s(x)$ is the usual I -Bessel function of order s and $K_c(n, r, n', r')$ is the Kloosterman sum

$$K_c(n, r, n', r') := e_{2mc}(-rr') \sum_{\substack{d \pmod{c}^* \\ \bar{d} \pmod{c}}} e_c(\bar{d}m\lambda^2 + n'd - r'\lambda + \bar{d}n + \bar{d}r\lambda),$$

where $e_c(x) := e^{\frac{2\pi i x}{c}}$ and the sum over d runs through the primitive residue classes modulo c and \bar{d} is the inverse of d modulo c .

In Section 2, we follow Bruinier and Funke [3] to define a pairing of harmonic Maass-Jacobi forms and skew-holomorphic Jacobi forms. We find that this pairing is determined by the principal part of the holomorphic part of a harmonic Maass-Jacobi form. In Section 3, we recall the Maass-Jacobi-Poincaré series from [2]. Given a harmonic Maass-Jacobi form, linear combinations of such Poincaré series allow one to construct a new harmonic Maass-Jacobi form whose holomorphic part has the same principal part as the given one. This is the key idea in our proof of Theorem 1. Finally, we give an explicit application of our results. The ring of Jacobi forms of even weights is generated (over the ring of modular forms) by certain weak Jacobi forms of index 1 and weights -2 and 0 , which we denote by $\phi_{-2,1}$ and $\phi_{0,1}$, respectively (see §8 and §9 of [5]). We show that $\phi_{-2,1}$ can be expressed as Jacobi-Poincaré series. It is likely that $\phi_{0,1}$ can also be realized as a Jacobi-Poincaré series,

but this requires the existence of a Maass-Jacobi Poincaré series of weight 0, which we have not constructed yet.

2. THE PAIRING

In this section, we introduce a pairing between skew-holomorphic Jacobi forms and harmonic Maass-Jacobi forms, which is vital to our proof of Theorem 1 in Section 3. Let $J_{k,m}^{sk}$ denote the space of skew-holomorphic Jacobi forms of weight k and index m and let $J_{k,m}^{sk,cusp}$ be the subspace of cusp forms (for details, see Skoruppa [8, 9]). If $\phi, \psi \in J_{k,m}^{sk,cusp}$, then the Petersson scalar product of ϕ and ψ is defined by

$$\langle \phi, \psi \rangle := \int_{\Gamma^J \backslash \mathbb{H} \times \mathbb{C}} \phi(\tau, z) \overline{\psi(\tau, z)} e^{-\frac{4\pi m v^2}{y}} y^k dV,$$

where $\Gamma^J := SL_2(\mathbb{Z}) \ltimes \mathbb{Z}^2$ is the Jacobi group and $dV := \frac{du dv dx dy}{y^3}$ is the Γ^J -invariant volume element on $\mathbb{H} \times \mathbb{C}$ (for details, see Skoruppa [7, 9]). Note that skew-holomorphic Jacobi forms have a theta decomposition, i.e., if $\phi(\tau, z) = \sum_{\substack{n, r \in \mathbb{Z} \\ D \geq 0}} c(n, r) e^{-\frac{\pi D y}{m}} q^n \zeta^r \in J_{k,m}^{sk}$, then

$$(5) \quad \phi(\tau, z) = \sum_{\mu \pmod{2m}} h_\mu(\tau) \theta_{m,\mu}(\tau, z),$$

where

$$h_\mu(\tau) := \sum_{N \geq 0} c_\mu(N) \bar{q}^{\frac{N}{4m}}$$

with

$$(6) \quad c_\mu(N) := \begin{cases} c\left(\frac{r^2 - N}{4m}, r\right) & \text{for } r \in \mathbb{Z}, r \equiv \mu \pmod{2m}, \text{ and } N \equiv \mu^2 \pmod{4m} \\ 0 & \text{if } N \not\equiv \mu^2 \pmod{4m} \end{cases}$$

and

$$(7) \quad \theta_{m,\mu}(\tau, z) := \sum_{\substack{r \in \mathbb{Z} \\ r \equiv \mu \pmod{2m}}} q^{\frac{r^2}{4m}} \zeta^r.$$

If $\phi(\tau, z) = \sum h_\mu(\tau) \theta_{m,\mu}(\tau, z) \in J_{k,m}^{sk,cusp}$ and $\psi(\tau, z) = \sum g_\mu(\tau) \theta_{m,\mu}(\tau, z) \in J_{k,m}^{sk,cusp}$, then analogous to Theorem 5.3 of [5], one finds that

$$(8) \quad \langle \phi, \psi \rangle = \int_{\mathcal{F}} \sum_{\mu \pmod{2m}} h_\mu(\tau) \overline{g_\mu(\tau)} y^{k-5/2} dx dy,$$

where \mathcal{F} is the standard fundamental domain for the action of $SL_2(\mathbb{Z})$ on \mathbb{H} .

