

# WEYL GROUP MULTIPLE DIRICHLET SERIES OVER FUNCTION FIELDS

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**ABSTRACT.** We construct a multiple Dirichlet series  $Z(s_1, \dots, s_r)$  in  $r$  variables over a function field  $\mathbb{F}_q(t)$  that is naturally associated to a simply laced rank  $r$  root system  $\Phi$  using the Chinta-Gunnells construction. This is the simplest example of an  $r$  variable Weyl group multiple Dirichlet series over a global field and is a derivative of [2] in a less general setting with slightly more detail.

## 1. PRELIMINARIES

**Function Fields.** We present an overview of the zeta function and Dirichlet  $L$ -functions attached to  $\mathbb{F}_q(t)$ . For a detailed discussion see [4]. Let  $q$  be a power of an odd prime and let  $\mathbb{F}_q[t]$  be the polynomial ring in  $t$  with coefficients in the finite field  $\mathbb{F}_q$ . This is a principal ideal domain. Moreover, the nonzero prime ideals in  $\mathbb{F}_q[t]$  are generated by irreducible polynomials. Let  $\mathbb{F}_q(t)$  denote the quotient field. Define the norm function  $N(m)$  by

$$N(m) = |m| = q^{\deg(m)},$$

for any  $m \in \mathbb{F}_q[t]$ . The zeta function  $\zeta(s)$  on  $\mathbb{F}_q[t]$  is defined as the Dirichlet series or Euler product

$$\zeta(s) = \sum_{m \text{ monic}} \frac{1}{|m|^s} = \prod_{P \text{ monic irr}} \left(1 - \frac{1}{|P|^s}\right)^{-1},$$

where the second equality holds since  $\mathbb{F}_q[t]$  is a unique factorization domain. As for questions of convergence, there are  $q^n$  monic polynomials of degree  $n$  so, provided  $\operatorname{Re}(s) > 1$ , we can sum up the Dirichlet series according to degree and obtain an explicit expression:

$$\zeta(s) = \sum_{n \geq 0} \frac{\# \text{ of monic poly of deg } n}{q^{ns}} = \sum_{n \geq 1} \frac{1}{q^{n(1-s)}} = \frac{1}{1 - q^{1-s}}.$$

The latter expression is meromorphic on  $\mathbb{C}$  with a simple pole at  $s = 1$  of residue  $\frac{1}{\log(q)}$ . Therefore  $\zeta(s)$  admits meromorphic continuation to  $\mathbb{C}$ . The zeta function also satisfies a functional equation. Define the completed zeta function (this is also the zeta function attached to  $\mathbb{F}_q(t)$ ) by

$$\zeta^*(s) = \frac{1}{1 - q^{-s}} \zeta(s).$$

Then

$$\zeta^*(s) = q^{2s-1} \zeta^*(1-s).$$

Recall that characters on  $\mathbb{F}_q[t]$  are multiplicative functions  $\chi : \mathbb{F}_q[t] \rightarrow \mathbb{C}$ . The two flavors we will care about are:

- Dirichlet characters: multiplicative functions  $\chi_d : \mathbb{F}_q[t] \rightarrow \mathbb{C}$  modulo  $d \in \mathbb{F}_q[t]$  (in that they are  $d$ -periodic) and such that  $\chi_d(m) = 0$  if  $(m, d) > 1$ .
- Hilbert symbols: Dirichlet characters modulo 1.

In either case, the image always lands in the roots of unity. If  $\chi$  is a Dirichlet character then its conjugate  $\bar{\chi}$  is also a Dirichlet character. Moreover,  $\bar{\chi}$  is the multiplicative inverse to  $\chi$  and the Dirichlet characters modulo  $d$  form a group under multiplication. This group is always finite and its order is  $\phi(d) = |(\mathbb{F}_q[t]/d\mathbb{F}_q[t])^\times|$ . Dirichlet characters also satisfy orthogonality relations:

**Theorem 1.1** (Orthogonality relations).

(i) For any two Dirichlet characters  $\chi$  and  $\psi$  modulo  $d$ ,

$$\frac{1}{\phi(d)} \sum'_{f \pmod{d}} \chi(f) \overline{\psi}(f) = \delta_{\chi, \psi}.$$

(ii) For any  $f, g \in (\mathbb{F}_q[t]/d\mathbb{F}_q[t])^\times$ ,

$$\frac{1}{\phi(d)} \sum_{\chi \pmod{d}} \chi(f) \overline{\chi}(g) = \delta_{f, g}.$$

The Dirichlet characters that are of interest to us are those given by the quadratic residue symbol on  $\mathbb{F}_q[t]$ . First let us recall this symbol. For any irreducible  $p \in \mathbb{F}_q[t]$  and any  $m \in \mathbb{F}_q[t]$ , we define the quadratic residue symbol  $\left(\frac{m}{p}\right)$  by

$$\left(\frac{m}{p}\right) \equiv m^{\frac{|p|-1}{2}} \pmod{p} = \begin{cases} 1 & \text{if } x^2 \equiv m \pmod{p} \text{ is solvable,} \\ -1 & \text{if } x^2 \equiv m \pmod{p} \text{ is not solvable,} \\ 0 & \text{if } m \equiv 0 \pmod{p}. \end{cases}$$

This symbol is only dependent upon  $m$  modulo  $p$  and is multiplicative in  $m$ . Moreover, if  $b \in \mathbb{F}_q^*$ , we have

$$\left(\frac{b}{p}\right) = \text{sgn}(b)^{\deg(p)}.$$

where  $\text{sgn}(b) = \pm 1$  depending on if  $b \in (\mathbb{F}_q^\times)^2$  or not. For  $m \in \mathbb{F}_q[t]$  we define  $\text{sgn}(m) = \text{sgn}(b_n)$  if  $m(t) = b_n t^n + b_{n-1} t^{n-1} + \dots + b_0$  (with  $b_n \neq 0$ ). We can extend the quadratic residue symbol multiplicatively in the denominator. If  $d = b p_1^{e_1} p_2^{e_2} \dots p_k^{e_k}$  is the prime factorization of  $d$  (with  $b \in \mathbb{F}_q^*$ ), then we define

$$\left(\frac{m}{d}\right) = \prod_{1 \leq i \leq k} \left(\frac{m}{p_i}\right)^{e_i}.$$

