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# A CHARACTER SUM FOR ROOT SYSTEM $G_2$

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ABSTRACT. A character sum analog of the Macdonald–Morris constant term identity for the root system $G_2$ is proved. The proof is based on recent evaluations of Selberg character sums and on a character sum analog of Dixon's summation formula. A conjectural evaluation is presented for a related sum.

## 1. INTRODUCTION

Let $GF(q)$ denote the finite field of $q$ elements, where $q$ is a power of an odd prime $p$. Throughout, $A$, $B$, and $C$ denote multiplicative characters on $GF(q)$. Let 1 and $\phi$ denote the trivial and quadratic characters on $GF(q)$, respectively. Define $A(0) = 0$, even if $A = 1$. Let $\operatorname{ord} C$ denote the order of $C$ (e.g., $\operatorname{ord} \phi = 2$).

Define the Gauss and Jacobi sums $G(A)$, $J(A, B)$ over $GF(q)$ by

$$G(A) = \sum_m A(m)\zeta^{T(m)}, \qquad J(A, B) = \sum_m A(m)B(1-m), \tag{1.1}$$

where the sums are over all $m \in GF(q)$, $\zeta = \exp(2\pi i/p)$, and $T$ denotes the trace map from $GF(q)$ to $GF(p)$. For nonnegative integers $n$, define the $n$-dimensional Selberg character sum $L_n(A, B, C\phi)$ over $GF(q)$ by

$$L_n(A, B, C\phi) = \sum_{\substack{F \\ \deg F = n}} A((-1)^n F(0))B(F(1))C\phi(D_F), \tag{1.2}$$

where the sum is over all monic polynomials $F$ over $GF(q)$ of degree $n$, and where $D_F$ denotes the discriminant of $F$.

Define

$$R_n(A, B, C) = \prod_{j=0}^{n-1} \frac{G(C^{j+1})G(AC^j)G(BC^j)}{G(C)G(ABC^{n-1+j})} \tag{1.3}$$

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and

$$
\begin{aligned}
S_n(A, B, C) &= q^{-n}R_n(A, B, C)\prod_{j=0}^{n-1}|G(ABC^{n-1+j})|^2 \\
&= q^{-n}G(C)^{-n}\prod_{j=0}^{n-1}G(C^{j+1})G(AC^j)G(BC^j)\overline{G}(ABC^{n-1+j}).
\end{aligned}
\tag{1.4}
$$

The generic Selberg character sum formula in Theorem 1.1 was conjectured in [5, (2.6); 2, (29)]. A proof of Theorem 1.1, based on the method of Anderson [1], is given in [4].

**Theorem 1.1.** *If*

$$ABC^{n-1+j} \text{ is nontrivial for all } j, \qquad 0 \le j \le n-1 \tag{1.5}$$

*or*

$$AC^a \text{ is nontrivial for all } a, \qquad 0 \le a \le n-1 \tag{1.6}$$

*or*

$$BC^b \text{ is nontrivial for all } b, \qquad 0 \le b \le n-1, \tag{1.7}$$

*then*

$$L_n(A, B, C\phi) = S_n(A, B, C). \tag{1.8}$$

Using Theorem 1.1 we prove a character sum analog of the Macdonald-Morris constant term identity for the root system $G_2$ [9, p. 994; 10, p. 45]. This analog, given in Theorem 1.2, was inspired by a pretty paper of Zeilberger [11].