We wish to review the definition of harmonic Maass-Jacobi forms of [2]. Therefore, we need to recall the slash action for Jacobi forms and a certain differential operator which is invariant under that action. If $\phi : \mathbb{H} \times \mathbb{C} \rightarrow \mathbb{C}$, then

$$(9) \quad \left(\phi \Big|_{k,m} A \right) (\tau, z) := \phi \left(\frac{a\tau + b}{c\tau + d}, \frac{z + \lambda\tau + \mu}{c\tau + d} \right) (c\tau + d)^{-k} e^{2\pi i m \left(-\frac{c(z + \lambda\tau + \mu)^2}{c\tau + d} + \lambda^2 \tau + 2\lambda z \right)}$$

for all $A = \left[\begin{pmatrix} a & b \\ c & d \end{pmatrix}, (\lambda, \mu) \right] \in \Gamma^J$. Furthermore, if $\partial_w := \frac{\partial}{\partial w}$ for a variable w , then

$$\begin{aligned} C^{k,m} := & -2(\tau - \bar{\tau})^2 \partial_{\tau\bar{\tau}} - (2k-1)(\tau - \bar{\tau}) \partial_{\bar{\tau}} + \frac{(\tau - \bar{\tau})^2}{4\pi im} \partial_{\tau z z} \\ & + \frac{k(\tau - \bar{\tau})}{4\pi im} \partial_{z\bar{z}} + \frac{(\tau - \bar{\tau})(z - \bar{z})}{4\pi im} \partial_{z z \bar{z}} - 2(\tau - \bar{\tau})(z - \bar{z}) \partial_{\tau\bar{z}} + k(z - \bar{z}) \partial_{\bar{z}} \\ & + \frac{(\tau - \bar{\tau})^2}{4\pi im} \partial_{\tau z \bar{z}} + \left(\frac{(z - \bar{z})^2}{2} + \frac{k(\tau - \bar{\tau})}{4\pi im} \right) \partial_{z\bar{z}} + \frac{(\tau - \bar{\tau})(z - \bar{z})}{4\pi im} \partial_{z z \bar{z}} \end{aligned}$$

which (up to the constant $\frac{5}{8} + \frac{3k-k^2}{2}$) is the *Casimir operator* with respect to the action in (9).

Definition 1. A function $\phi : \mathbb{H} \times \mathbb{C} \rightarrow \mathbb{C}$ is a harmonic Maass-Jacobi form of weight k and index m if ϕ is real-analytic in $\tau \in \mathbb{H}$ and $z \in \mathbb{C}$ and satisfies the following conditions:

- (1) For all $A \in \Gamma^J$, $(\phi |_{k,m} A) = \phi$.
- (2) We have that $C^{k,m}(\phi) = 0$.
- (3) We have that $\phi(\tau, z) = O\left(e^{ay} e^{2\pi m v^2/y}\right)$ as $y \rightarrow \infty$ for some $a > 0$.

Of particular interest are harmonic Maass-Jacobi forms, which are holomorphic in z ; the space of such forms is denoted by $\widehat{\mathbb{J}}_{k,m}$.

The differential operator

$$\xi_{k,m} := y^{k-3/2} \left(-2iy \partial_{\bar{\tau}} - 2iv \partial_{\bar{z}} + \frac{y}{4\pi m} \partial_{z\bar{z}} \right)$$

plays an important role in this context. It maps harmonic Maass-Jacobi forms that are holomorphic in the Jacobi variable z to skew-holomorphic Jacobi forms. Moreover, with $\widehat{\mathbb{J}}_{k,m}^{cusp} \subset \widehat{\mathbb{J}}_{k,m}$ we denote the space of harmonic Maass-Jacobi forms, which appear in the pre-image of skew-holomorphic Jacobi cusp forms under $\xi_{k,m}$. The next proposition was proved in [2].