So the quadratic residue symbol now makes sense for any nonzero  $d \in \mathbb{F}_q[t]$ . Moreover, it only depends upon  $m$  modulo  $d$ , the ideal generated by  $d$ , and is multiplicative in  $d$ . The quadratic residue symbol also admits the following reciprocity law:

**Theorem 1.2** (Quadratic reciprocity). *If  $d, m \in \mathbb{F}_q[t]$  are relatively prime and nonzero, then*

$$\left(\frac{d}{m}\right) = (-1)^{\frac{q-1}{2} \deg(d) \deg(m)} \text{sgn}(d)^{\deg(m)} \text{sgn}(m)^{-\deg(d)} \left(\frac{m}{d}\right).$$

Note that if  $q \equiv 1 \pmod{4}$  and  $d$  and  $m$  are monic, then the sign in the statement of quadratic reciprocity is always 1 so that reciprocity is perfect:

$$\left(\frac{d}{m}\right) = \left(\frac{m}{d}\right).$$

We can now define the quadratic Dirichlet characters. For any nonzero square-free monic  $d \in \mathbb{F}_q[t]$ , define the quadratic Dirichlet character  $\chi_d$  by the following quadratic residue symbol:

$$\chi_d(m) = \left(\frac{d}{m}\right).$$

This quadratic Dirichlet character is attached to the quadratic extension  $\mathbb{F}_q(t)(\sqrt{d})$ . If  $b \in \mathbb{F}_q^\times$ , we define  $\chi_b$  by

$$\chi_b(m) = \left(\frac{b}{m}\right) = \text{sgn}(b)^{\deg(m)}.$$

We extend  $\chi_d$  multiplicatively in the denominator so that  $\chi_d$  makes sense for any nonzero  $d \in \mathbb{F}_q[t]$ . In particular,  $\chi_d(m) = \pm 1$  provided  $d$  and  $m$  are relatively prime and  $\chi_d(m) = 0$  if  $(m, d) > 1$ . Quadratic reciprocity implies that  $\chi_d$  is a Dirichlet character modulo  $d$ . Indeed, for any  $m$  we can take  $d$  modulo  $m$  so that  $\deg(d + m) = \deg(m)$  and  $\text{sgn}(d + m) = \text{sgn}(m)$ . Lastly, note that if  $q \equiv 1 \pmod{4}$  and  $d$  and  $m$  are monic,

$$\chi_d(m) = \chi_m(d),$$

is a reformulation of reciprocity being perfect. We now discuss the Hilbert symbols. The only ones we will need are those given by the quadratic reisdue symbol. There are only two of them: one nontrivial and one trivial. The nontrivial Hilbert symbol  $\psi$  is defined by

$$\psi(m) = (-1)^{\deg(m)}.$$

The other Hilbert symbol is  $\psi^2 = \chi_1$ . To see that  $\psi$  is given by a quadratic Dirichlet character, just notice that for  $\theta \in \mathbb{F}^\times - (\mathbb{F}^\times)^2$  we have  $\chi_\theta(m) = (-1)^{\deg(m)}$ . The Hilbert symbols are necessary because they control the possible sign change in the statement of quadratic reciprocity coming from the  $\text{sgn}(d)^{\deg(m)}$  and  $\text{sgn}(m)^{-\deg(d)}$  factors. Technically speaking, we would also require Hilbert symbols to keep track of the  $(-1)^{\frac{q-1}{2} \deg(d) \deg(m)}$  factor but as we will assume  $q \equiv 1 \pmod{4}$ , we will not discuss this additional difficulty.

We are now ready to discuss the  $L$ -functions associated to quadratic Dirichlet characters. We define the  $L$ -function  $L(s, \chi_d)$  attached to  $\chi_d$  by a Dirichlet series or Euler product:

$$L(s, \chi_d) = \sum_{m \text{ monic}} \frac{\chi_d(m)}{|m|^s} = \prod_{P \text{ monic irr}} \left(1 - \frac{\chi_d(P)}{|P|^s}\right)^{-1}.$$

By definition of the quadratic Dirichlet character,  $L(s, \chi_d) \ll \zeta(s)$  for  $\text{Re}(s) > 1$  so that  $L(s, \chi_d)$  is locally absolutely uniformly convergent in this region.  $L(s, \chi_d)$  also admits meromorphic continuation to  $\mathbb{C}$  with a simple pole at  $s = 1$  if  $d$  is a perfect square and is analytic otherwise (see [4] for a proof). The completed  $L$ -function is defined as follows:

$$L^*(s, \chi_d) = \begin{cases} \frac{1}{1-q^{-s}} L(s, \chi_d) & \text{if } \deg(d) \text{ is even,} \\ L(s, \chi_d) & \text{if } \deg(d) \text{ is odd,} \end{cases}$$

and satisfies the functional equation

$$L^*(s, \chi_d) = \begin{cases} q^{2s-1} |d|^{\frac{1}{2}-s} L^*(1-s, \chi_d) & \text{if } \deg(d) \text{ is even,} \\ q^{2s-1} (q|d|)^{\frac{1}{2}-s} L^*(1-s, \chi_d) & \text{if } \deg(d) \text{ is odd.} \end{cases}$$

Note that in the case  $\deg(d)$  is even, the conductor is  $|d|$  and in the case  $\deg(d)$  is odd, the conductor is  $q|d|$ . In other words, the gamma factors depend upon the degree of  $d$ .