**Theorem 1.2.** *Let*

$$L = \sum_{\substack{F(0)=-1 \\ \deg F=3}} B^2(F(1))C\phi(D_F), \tag{1.9}$$

*where the sum is over all monic cubic polynomials $F$ over $GF(q)$ with constant term $-1$. Then*

$$L = q^2 - 2q + 3, \quad \text{if } B^2 = 1,\ C = \phi, \tag{1.10}$$

$$L = (2 - 4/q)G(\overline{C})^3, \quad \text{if } B^2 = 1,\ \operatorname{ord} C = 3, \tag{1.11}$$

$$L = (1 - 3/q)G(\overline{C})^3, \quad \text{if } B^2 = C^2,\ \operatorname{ord} C = 3, \tag{1.12}$$

*and*

$$L = P(B, C) + P(B\phi, C) \quad \text{otherwise}, \tag{1.13}$$

*where*

$$P(B, C) = \frac{G(C^2)G(C^3)G(B^2)G(\overline{B}^2\overline{C}^3)G(\overline{BC}^2)G(B^3C^3)}{G(B)G(BC)G(C)^2}. \tag{1.14}$$

Note the completely direct analogy between $P(B, C)$ and the product of gamma functions in the Macdonald-Morris identity for $G_2$. The form of the sum $L$ in (1.9) is suggested by identifying the polynomial $F(W)$ in (1.9) with $(W-x/y)(W-y/z)(W-z/x)$, where $x, y, z$ are the variables in the constant term identity for $G_2$ in [11, Theorem, p. 880]. The form of the sum $L$ is not directly analogous to the trigonometric integral [10, p. 46] or the beta integral [6, (1.7)] associated with $G_2$.

We remark that if $B^2$ is replaced by a nonsquare character in (1.9), then the resulting sum vanishes. This follows from (2.1) below and [5, (2.2)].

Our proof of Theorem 1.2 employs the character sum analog of Dixon's summation formula [11, p. 881] given in Theorem 1.3. A proof of this analog (and more general results) can be found in [7]; we give a different proof in the Appendix.

**Theorem 1.3.** *Define*

$$\delta(A) = \begin{cases} 0, & \text{if } A \neq 1, \\ 1, & \text{if } A = 1. \end{cases} \tag{1.15}$$

*Then for all characters $D$, $E$, $F$ on $GF(q)$,*

$$\begin{aligned}(q-1)^{-1}\sum_A G(AD)G(AE)G(AF)\overline{G}(A\overline{D})\overline{G}(A\overline{E})\overline{G}(A\overline{F}) \\ = (q-1)q^2\delta(D^2E^2F^2) + Q(D, E, F) + Q(D\phi, E\phi, F\phi),\end{aligned} \tag{1.16}$$

*where*

(1.17)
$$Q(D, E, F) = DEF(-1)G(DE)G(DF)G(EF)G(D)G(E)G(F)/G(DEF).$$

Our proof of Theorem 1.2 also requires the evaluations of the Selberg sums $L_3(\overline{C}^2, 1, C\phi)$ and $L_3(\overline{C}, \overline{C}, C\phi)$ given in Theorem 1.4. These two Selberg sums are not covered by Theorem 1.1, but they can be evaluated by a suitable modification of the proof of [4, Theorem 1.1]. We omit the details.

**Theorem 1.4.** *If $C^2 \neq 1$, then*

$$\frac{L_3(\overline{C}^2, 1, C\phi)}{R_3(\overline{C}^2, 1, C)} = \frac{L_3(\overline{C}, \overline{C}, C\phi)}{R_3(\overline{C}, \overline{C}, C)} = 2 - q. \tag{1.18}$$

Inspired by Theorem 1.2, Greg Anderson suggested that the sum

$$Y(B, C) := \sum_{x, y \in GF(q)} B(x^2 - 4y)C(y^2 + 18y + 12xy - 4x^3 - 27) \tag{1.19}$$

has an elegant product formula. Since the discriminant of the polynomial $F(z) = z^3 - rz^2 + sz - 1$ is $r^2s^2 + 18rs - 4s^3 - 4r^3 - 27$, one sees via the transformation $x = r + s$, $y = rs$ that

$$L = Y(B, C\phi) + Y(B\phi, C\phi). \tag{1.20}$$

Thus the following conjecture implies Theorem 1.2.