Proposition 1. ([2]) *The map*

$$\xi_{k,m} : \widehat{\mathbb{J}}_{k,m}^{cusp} \rightarrow J_{3-k,m}^{sk,cusp}$$

is surjective.

If $\phi \in \widehat{\mathbb{J}}_{k,m}^{cusp}$ and $\psi \in J_{3-k,m}^{sk,cusp}$, then we define the (non-degenerate) pairing

$$(10) \quad \{\phi, \psi\} := \langle \xi_{k,m}(\phi), \psi \rangle.$$

The following result extends Proposition 3.5 of [3] to Jacobi forms and shows that the pairing in (10) is determined by the principal part P_{ϕ^+} of ϕ^+ .

Proposition 2. Let $\phi = \phi^+ + \phi^- \in \widehat{\mathbb{J}}_{k,m}^{cusp}$ with ϕ^+ and ϕ^- as in (1) and (2) and let $\psi(\tau, z) = \sum_{\substack{n,r \in \mathbb{Z} \\ D > 0}} d(n, r) e^{-\frac{\pi D y}{m}} q^n \zeta^r \in J_{3-k,m}^{sk,cusp}$. If k is even, then

$$\{\phi, \psi\} = \sum_{\substack{r \pmod{2m} \\ D > 0}} c^+(n, r) \overline{d(n, r)}.$$

Proof: Let

$$\psi(\tau, z) = \sum_{\mu \pmod{2m}} g_\mu(\tau) \theta_{m,\mu}(\tau, z)$$

with

$$g_\mu(\tau) = \sum_{N > 0} d_\mu(N) \bar{q}^{\frac{N}{4m}}$$

be the theta decomposition of ψ . It is easy to see that elements in $\widehat{\mathbb{J}}_{k,m}^{cusp}$ and hence also their holomorphic and non-holomorphic parts have theta decompositions. More precisely, we have

$$\phi(\tau, z) = \sum_{\mu \pmod{2m}} h_\mu(\tau) \theta_{m,\mu}(\tau, z),$$

where $h_\mu = h_\mu^+ + h_\mu^-$,

$$h_\mu^+(\tau) = \sum_{N \ll \infty} c_\mu^+(N) q^{-\frac{N}{4m}},$$

$$h_\mu^-(\tau) = \sum_{N > 0} c_\mu^-(N) \Gamma\left(\frac{3}{2} - k, \frac{\pi N y}{m}\right) q^{-\frac{N}{4m}},$$

and $c_\mu^\pm(N)$ is as in (6).

We now follow the proof of Proposition 3.5 in [3]. First, if k is even, then one verifies that

$$(11) \quad \sum_{\mu \pmod{2m}} h_\mu \bar{g}_\mu d\tau \quad \text{is an } SL_2(\mathbb{Z})\text{-invariant 1-form on } \mathbb{H}.$$

Set $L_k := -2iy^2 \partial_{\bar{\tau}}$ and $\xi_k := y^{k-2} \bar{L}_k$. From (8) we have

$$\{\phi, \psi\} = \lim_{t \rightarrow \infty} \frac{1}{4m} \sum_{j=0}^{4m-1} \int_{\mathcal{F}_{t,j}} \sum_{\mu \pmod{2m}} \overline{\xi_{k-\frac{1}{2}}(h_\mu)(\tau) g_\mu(\tau) y^{\frac{1}{2}-k}} dx dy,$$

where each

$$\mathcal{F}_{t,j} := \left\{ \tau \in \mathbb{H} \mid |\tau - j| \geq 1, 0 \leq x - j \leq \frac{1}{2}, y \leq t, \text{ or } |\tau - j - 1| \geq 1, \frac{1}{2} \leq x - j \leq 1, y \leq t \right\}$$

is a translation by j of the truncated fundamental domain $\mathcal{F}_t := \{\tau \in \mathcal{F} \mid y \leq t\}$, and where, in addition, the “left half” is “cut and pasted” to the right. Let $d\omega := \frac{dx dy}{y^2}$ denote the usual

invariant volume form on \mathbb{H} . With the help of Stokes' Theorem, we find that