**Root Systems.** Throughout let  $V$  be an  $r$ -dimensional Euclidean vector space with standard inner product  $(\cdot, \cdot)$ . For any nonzero  $v \in V$ , let

$$H_v = \{u \in V : (v, u) = 0\},$$

be the hyperplane perpendicular to  $v$ . Accordingly, let

$$s_v(w) = w - 2 \frac{(v, w)}{(v, v)} v,$$

be the reflection through the hyperplane  $H_v$ . Lastly, we will define an operator  $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$  by

$$\langle w, v \rangle = 2 \frac{(v, w)}{(v, v)},$$

Note that  $\langle \cdot, \cdot \rangle$  is not an inner product as it need not be symmetric and is linear only in the first argument. However, we have the simplified formula

$$s_v(w) = w - \langle w, v \rangle v.$$

Recall that a root system  $\Phi$  in  $V$ , whose elements  $\alpha \in \Phi$  are called roots, is a finite set of nonzero vectors that satisfy the following conditions:

- (i)  $\Phi$  is a spanning set for  $V$ .
- (ii) For any root  $\alpha \in \Phi$ , then the only scalar multiples of  $\alpha$  that belong to  $\Phi$  are  $\alpha$  itself and  $-\alpha$ .
- (iii) For every root  $\alpha \in \Phi$ ,  $\Phi$  is closed under the reflection  $s_\alpha$  through the hyperplane  $H_\alpha$  perpendicular to  $\alpha$ .
- (iv) If  $\alpha, \beta \in \Phi$  are roots, then the projection of  $\beta$  onto the line through  $\alpha$  is an integer or half-integer multiple of  $\alpha$ .

The last two conditions can be equivalently expressed in more algebraic forms:

- (iii) For any two roots  $\alpha, \beta \in \Phi$ ,  $\Phi$  contains the element

$$s_\alpha(\beta) = \beta - 2 \frac{(\alpha, \beta)}{(\alpha, \alpha)} \alpha = \beta - \langle \beta, \alpha \rangle \alpha.$$

- (iv) If  $\alpha, \beta \in \Phi$  are roots, then the number  $\langle \beta, \alpha \rangle = 2 \frac{(\alpha, \beta)}{(\alpha, \alpha)}$  is an integer.

We suppose that our root system  $\Phi$  is irreducible and simply laced. In other words, no root  $\alpha$  is orthogonal to all other roots other than  $-\alpha$ . Letting  $\Delta = \{\alpha_1, \dots, \alpha_r\}$  be a set of simple roots for  $\Phi$ ,  $\Phi$  admits the decomposition

$$\Phi = \Phi_+ \cup \Phi_-,$$

into positive and negative roots where every positive root is a nonnegative linear combination of simple roots with integer coefficients and  $\Phi_- = -\Phi_+$ . We denote the Weyl group associated to  $\Phi$  by  $W$ . Then  $W$  is generated by the simple reflections  $\sigma_i = \sigma_{\alpha_i}$ :

$$W = \langle \sigma_i : 1 \leq i \leq r \rangle.$$

For any base  $\Delta$ , the fundamental Weyl chamber  $\mathcal{C}(\Delta)$  is

$$\mathcal{C}(\Delta) = \{v \in V : (v, \alpha) > 0 \text{ for all } \alpha \in \Delta\}.$$

The fundamental Weyl chamber is a connected component of  $V - \bigcup_{\alpha \in \Phi} H_\alpha$  and  $W$  acts simply transitively on the Weyl chambers. Since  $\Phi$  is simply laced, the Dynkin diagram of  $\Phi$  is the graph with nodes  $i$  for  $1 \leq i \leq r$  where the nodes  $i$  and  $j$  are adjacent, via a single edge, if and only if  $(\sigma_i \sigma_j)^3 = 1$ . If  $i$  and  $j$  are not adjacent then  $(\sigma_i \sigma_j)^2 = 1$ . We write  $i \sim j$  if  $i$  and  $j$  are adjacent in the Dynkin diagram. The action of the simple reflection  $\sigma_i$  on the simple root  $\alpha_j$  is given by the following:

$$\sigma_i \alpha_j = \begin{cases} \alpha_i + \alpha_j & \text{if } i \sim j, \\ -\alpha_j & \text{if } i = j, \\ \alpha_j & \text{otherwise.} \end{cases}$$

Letting  $r(i, j)$  be the order of  $\sigma_i \sigma_j$  we have

$$r(i, j) = \begin{cases} 3 & \text{if } i \sim j, \\ 1 & \text{if } i = j, \\ 2 & \text{otherwise.} \end{cases}$$

Equivalently, we have the relations

$$\begin{aligned}\sigma_i^2 &= 1 && \text{for all } i, \\ \sigma_i \sigma_j \sigma_i &= \sigma_j \sigma_i \sigma_j && \text{if } i \sim j, \\ \sigma_i \sigma_j &= \sigma_j \sigma_i && \text{otherwise,}\end{aligned}$$

These relations give a presentation for the Weyl group:

$$W = \left\langle \sigma_i \text{ for } 1 \leq i \leq r : \begin{array}{l} \sigma_i^2=1 \text{ for all } i, \\ \sigma_i \sigma_j \sigma_i = \sigma_j \sigma_i \sigma_j \text{ if } i \sim j, \\ \sigma_i \sigma_j = \sigma_j \sigma_i \text{ otherwise.} \end{array} \right\rangle$$

Since  $\Delta$  is a basis for  $\Phi$ , every root  $\alpha \in \Phi$  admits the unique expression

$$\alpha = \sum_{1 \leq i \leq r} k_i \alpha_i,$$

where all of the  $k_i$  integers and either all  $k_i \geq 0$  or all  $k_i \leq 0$ . Accordingly, we define  $\text{Supp}(\alpha)$  to be the subset of  $1 \leq i \leq r$  such that  $k_i \neq 0$ . We also define the height  $h(\alpha)$  of  $\alpha$  by

$$h(\alpha) = \sum_{1 \leq i \leq r} k_i.$$

This induces a partial ordering  $<$  on the roots where  $\alpha \leq \beta$  if either  $\alpha = \beta$  or  $\beta - \alpha$  is a nonnegative combination of simple roots. There is a unique highest root with respect to this ordering. More generally, let  $\Lambda_\Phi$  be the lattice generated by the roots. Then

$$\Lambda_\Phi = \mathbb{Z}\alpha_1 \oplus \mathbb{Z}\alpha_2 \oplus \cdots \oplus \mathbb{Z}\alpha_r,$$