**Conjecture 1.5.** *We have*

$$Y(B\phi, C\phi) = q^2 - 2q + 2 = (q^2 - 2q + 2)P(B, C), \quad \text{if } B = C = \phi, \tag{1.21}$$

$$Y(B\phi, C\phi) = (1 - 2/q)G(\overline{C})^3 = (2 - q)qP(B, C), \quad \text{if } \operatorname{ord} C = 3,\ B \in \{1, \phi, C\}, \tag{1.22}$$

*and*

$$Y(B\phi, C\phi) = P(B, C), \quad \textit{otherwise.} \tag{1.23}$$

For character sum analogs of Macdonald-Morris constant term identities connected with various other root systems, see [3]. For most root systems (e.g., $F_4, E_6, E_7, E_8, \ldots$), no analogs are known.

## 2. Proof of Theorem 1.2

By (1.2) and (1.9),

$$L = \frac{1}{q-1}\sum_A L_3(A, B^2, C\phi). \tag{2.1}$$

Define

$$d(A, B, C) = L_3(A, B, C\phi) - S_3(A, B, C). \tag{2.2}$$

Then by (2.1) and Theorem 1.1,

$$L = T + \frac{1}{q-1}\sum_{A\in\{1,\overline{C},\overline{C}^2\}} d(A, B^2, C), \tag{2.3}$$

where

$$T = \frac{1}{q-1}\sum_A S_3(A, B^2, C). \tag{2.4}$$

By (2.4) and (1.4),

(2.5)

$$\begin{aligned} T &= \frac{1}{q-1}\sum_A S_3(A\overline{BC}^2, B^2, C) \\ &= \frac{G(C)G(C^2)G(C^3)G(B^2)G(B^2C)G(B^2C^2)}{(q-1)q^3G(C)^3}\sum_A\prod_{j=0}^{2} G(A\overline{B}C^{j-2})\overline{G}(ABC^j). \end{aligned}$$

Apply Theorem 1.3 with

$$D = \overline{BC}^2, \qquad E = \overline{BC}, \qquad F = \overline{B} \tag{2.6}$$

to obtain, for all characters $B$, $C$,

$$\begin{aligned} T = {} & \frac{G(C^2)G(C^3)G(B^2)G(B^2C)G(B^2C^2)}{q^3G(C)^2} \\ & \cdot\{(q-1)q^2\delta(B^6C^6) + Q(\overline{BC}^2, \overline{BC}, \overline{B}) + Q(\overline{B}\phi\overline{C}^2, \overline{B}\phi\overline{C}, \overline{B}\phi)\}. \end{aligned} \tag{2.7}$$

By definition (1.17),

(2.8)

$$\begin{aligned} & Q(\overline{BC}^2, \overline{BC}, \overline{B}) \\ & \quad = BC(-1)G(\overline{B}^2\overline{C}^3)G(\overline{B}^2\overline{C}^2)G(\overline{B}^2\overline{C})G(\overline{BC}^2)G(\overline{BC})G(\overline{B})/G(\overline{B}^3\overline{C}^3). \end{aligned}$$

Define

$$W(B, C) = G(\overline{B}^2\overline{C}^3)G(\overline{B}^2\overline{C}^2)G(\overline{B}^2\overline{C})G(\overline{BC}^2)G(\overline{BC})G(\overline{B})G(B^3C^3)/q. \tag{2.9}$$

By (2.8) and (2.9),

$$W(B, C) = Q(\overline{BC}^2, \overline{BC}, \overline{B}), \quad \text{if } B^3C^3 \neq 1. \tag{2.10}$$

Assume first that

$$B^2, \; B^2C, \; \text{and } B^2C^2 \text{ are nontrivial.} \tag{2.11}$$

By (2.11), if $B^3C^3 = 1$, then

$$W(B, C) = -q^2 \quad \text{and} \quad Q(\overline{BC}^2, \overline{BC}, \overline{B}) = -q^3. \tag{2.12}$$

Hence (2.10) has the extension

$$(q-1)q^2\delta(B^3C^3) + Q(\overline{BC}^2, \overline{BC}, \overline{B}) = W(B, C). \tag{2.13}$$

Since $\delta(B^6C^6) = \delta(B^3C^3) + \delta(\phi B^3C^3)$, the expression in braces in (2.7) equals

$$W(B, C) + W(B\phi, C). \tag{2.14}$$

Again using (2.11), we thus obtain

$$T = P(B, C) + P(B\phi, C). \tag{2.15}$$

By (2.11) and Theorem 1.1, each summand $d(\overline{C}^a, B^2, C)$ in (2.3) vanishes. Thus $L = T$ and the result follows from (2.15) under the assumption (2.11).