$$\begin{aligned}
& \frac{1}{4m} \sum_{j=0}^{4m-1} \int_{\mathcal{F}_{t,j}} \sum_{\mu \pmod{2m}} \overline{\xi_{k-\frac{1}{2}}(h_\mu)(\tau) g_\mu(\tau)} y^{\frac{1}{2}-k} dx dy \\
&= \frac{1}{4m} \sum_{j=0}^{4m-1} \int_{\mathcal{F}_{t,j}} \sum_{\mu \pmod{2m}} L_{k-\frac{1}{2}}(h_\mu) \overline{g_\mu} d\omega \\
&\stackrel{\text{Stokes}}{=} \frac{-1}{4m} \sum_{j=0}^{4m-1} \int_{\partial \mathcal{F}_{t,j}} \sum_{\mu \pmod{2m}} h_\mu \overline{g_\mu} d\tau \\
&\stackrel{(11)}{=} \frac{1}{4m} \int_0^{4m} \sum_{\mu \pmod{2m}} h_\mu(x+it) \overline{g_\mu(x+it)} dx \\
&= \sum_{\substack{\mu \pmod{2m} \\ N>0}} c_\mu^+(N) \overline{d_\mu(N)} + \sum_{\substack{\mu \pmod{2m} \\ N>0}} c_\mu^-(N) \overline{d_\mu(N)} \Gamma\left(\frac{3}{2}-k, \frac{\pi N t}{m}\right),
\end{aligned}$$

where the last equation follows from inserting the Fourier expansions of h_μ and g_μ . Finally, $\Gamma\left(\frac{3}{2}-k, \frac{\pi N t}{m}\right) = O\left(\left(\frac{\pi N t}{m}\right)^{\frac{1}{2}-k} e^{-\frac{\pi N t}{m}}\right)$ as $t \rightarrow \infty$, which shows that

$$\{\phi, \psi\} = \sum_{\substack{\mu \pmod{2m} \\ N>0}} c_\mu^+(N) \overline{d_\mu(N)} = \sum_{\substack{r \pmod{2m} \\ D>0}} c^+(n, r) \overline{d(n, r)}.$$

□

3. MAASS-JACOBI-POINCARÉ SERIES AND THE PROOF OF THEOREM 1

In [2], we investigated Maass-Jacobi-Poincaré series, which we will now recall after introducing necessary notation. Let $M_{\nu, \mu}$ be the usual M -Whittaker function. Let $D = r^2 - 4nm \neq 0$, and for $s \in \mathbb{C}$, $\kappa \in \frac{1}{2}\mathbb{Z}$, and $t \in \mathbb{R} \setminus \{0\}$, define

$$\mathcal{M}_{s, \kappa}(t) := |t|^{-\frac{\kappa}{2}} M_{\text{sgn}(t)\frac{\kappa}{2}, s-\frac{1}{2}}(|t|)$$

and

$$\phi_{k, m, s}^{(n, r)}(\tau, z) := \mathcal{M}_{s, k-\frac{1}{2}}\left(-\frac{\pi D y}{m}\right) e^{2\pi i r z - \frac{\pi r^2 y}{2m} + 2\pi i n x}.$$

Set $\Gamma_\infty^J := \left\{ \left[\begin{pmatrix} 1 & \eta \\ 0 & 1 \end{pmatrix}, (0, n) \right] \mid \eta, n \in \mathbb{Z} \right\}$. Then the Poincaré series

$$(12) \quad P_{k, m, s}^{(n, r)}(\tau, z) := \sum_{A \in \Gamma_\infty^J \backslash \Gamma^J} (\phi_{k, m, s}^{(n, r)} \mid_{k, m} A)(\tau, z)$$

converges absolutely and uniformly for $\text{Re}(s) > \frac{5}{4}$ and $P_{k, m, s}^{(n, r)} \in \widehat{\mathbb{J}}_{k, m}$ if $s = \frac{k}{2} - \frac{1}{4}$, $k > 3$ or if $s = \frac{5}{4} - \frac{k}{2}$, $k < 0$. In [2], we determined the Fourier expansion of $P_{k, m, s}^{(n, r)}$, which features a

certain theta series $\vartheta_{k,m}^{(r)}$. It is not difficult to see that

$$(13) \quad \vartheta_{k,m}^{(r)}(\tau, z) = q^{-\frac{r^2}{4m}} \left(\theta_{m,r}(\tau, z) + (-1)^k \theta_{m,-r}(\tau, z) \right).$$