and every  $\alpha \in \Lambda_\Phi$  admits a unique expression

$$\alpha = \sum_{1 \leq i \leq r} k_i \alpha_i,$$

with the  $k_i \in \mathbb{Z}$ . Note that  $\alpha$  need not be a root so the  $k_i$  can have mixed sign. Clearly  $\Phi \subset \Lambda_\Phi$ . Clearly, height, support, and the ordering  $<$  on  $\Phi$  all extend to  $\Lambda_\Phi$  in the obvious way. Also, recall that the Weyl vector  $\rho$  is given by

$$\rho = \frac{1}{2} \sum_{\alpha \in \Phi^+} \alpha.$$

Note that the Weyl vector is not a root. Nevertheless,  $\rho - w\rho$  is a root for all  $w \in W$ . Lastly, for  $w \in W$  set

$$\Phi(w) = \{\alpha \in \Phi^+ : w\alpha \in \Phi^-\},$$

to be the set of positive roots sent to negative roots by  $w$ . Recall that  $\sigma_i$  permutes all of the positive roots except  $\alpha_i$  which is sent to its negative. So  $\Phi(\sigma_i) = \{\alpha_i\}$  for all  $1 \leq i \leq r$ . Let  $\ell : W \rightarrow \mathbb{Z}_{\geq 0}$  denote the length function. Then  $\ell(w)$  is number of simple reflections in the reduced expression for  $w \in W$ . We define

$$\text{sgn}(w) = (-1)^{\ell(w)}.$$

## 2. THE CHINTA-GUNNELLS CONSTRUCTION

The Chinta-Gunnells construction is a way of building a Weyl group multiple Dirichlet series that is more multiplicative in nature. This construction is in contrast to building these objects using correction polynomials which is naturally additive. More precisely, the coefficients of a Weyl group multiple Dirichlet series are not multiplicative but only just. These coefficients satisfy a twisted version of multiplicativity instead. One might hope that the subseries corresponding to powers of a fixed prime, or  $p$ -th parts as they are called, contain enough structure to build the multiple Dirichlet series. This is indeed the case. The Chinta-Gunnells construction is a way of building the  $p$ -th parts of a multiple Dirichlet series by averaging over the elements of a Weyl group  $W$  attached to some root system  $\Phi$ . More precisely, we define an action

of the Weyl group  $W$  on rational functions  $f \in \mathbb{C}(\mathbf{x}, u)$  where  $\mathbf{x} = (x_1, \dots, x_r)$  and  $u$  is a parameter. From this action, we will construct a rational function  $Z_\Phi(\mathbf{x}; q) \in \mathbb{C}(\mathbf{x}, u)$  that is  $W$ -invariant and satisfies certain limiting properties. Setting  $u = q$  and expanding  $Z_\Phi(\mathbf{x}; q)$  as a power series in the  $x_i$ , the  $W$ -invariance will force the coefficients of this power series to satisfy certain functional equations. We will use these coefficients to build the associated global Weyl group multiple Dirichlet series  $Z(\mathbf{s}) = Z(s_1, \dots, s_r)$  over the rational function field  $\mathbb{F}_q(t)$ . In fact, under a change of variables,  $Z_\Phi(\mathbf{x}; q)$  equals the  $p$ -th part of a Weyl group multiple Dirichlet series over  $\mathbb{F}_q(t)$ . So from the  $W$ -invariance, we see that the  $p$ -th parts satisfy a group of functional equations that is naturally isomorphic to  $W$  just like the global Weyl group multiple Dirichlet series. However, a much more beautiful phenomena occurs. Under a simple change of variables  $(\mathbf{x}, u) = (x_1, \dots, x_r, u) \rightarrow (q^{1-s_1}, \dots, q^{1-s_r}, q^{-1})$ , the  $W$ -invariant rational function  $Z_\Phi(\mathbf{x}; u)$  used to construct the  $p$ -th parts of  $Z(\mathbf{x})$  actually equals the global Weyl group multiple Dirichlet series  $Z(\mathbf{s})$ . That is,

$$Z_\Phi(q^{1-s_1}, \dots, q^{1-s_r}; q^{-1}) = Z(s_1, \dots, s_r).$$

Throughout we assume  $\Phi$  is an irreducible and simply laced root system.

**The Chinta-Gunnells Action.** Let  $\alpha_1, \dots, \alpha_r$  be simple roots for  $\Phi$ . Let  $\mathbb{C}(\mathbf{x}, u)$  be the field of rational functions in the variables  $\mathbf{x} = (x_1, \dots, x_r)$  and formal parameter  $u$ . Moreover, let  $\mathbf{x}_i = x_i$  for  $1 \leq i \leq r$ . For  $\alpha \in \Lambda_\Phi$  in the root lattice, set  $\mathbf{x}^\alpha = x_1^{k_1} \cdots x_r^{k_r}$  if  $\alpha = \sum_{1 \leq i \leq r} k_i \alpha_i$ . We first define an action of simple reflection  $\sigma_i$  on  $r$ -tuples  $\mathbf{x} = (x_1, \dots, x_r)$  component-wise by

$$(\sigma_i \mathbf{x})_j = \begin{cases} \sqrt{u} x_i x_j & \text{if } i \sim j, \\ \frac{1}{u x_j} & \text{if } i = j, \\ x_j & \text{otherwise.} \end{cases}$$

It is easy to verify directly that action of simple reflections extends to a  $W$ -action on  $\mathbb{C}^r$ . That is, we have the follow relations:

$$\begin{aligned} \sigma_i^2 \mathbf{x} &= \mathbf{x} & \text{for all } i, \\ \sigma_i \sigma_j \sigma_i \mathbf{x} &= \sigma_j \sigma_i \sigma_j \mathbf{x} & \text{if } i \sim j, \\ \sigma_i \sigma_j \mathbf{x} &= \sigma_j \sigma_i \mathbf{x} & \text{otherwise.} \end{aligned} \tag{1}$$

One can also prove the useful relation

$$(w \mathbf{x})^\alpha = u^{\frac{h(w\alpha - \alpha)}{2}} \mathbf{x}^{w\alpha}, \tag{2}$$

which follows by induction on the length of  $w$ . Second, we define sign operators  $\varepsilon_i$  on  $r$ -tuples  $\mathbf{x}$ . For  $1 \leq i \leq r$ , define  $\varepsilon_i \mathbf{x}$  component-wise by

$$(\varepsilon_i \mathbf{x})_j = \begin{cases} -x_j & \text{if } i \sim j, \\ x_j & \text{otherwise.} \end{cases}$$