Now drop the assumption (2.11). For brevity, set

$$R(a, b) = R(\overline{C}^a, \overline{C}^b, C), \tag{2.16}$$

$$U(a, b) = L_3(\overline{C}^a, \overline{C}^b, C\phi)/R(a, b), \tag{2.17}$$

$$V(a, b) = S_3(\overline{C}^a, \overline{C}^b, C)/R(a, b), \tag{2.18}$$

where $0 \leq a, b \leq 2$. Observe that $R(a, b)$, $U(a, b)$, $V(a, b)$ are symmetric in $a, b$. We proceed to evaluate these functions.

From (1.3),

$$R(0, 0) = G^2(C^2)/G(C^4), \tag{2.19}$$

$$R(1, 0) = G(\overline{C})G(C^2)/G(C), \tag{2.20}$$

$$R(2, 0) = R(2, 2) = R(2, 1) = -|G(C^2)|^2 G(C^3)G(\overline{C})/G^2(C), \tag{2.21}$$

$$R(1, 1) = -G(C^3)G^2(\overline{C})/G(C). \tag{2.22}$$

From (1.4),

$$V(0, 0) = \begin{cases} q^{-3}, & \text{if } C = 1, \\ q^{-2}, & \text{if } C = \phi, \\ q^{-1}, & \text{if ord}\, C = 3 \text{ or } 4, \\ 1, & \text{if ord}\, C > 4, \end{cases} \tag{2.23}$$

$$V(1, 0) = \begin{cases} q^{-3}, & \text{if } C = 1, \\ q^{-1}, & \text{if ord}\, C = 2 \text{ or } 3, \\ 1, & \text{if ord}\, C > 3, \end{cases} \tag{2.24}$$

$$V(2,0)=V(2,2)=V(1,1)=\begin{cases} q^{-3}, & \text{if } C=1,\\ q^{-2}, & \text{if } C=\phi,\\ q^{-1}, & \text{if } \operatorname{ord} C>2,\end{cases} \tag{2.25}$$

$$V(2,1)=\begin{cases} q^{-3}, & \text{if } C=1,\\ q^{-1}, & \text{if } C\neq 1.\end{cases} \tag{2.26}$$

By [5, Theorem 4.1],

$$U(0,0)=\begin{cases} 4-3q, & \text{if } C=1,\\ -q^3+3q^2-5q+4, & \text{if } C=\phi,\\ q^2-3q+3, & \text{if } \operatorname{ord} C=3,\\ q^{-1}, & \text{if } \operatorname{ord} C=4,\\ 1, & \text{if } \operatorname{ord} C>4.\end{cases} \tag{2.27}$$

We claim that

$$U(1,0)=\begin{cases} 4-3q, & \text{if } C=1,\\ 2-q, & \text{if } C=\phi,\\ q^2-3q+3, & \text{if } \operatorname{ord} C=3,\\ 1, & \text{if } \operatorname{ord} C>3.\end{cases} \tag{2.28}$$

The cases $C=1$, $C=\phi$ of (2.28) follow from [5, (2.13), (2.14)]. The case where $\operatorname{ord} C=3$ follows from (2.27), since by [5, Lemmas 2.1, 2.2],

$$U(1,0)=U(0,0) \quad \text{if } \operatorname{ord} C=3.$$

The last case where $\operatorname{ord} C>3$ follows from (2.24) and Conjecture 1.1 (note that the hypothesis (1.5) of Theorem 1.1 holds with $A=\overline{C}$, $B=1$). Next we claim that

$$U(2,0)=U(2,2)=\begin{cases} 4-3q, & \text{if } C=1,\\ -q^3+3q^2-5q+4, & \text{if } C=\phi,\\ 2-q, & \text{if } \operatorname{ord} C>2.\end{cases} \tag{2.29}$$