For brevity, we will only recall the part of the Fourier expansion, which is needed for the purpose of this paper. Let $P_{k,m,s}^{(n,r)+}$ denote the holomorphic part of $P_{k,m,s}^{(n,r)}$. If $D > 0$ and $s = \frac{5}{4} - \frac{k}{2}$, $k < 0$, then Corollary 1 of [2] and (13) imply that

$$(14) \quad P_{k,m,s}^{(n,r)+} = \Gamma\left(\frac{5}{2} - k\right) q^{-\frac{D}{4m}} \left(\theta_{m,r}(\tau, z) + (-1)^k \theta_{m,-r}(\tau, z) \right) + \sum_{\substack{n', r' \in \mathbb{Z} \\ D' \leq 0}} c_{n',r'}^{(k)}(n', r') q^{n'} \zeta^{r'},$$

where (as before) $D' = r'^2 - 4n'm$. If $D' < 0$, then $c_{n',r'}^{(k)}(n', r')$ is as in (4).

Proof of Theorem 1. Let $\phi \in \widehat{\mathbb{J}}_{k,m}^{cusp}$ ($k < 0$) with holomorphic part ϕ^+ as in (1) and principal part

$$P_{\phi^+}(\tau, z) = \sum_{\substack{\mu \pmod{2m} \\ N > 0}} c_{\mu}^+(N) q^{-\frac{N}{4m}} \theta_{m,\mu}(\tau, z)$$

with $c_{\mu}^+(N)$ as in (6). Equation (14) together with the identity $c_{-\mu}^+(N) = (-1)^k c_{\mu}^+(N)$ shows that the holomorphic part of

$$\varphi := \frac{1}{2\Gamma\left(\frac{5}{2} - k\right)} \sum_{\substack{r \pmod{2m} \\ D > 0}} c^+(n, r) P_{k,m,\frac{5}{4}-\frac{k}{2}}^{(n,r)} = \frac{1}{2\Gamma\left(\frac{5}{2} - k\right)} \sum_{\substack{\mu \pmod{2m} \\ N > 0}} c_{\mu}^+(N) P_{k,m,\frac{5}{4}-\frac{k}{2}}^{\left(\frac{\mu^2 - N}{4m}, \mu\right)}$$

has the same principal part as ϕ^+ . Consider $\psi := \phi - \varphi \in \widehat{\mathbb{J}}_{k,m}^{cusp}$. Suppose that ψ has a non-trivial non-holomorphic part. Then $\xi_{k,m}(\psi) \neq 0$ and hence $\{\psi, \xi_{k,m}(\psi)\} = \langle \xi_{k,m}(\psi), \xi_{k,m}(\psi) \rangle \neq 0$. On the other hand, Proposition 2 expresses $\{\psi, \xi_{k,m}(\psi)\}$ in terms of the principal part of ψ , which is zero by construction. This gives a contradiction and thus ψ is necessarily holomorphic, i.e., ψ is a weak Jacobi form. Again, the principal part of ψ is zero and hence ψ is a holomorphic Jacobi form (as in [5]) of weight $k < 0$. We conclude that $\psi = 0$ and Theorem 1 follows. \square

We end with an explicit example. Let $\phi_{-2,1}(\tau, z) = \zeta - 2 + \zeta^{-1} + \dots$ be the weak Jacobi form of weight -2 and index 1 alluded to in the introduction. Note that

$$\sum_{\substack{n, r \in \mathbb{Z} \\ D=1}} q^n \zeta^r = \sum_{r \equiv 1 \pmod{2}} q^{\frac{r^2-1}{4}} \zeta^r = q^{-\frac{1}{4}} \theta_{1,1}(\tau, z)$$

appears as the principal part of $\phi_{-2,1}(\tau, z)$ and also of $\frac{1}{2\Gamma\left(\frac{9}{2}\right)} P_{-2,1,\frac{9}{4}}^{(0,1)}(\tau, z)$. Hence we find that

$$\phi_{-2,1} = \frac{1}{2\Gamma\left(\frac{9}{2}\right)} P_{-2,1,\frac{9}{4}}^{(0,1)}.$$

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MATHEMATISCHES INSTITUT, UNIVERSITÄT KÖLN, WEYERTAL 86-90, D-50931 KÖLN, GERMANY
E-mail address: `kbringma@math.uni-koeln.de`

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF NORTH TEXAS, DENTON, TX 76203, USA
E-mail address: `richter@unt.edu`