The following relations are also easily verified for all  $i$  and  $j$ :

$$\begin{aligned} \varepsilon_i^2 \mathbf{x} &= \mathbf{x}, \\ \varepsilon_i \varepsilon_j \mathbf{x} &= \varepsilon_j \varepsilon_i \mathbf{x}, \\ \sigma_i \varepsilon_j \mathbf{x} &= \begin{cases} \varepsilon_i \varepsilon_j \sigma_i \mathbf{x} & \text{if } i \sim j, \\ \varepsilon_j \sigma_i \mathbf{x} & \text{otherwise.} \end{cases} \end{aligned} \tag{3}$$

Given  $f \in \mathbb{C}(\mathbf{x}, u)$ , we will need to decompose  $f$  with respect to  $\varepsilon_i$ . Accordingly, set

$$f_i^\pm(\mathbf{x}; u) = \frac{f(\mathbf{x}; u) \pm f(\varepsilon_i \mathbf{x}; u)}{2}.$$

These are the even and odd parts of  $f$  with respect to the involution  $\varepsilon_i$ . We state some properties of this operation that will be useful:

**Proposition 2.1.** *Let  $f, g \in \mathbb{C}(\mathbf{x}, u)$  and  $1 \leq i \leq r$ . Then the following properties are true:*

(i) *Taking the even or odd part with respect to  $\varepsilon_i$  is additive. That is,*

$$(f + g)_i^\pm(\mathbf{x}; u) = f_i^\pm(\mathbf{x}; u) + g_i^\pm(\mathbf{x}; u)$$

(ii) *If  $f$  is a function of  $x_i$  and  $u$  alone, then*

$$(fg)_i^\pm(\mathbf{x}; u) = f(x_i; u)g_i^\pm(\mathbf{x}; u).$$

(iii)  *$f_i^\pm(\mathbf{x}; u)$  decompose  $f(\mathbf{x}; u)$ . That is,*

$$f_i(\mathbf{x}; u) = f_i^+(\mathbf{x}; u) + f_i^-(\mathbf{x}; u)$$

(iv)

$$f_{ii}^{\pm\pm}(\mathbf{x}; u) = f_i^\pm(\mathbf{x}; u) \quad \text{and} \quad f_{ii}^{\pm\mp}(\mathbf{x}; u) = 0.$$

*Proof.* Properties (i) and (iii) are clear. Property (ii) follows since  $\varepsilon_i$  does not change the sign of  $x_i$ . As for (iv), this can be verified by direct computation.  $\square$

We can now define a  $W$ -action  $\mathbb{C}(\mathbf{x}, u)$ . For any simple reflection  $\sigma_i$  and  $f \in \mathbb{C}(\mathbf{x}, u)$ , we set

$$f|^\text{CG}\sigma_i(\mathbf{x}; u) = -\frac{1 - ux_i}{ux_i(1 - x_i)}f_i^+(\sigma_i\mathbf{x}; u) + \frac{1}{\sqrt{ux_i}}f_i^-(\sigma_i\mathbf{x}; u).$$

While we will not need it, there is an equivalent way to define this action that is sometimes used. For  $f \in \mathbb{C}(\mathbf{x}, u)$ , we have

$$f|^\text{CG}\sigma_i(\mathbf{x}; u) = f(\sigma_i\mathbf{x}; u)J(x_i; u, 0) + f(\varepsilon_i\sigma_i\mathbf{x}; u)J(x_i; u, 1),$$

where, for  $\delta \in \{0, 1\}$ , we set

$$J(x; u, \delta) = \frac{1}{2} \left( -\frac{1 - ux}{ux(1 - x)} + \frac{(-1)^\delta}{\sqrt{ux}} \right).$$

In any case, the action  $|^\text{CG}\sigma_i$  of simple reflections  $\sigma_i$  on functions  $f \in \mathbb{C}(\mathbf{x}, u)$  extends to a  $W$ -action on  $\mathbb{C}(\mathbf{x}, u)$ :

**Proposition 2.2.** *The action of simple reflections  $\sigma_i$  on  $\mathbb{C}(\mathbf{x}, u)$  extends to a  $W$ -action.*

*Proof.* See [2] for a proof.  $\square$

We call the extended  $W$ -action  $|^\text{CG}w$  the **Chinta-Gunnells action**. We now state some basic properties of this action:

**Proposition 2.3.** *Let  $f, g \in \mathbb{C}(\mathbf{x}, u)$  and  $w \in W$ . Then the following are true:*

(i) *The Chinta-Gunnells action is additive. That is,*

$$(f + g)|^\text{CG}w(\mathbf{x}; u) = f|^\text{CG}w(\mathbf{x}; u) + g|^\text{CG}w(\mathbf{x}; u).$$

(ii) *If  $f$  is an even function in all of the  $x_i$ , then*

$$fg|^\text{CG}w(\mathbf{x}; u) = f(w\mathbf{x}; u) \cdot g|^\text{CG}w(\mathbf{x}; u).$$

*Proof.* Both (i) and (ii) can be proved for a simple reflection  $\sigma_i$  and then in general by induction on the length of  $w$ . See [1] for a full proof.  $\square$

**The Chinta-Gunnells Average.** We will now construct the desired  $W$ -invariant function. To begin, define products

$$\Delta_\Phi(\mathbf{x}) = \prod_{\alpha \in \Phi^+} (1 - u^{h(\alpha)} \mathbf{x}^{2\alpha}) \quad \text{and} \quad D_\Phi(\mathbf{x}) = \prod_{\alpha \in \Phi^+} (1 - u^{h(\alpha)-1} \mathbf{x}^{2\alpha}).$$

Also set

$$j(w, \mathbf{x}) = \frac{\Delta_\Phi(\mathbf{x})}{\Delta_\Phi(w\mathbf{x})}.$$

Then  $j(w, \mathbf{x})$  immediately satisfies the 1-cocycle relation

$$j(ww', \mathbf{x}) = j(w, w'\mathbf{x})j(w', \mathbf{x}),$$

for any  $w, w' \in W$ . We will need a useful lemma telling us how to compute  $j(w, \mathbf{x})$  in general:

**Lemma 2.1.** *For any simple reflection  $\sigma_i$ ,*

$$j(\sigma_i, \mathbf{x}) = -ux_i^2.$$

Moreover, for any  $w \in W$ ,

$$j(w, \mathbf{x}) = \text{sgn}(w) u^{h(\rho - w^{-1}\rho)} \mathbf{x}^{2(\rho - w^{-1}\rho)}.$$

*Proof.* The second statement follows from the first and the cocycle relation for  $j(w, \mathbf{x})$ . As for the first statement, write

$$\Delta_\Phi(\mathbf{x}) = (1 - u\mathbf{x}^{2\alpha_i}) \prod_{\substack{\alpha \in \Phi^+ \\ \alpha \neq \alpha_i}} (1 - u^{h(\alpha)} \mathbf{x}^{2\alpha})$$

Now  $\sigma_i$  permutes all of the positive roots except for  $\alpha_i$  which it sends to its negative (that is  $\Phi(\sigma_i) = \{\alpha_i\}$ ). Using Equation (2) and that  $\sigma_i\alpha_i = -\alpha_i$  gives

$$\Delta_\Phi(\sigma_i\mathbf{x}) = (1 - u(\sigma_i\mathbf{x})^{2\alpha_i}) \prod_{\substack{\alpha \in \Phi^+ \\ \alpha \neq \alpha_i}} (1 - u^{h(\alpha)} (\sigma_i\mathbf{x})^{2\alpha}) = (1 - u^{-1} \mathbf{x}^{-2\alpha_i}) \prod_{\substack{\alpha \in \Phi^+ \\ \alpha \neq \alpha_i}} (1 - u^{h(\sigma_i\alpha)} \mathbf{x}^{2\sigma_i\alpha}).$$

But since  $\sigma_i$  permutes all of the positive roots except  $\alpha_i$ , the two products over  $\alpha \in \Phi^+$  with  $\alpha \neq \alpha_i$  are identical. Then the identity  $-ux_i^2(1 - u^{-1}\mathbf{x}^{-2\alpha_i}) = (1 - u\mathbf{x}^{2\alpha_i})$  implies

$$\Delta_\Phi(\sigma_i\mathbf{x}) = -u^{-1}x_i^{-2}\Delta_\Phi(\mathbf{x}),$$

which is to say that

$$j(\sigma_i, \mathbf{x}) = -ux_i^2.$$

□

Notice that by Lemma 2.1,  $j(w, \mathbf{x})$  is an even functions of all the  $x_i$ . So is  $\Delta_\Phi(\mathbf{x})$ , so (ii) of Proposition 2.3 applies to both of these functions. Now define the **Chinta-Gunnells average**  $Z_\Phi(\mathbf{x}; u)$  by

$$Z_\Phi(\mathbf{x}; u) = \frac{Z_W(\mathbf{x}; u)}{\Delta_\Phi(\mathbf{x})},$$

where

$$Z_W(\mathbf{x}; u) = \sum_{w \in W} j(w, \mathbf{x}) (1|^{CG} w)(\mathbf{x}; u).$$

It turns out that  $Z_\Phi(\mathbf{x}; u)$  is  $W$ -invariant under the Chinta-Gunnells action and satisfies certain limiting properties (the limiting properties are the more difficult part to verify):

**Theorem 2.1.**  $Z_\Phi(\mathbf{x}; u)$  is a rational function in  $\mathbb{C}(\mathbf{x}, u)$  that is  $W$ -invariant with respect to the Chinta-Gunnells action and satisfies the following properties:

- (i) Let  $1 \leq i \leq r$ . If  $\mathbf{x} = (x_1, \dots, x_r)$  is such that  $x_j = 0$  provided  $i \sim j$ , then  $(1 - x_i)Z_\Phi(\mathbf{x}; u)$  is independent of  $x_i$ .



(ii)  $Z_\Phi(\mathbf{0}; u) = 1$ .

*Proof.* The fact that  $Z_\Phi(\mathbf{x}; u)$  is a rational function is clear from the definition of the Chinta-Gunnells action. The  $W$ -invariance follows from Proposition 2.3 and Lemma 2.1 combined with the 1-cocycle relation for  $j(w, \mathbf{x})$ . For property (ii), see [1] for a proof.  $\square$

It was also proven in [1] that  $Z_\Phi(\mathbf{x}; u)$  can be written as

$$Z_\Phi(\mathbf{x}; u) = \frac{N_\Phi(\mathbf{x}; u)}{D_\Phi(\mathbf{x}; u)},$$

for some polynomial  $N_\Phi(\mathbf{x}; u)$ . Actually, this implies that  $Z_\Phi(\mathbf{x}; u)$  is locally absolutely uniformly convergent away from the points  $1 - u^{h(\alpha)-1} \mathbf{x}^{2\alpha} = 0$  for all  $\alpha \in \Phi^+$ . In particular, we have such convergence for  $|\mathbf{x}|$  sufficiently small provided  $u$  is fixed. For our purposes, it will be convenient to use this expression for  $Z_\Phi(\mathbf{x}; u)$  since  $D_\Phi(\mathbf{x}; u)$  is an explicit description for the polar structure of  $Z_\Phi(\mathbf{x}; u)$ .