The first equality in (2.29) follows from [5, Lemmas 2.1, 2.2]. The cases $C=1$, $C=\phi$ of (2.29) follow from [5, (2.13), (2.14)], while the remaining case follows from Theorem 1.4. The same argument shows that

$$U(1,1)=\begin{cases} 4-3q, & \text{if } C=1,\\ (2-q)/q, & \text{if } C=\phi,\\ 2-q, & \text{if } \operatorname{ord} C>2.\end{cases} \tag{2.30}$$

Finally, we claim that

$$U(2,1)=\begin{cases} 4-3q, & \text{if } C=1,\\ 2-q, & \text{if } C\neq 1.\end{cases} \tag{2.31}$$

The cases $C=1$, $C=\phi$ of (2.31) follow from [5, (2.13), (2.14)], while the cases where $C^2\neq 1$ follow from (2.30), since

$$U(2,1)=U(1,1) \quad \text{if } \operatorname{ord} C>2 \tag{2.32}$$

by [5, Lemmas 2.1, 2.2].

For $0 \le a, b \le 2$, set

$$d(a, b) = \{U(a, b) - V(a, b)\}R(a, b), \tag{2.33}$$

so that by (2.2),

$$d(a, b) = d(\overline{C}^a, \overline{C}^b, C). \tag{2.34}$$

From (2.19)–(2.31), we obtain the following evaluation of $d(a, b)$:

$$d(0, 0) = \begin{cases} -(4 - 3q - q^{-3}), & \text{if } C = 1, \\ -(-q^3 + 3q^2 - 5q + 4 - q^{-2}), & \text{if } C = \phi, \\ (q^2 - 3q + 3 - q^{-1})G^3(\overline{C})/q, & \text{if } \operatorname{ord} C = 3, \\ 0, & \text{if } \operatorname{ord} C > 3; \end{cases} \tag{2.35}$$

$$d(1, 0) = \begin{cases} -(4 - 3q - q^{-3}), & \text{if } C = 1, \\ -(2 - q - q^{-1}), & \text{if } C = \phi, \\ (q^2 - 3q + 3 - q^{-1})G^3(\overline{C})/q, & \text{if } \operatorname{ord} C = 3, \\ 0, & \text{if } \operatorname{ord} C > 3; \end{cases} \tag{2.36}$$

$$d(2, 0) = d(2, 2) = \begin{cases} -(4 - 3q - q^{-3}), & \text{if } C = 1, \\ -(-q^3 + 3q^2 - 5q + 4 - q^{-2}), & \text{if } C = \phi, \\ -(2 - q - q^{-1})G(C^3)G^3(\overline{C})/q, & \text{if } \operatorname{ord} C > 2; \end{cases} \tag{2.37}$$

$$d(1, 1) = \begin{cases} -(4 - 3q - q^{-3}), & \text{if } C = 1, \\ -(2 - q - q^{-1})\phi(-1), & \text{if } C = \phi, \\ -(2 - q - q^{-1})G(C^3)G^3(\overline{C})C(-1)/q, & \text{if } \operatorname{ord} C > 2; \end{cases} \tag{2.38}$$

and

$$d(2, 1) = \begin{cases} -(4 - 3q - q^{-3}), & \text{if } C = 1, \\ -(2 - q - q^{-1}), & \text{if } C = \phi, \\ -(2 - q - q^{-1})G(C^3)G^3(\overline{C})/q, & \text{if } \operatorname{ord} C > 2. \end{cases} \tag{2.39}$$

We now evaluate $L$ from (2.3), using (2.7), (2.8), and (2.35)–(2.39), and Theorem 1.2 follows.

## 3. Appendix

Here we give a proof of Theorem 1.3. Let $H$ denote the left side of (1.16). First suppose that $DE = 1$. Then

$$\begin{aligned} H &= \frac{1}{q-1}\sum_A |G(AE)|^2|G(A\overline{E})|^2 G(AF)\overline{G}(A\overline{F}) \\ &= \begin{cases} M - (q+1)G(EF)\overline{G}(E\overline{F}), & \text{if } E^2 = 1, \\ M - qG(\overline{E}F)\overline{G}(\overline{EF}) - qG(EF)\overline{G}(E\overline{F}), & \text{if } E^2 \ne 1, \end{cases} \end{aligned} \tag{3.1}$$

where

$$M = \frac{q^2}{q-1}\sum_A G(AF)\overline{G}(A\overline{F}). \tag{3.2}$$

By (1.1),

$$M = \frac{q^2}{q-1}\sum_t\sum_u\sum_A AF(t)\overline{A}F(u)\zeta^{T(t-u)} = q^2(q-1)\delta(F^2). \tag{3.3}$$

Using (3.3) in (3.1), we easily deduce (1.16) in the case $DE = 1$.

By symmetry, it remains to prove (1.16) in the case

$$DE \neq 1, \qquad DF \neq 1, \qquad EF \neq 1. \tag{3.4}$$

By (1.1),

(3.5)

$$\begin{aligned} H &= \frac{1}{q-1}\sum_{t,u,v}\ \sum_{x,y,z\neq 0}\ \sum_A A\left(\frac{tuv}{xyz}\right) D(tx)E(uy)F(vz)\zeta^{T(t+u+v-x-y-z)} \\ &= \frac{1}{q-1}\sum_{t,u,v}\sum_{x,y,z}\sum_A A(tuv)D(txy)E(uyz)F(vzx)\zeta^{T(y(t-1)+z(u-1)+x(v-1))}, \end{aligned}$$

where the last equality results from replacing $t$ by $ty$, $u$ by $uz$, and $v$ by $vx$. By (3.4), it follows that

$$\begin{aligned} H = {} & \frac{1}{q-1}G(DE)G(DF)G(EF) \\ & \times \sum_{t,u,v}\sum_A A(tuv)\overline{DE}(1-t)\overline{EF}(1-u)\overline{DF}(1-v)D(t)E(u)F(v). \end{aligned} \tag{3.6}$$

Thus,

(3.7)

$$\begin{aligned} & H/\{G(DE)G(DF)G(EF)\} \\ &\quad = \sum_{t,v\neq 0} \overline{DE}(1-t)\overline{EF}(1-1/(tv))\overline{DF}(1-v)D(t)\overline{E}(tv)F(v) \\ &\quad = \sum_{t,v\neq 0} \overline{DE}(1-t/v)\overline{EF}(1-1/t)\overline{DF}(1-v)D(t/v)\overline{E}(t)F(v) \\ &\quad = \sum_{t,v} EF(v)DF(t)\overline{EF}(t-1)\overline{DF}(1-v)\overline{DE}(v-t) \\ &\quad = EF(-1)\sum_{t,v\neq 0} \overline{DF}\left(\frac{1+v}{t}\right)\overline{EF}\left(\frac{1+t}{v}\right)\overline{DE}(v-t) \\ &\quad = EF(-1)\{J(\overline{DEF}, DE)J(E, \overline{DE}) + J(\overline{DEF}\phi, DE)J(E\phi, \overline{DE})\}, \end{aligned}$$

where the last equality follows from [2, (28)]. Since $DE \neq 1$, we can apply the formula [8]

$$J(A, B) = G(A)G(\overline{AB})A(-1)/G(\overline{B}), \quad \text{if } B \neq 1 \tag{3.8}$$

to express all of the Jacobi sums in (3.7) in terms of Gauss sums. Then (1.16) readily follows.

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