**Remark 2.1.** *Since  $W$  is finite, it is very easy to construct  $W$ -invariant rational functions in general by choosing any rational function  $g$  and averaging over  $g|^{CG}w$  for  $w \in W$ . This is why property (i) in Theorem 2.1 is essential. Indeed, it is the only condition that carries information about the combinatorics of the root system  $\Phi$  because it depends upon the associated Dynkin diagram. Actually, from property (i), one can reconstruct the Dynkin diagram of  $\Phi$  by inspecting which variables the functions  $(1 - x_i)Z_\Phi(\mathbf{x}; u)$  are independent of. Since the Dynkin diagram is a unique graphic representation of a root system, property (i) encodes the entire root system  $\Phi$  algebraically into  $Z_\Phi(\mathbf{x}; u)$ .*

### 3. PROPERTIES OF THE CHINTA-GUNNELLS AVERAGE

From now on we take  $u$  to be positive. We will prove some basic properties of the Chinta-Gunnells average  $Z_\Phi(\mathbf{x}; u)$ . Expanding  $Z_\Phi(\mathbf{x}; u)$  as a power series in  $x_1, \dots, x_r$  yields

$$Z_\Phi(\mathbf{x}; u) = \sum_{k_1, \dots, k_r \geq 0} a(k_1, \dots, k_r; u) x_1^{k_1} \cdots x_r^{k_r},$$

for some coefficients  $a(k_1, \dots, k_r; u)$ . We can specify some of the coefficients immediately by using Theorem 2.1. Indeed, since  $Z_\Phi(\mathbf{0}; u) = 1$  by property (ii) of Theorem 2.1, this forces the constant term in the power series expansion to be 1. So,

$$a(0, \dots, 0; u) = 1.$$

Actually, since every factor of  $D(\mathbf{x}; u)$  is of the form  $(1 - u^2 \mathbf{x}^{2\alpha})$  for some  $\alpha \in \Phi^+$  we see that the constant term of  $D(\mathbf{x}; u)$  is 1 and so constant term of  $N(\mathbf{x}; u)$  must also be 1. Moreover, taking  $\mathbf{x}$  as in property (i) of Theorem 2.1, we see that  $(1 - x_i)$  divides  $Z_\Phi(\mathbf{x}; u)$  and is the only part of  $Z_\Phi(\mathbf{x}; u)$  depending upon  $x_i$  (for such  $\mathbf{x}$ ). As the power series coefficients are independent of  $\mathbf{x}$ , this forces

$$a(k_1, \dots, k_r; u) = 1,$$

provided  $k_j = 0$  for all  $i \sim j$ . In particular,

$$a(0, \dots, k_i, \dots, 0; u) = 1,$$

for all  $k_i \geq 0$  and  $1 \leq i \leq r$ . We will now discuss the size of the coefficients in general. It will also be convenient to set  $|k| = \sum_{1 \leq i \leq r} k_i$ . Our first property is that for a fixed root system  $\Phi$ , these coefficients are polynomially bounded in  $u$ .

**Proposition 3.1.** *For a fixed  $\Phi$ , there exist constants  $c_1, c_2 > 0$  such that*

$$|a(k_1, \dots, k_r; u)| < c_1 u^{c_2 |k|}.$$

*Proof.* Since  $N_\Phi(\mathbf{x}; u)$  and  $D_\Phi(\mathbf{x}; u)$  are both polynomially bounded in  $u$ , the claim follows.  $\square$

Proposition 3.1 will guarantee convergence of  $Z_\Phi(\mathbf{x}; u)$  provided the real parts of the  $x_i$  are all sufficiently small. Our second property of  $Z_\Phi(\mathbf{x}; u)$  describes functional equations for coefficients in various power series expansions of  $Z_\Phi(\mathbf{x}; u)$ . Roughly speaking we make take the power series expansion of  $Z_\Phi(\mathbf{x}; u)$  in all of the  $x_i$  save for  $x_j$ . Then the coefficients of this power series are functions of  $x_j$ . The invariance of  $Z_\Phi(\mathbf{x}; u)$  under  $\sigma_j$  will force these coefficients to satisfy certain functional equations. To set up some notation, for any index  $1 \leq j \leq r$  and  $r$ -tuples  $k = (k_1, \dots, k_r)$ , set

$$\widehat{k} = (k_1, \dots, k_{j-1}, k_{j+1}, \dots, k_r),$$

and let  $|\widehat{k}| = \sum_{i \neq j} k_i$ . For fixed index  $j$  and an  $(r-1)$ -tuple  $\widehat{k}$ , define

$$T(x_j; \widehat{k}, u) = \sum_{k_j \geq 0} a(k_1, \dots, k_r; u) x_j^{k_j},$$

and let

$$n(\widehat{k}) = \sum_{i \sim j} k_i.$$

Then we have the following proposition:

**Proposition 3.2.** *Fix an index  $1 \leq j \leq r$  and an  $(r-1)$ -tuple  $\widehat{k}$ . Then the following are true:*

(i) *If  $n(\widehat{k})$  is even,  $T(x_j; \widehat{k}, u)$  satisfies the functional equation*

$$(1 - x_j)T(x_j; \widehat{k}, u) = \left(1 - \frac{1}{ux_j}\right) (\sqrt{u}x_j)^{n(\widehat{k})} T\left(\frac{1}{ux_j}; \widehat{k}, u\right).$$

(ii) *If  $n(\widehat{k})$  is odd,  $T(x_j; \widehat{k}, u)$  satisfies the functional equation*

$$T(x_j; \widehat{k}, u) = (\sqrt{u}x_j)^{n(\widehat{k})-1} T\left(\frac{1}{ux_j}; \widehat{k}, u\right).$$

(iii) *If  $|x_j| < u^{-c_2}$ , then*

$$|T(x_j; \widehat{k}, u)| \ll c_1 u^{c_2 |\widehat{k}|}.$$

*Proof.* We first prove statement (i). So suppose  $n(\widehat{k})$  is even. Acting by  $\sigma_j$  on  $Z_\Phi(\mathbf{x}; u)$ , the  $W$ -invariance implies

$$Z_\Phi(\mathbf{x}; u) = -\frac{1 - ux_j}{ux_j(1 - x_j)} Z_{\Phi,j}^+(\sigma_j \mathbf{x}; u) + \frac{1}{\sqrt{u}x_j} Z_{\Phi,j}^-(\sigma_j \mathbf{x}; u). \quad (4)$$

Taking the  $Z_{\Phi,j}^+(\mathbf{x}; u)$  part of both sides, using all Proposition 2.1 properties, and then multiplying by  $(1 - x_j)$ , yields

$$(1 - x_j)Z_{\Phi,j}^+(\mathbf{x}; u) = \left(1 - \frac{1}{ux_j}\right) Z_{\Phi,j}^+(\sigma_j \mathbf{x}; u). \quad (5)$$

On the other hand, by property (i) of Proposition 2.1, we see that

$$Z_{\Phi,j}^+(\mathbf{x}; u) = \sum_{\widehat{k} \text{ with } n(\widehat{k}) \text{ even}} T(x_j; \widehat{k}, u) \prod_{i \neq j} x_i^{k_i}.$$

Acting by  $\sigma_j$ , we also get

$$Z_{\Phi,j}^+(\sigma_j \mathbf{x}; u) = \sum_{\widehat{k} \text{ with } n(\widehat{k}) \text{ even}} T\left(\frac{1}{ux_j}; \widehat{k}, u\right) (\sqrt{u}x_j)^{n(\widehat{k})} \prod_{i \neq j} x_i^{k_i}.$$

Using these two expressions for  $Z_{\Phi,j}^+(\mathbf{x}; u)$  and  $Z_{\Phi,j}^+(\sigma_j \mathbf{x}; u)$  and comparing coefficients in Equation (5) gives the result. Statement (ii) is proved in the same way by taking the odd parts in Equation (4). For statement (iii), Proposition 3.1 implies

$$|T(x_j; \widehat{k}, u)| < \sum_{k_j \geq 0} |a(k_1, \dots, k_r; u) x_j^{k_j}| < c_1 u^{c_2 |\widehat{k}|} \sum_{k_j \geq 0} u^{c_2} |x_j|^{k_j}.$$

The latter sum is a geometric series which converges absolutely (and hence is at most a constant) provided  $|u^{c_2} x_j| < 1$ , or equivalently,  $|x_j| < u^{-c_2}$ .  $\square$

Lastly, we show a connection between the  $W$ -invariant function  $Z_\Phi(\mathbf{x}; u)$  and data of the root system  $\Phi$ . This is seen by inspecting the parameter  $u$  in  $Z_W(\mathbf{x}; u)$ . Expanding this function as a power series in  $x_1, \dots, x_r$ , yields

$$Z_W(\mathbf{x}; u) = \sum_{k_1, \dots, k_r \geq 0} b(k_1, \dots, k_r; u) x_1^{k_1} \cdots x_r^{k_r}.$$

The nonzero terms of this series are in bijection with the elements of  $W$ . Indeed, for this we may ignore questions of convergence so set  $u = 1$ . Then the Chinta-Gunnells action simplifies, and from the definition of  $Z_W(\mathbf{x}; u)$ , we compute

$$Z_W(\mathbf{x}; 1) = \sum_{w \in W} (-1)^{\ell(w) + h(\rho - w\rho)} \mathbf{x}^{\rho - w\rho}.$$

But then

$$b(k_1, \dots, k_r; 1) = \begin{cases} (-1)^{\ell(w) + h(\rho - w\rho)} & \text{if } \rho - w\rho = \sum_{1 \leq i \leq r} k_i \alpha_i \text{ for some } w \in W, \\ 0 & \text{otherwise,} \end{cases}$$

provided all of the monomials  $\mathbf{x}^{\rho - w\rho}$  are distinct. This is indeed true because the Weyl vector lies in the interior of the fundamental Weyl chamber and the Weyl group acts on the Weyl chambers simply transitively.

#### 4. THE WEYL GROUP MULTIPLE DIRICHLET SERIES

We now assume  $q \equiv 1 \pmod{4}$ . This requirement is not strictly necessary, but it does allow for some technical simplifications as the statement of quadratic reciprocity is perfect. As before, let  $\Phi$  be an irreducible and simply laced root system. Let  $q$  be a power of a fixed prime  $p$  and consider the rational function field  $\mathbb{F}_q(t)$ . Set  $u = q$ . We will construct the Weyl group multiple Dirichlet series associated to a root system  $\Phi$  over the field  $\mathbb{F}_q(t)$  from the Chinta-Gunnells average  $Z_\Phi(\mathbf{x}; q)$ . The idea is to use the coefficients  $a(k_1, \dots, k_r; q)$  in the power series expansion

$$Z_\Phi(\mathbf{x}; q) = \sum_{k_1, \dots, k_r \geq 0} a(k_1, \dots, k_r; q) x_1^{k_1} \cdots x_r^{k_r},$$

to build the associated multiple Dirichlet series. For simplicity, we work over the function field  $\mathbb{F}_q(t)$  but our construction can be done over other fields. Let  $P$  be a monic irreducible in  $\mathbb{F}_q[t]$ . The series

$$Z_\Phi(|P|^{s_1}, \dots, |P|^{s_r}; |P|) = \sum_{k_1, \dots, k_r \geq 0} \frac{a(k_1, \dots, k_r; |P|)}{|P|^{k_1 s_1 + \cdots + k_r s_r}},$$

is called the  **$P$ -th part** of  $Z(s_1, \dots, s_r)$ . We are now ready to start defining the Weyl group multiple Dirichlet series  $Z(s_1, \dots, s_r)$ . We will first define coefficients  $H(m_1, \dots, m_r)$  via the following two properties:

- (i) For any monic irreducible  $P$  and nonnegative integers  $k_1, \dots, k_r \geq 0$ , define

$$H(P^{k_1}, \dots, P^{k_r}) = a(k_1, \dots, k_r; |P|).$$

- (ii) For any  $r$ -tuple  $(m_1 n_1, \dots, m_r n_r)$  of monic polynomials in  $\mathbb{F}_q(t)$  such that  $(m_1 \cdots m_r, n_1 \cdots n_r) = 1$ , we set

$$H(m_1 n_1, \dots, m_r n_r) = H(m_1, \dots, m_r) H(n_1, \dots, n_r) \prod_{i \sim j} \left( \frac{m_i}{n_j} \right) \left( \frac{n_i}{m_j} \right).$$

Observe that property (ii) prevents  $H(m_1, \dots, m_r)$  from being multiplicative. We refer to property (ii) as **twisted multiplicativity** for the coefficients  $H(m_1, \dots, m_r)$ . Moreover, these coefficients satisfy some nice properties:

**Proposition 4.1.** *The coefficients  $H(m_1, \dots, m_r)$  satisfy the following properties:*

- (i) *There is a constant  $C > 0$  such that*

$$|H(m_1, \dots, m_r)| \ll |m_1 \cdots m_r|^C.$$

- (ii) *If  $m_1, \dots, m_r$  are pairwise relatively prime, then*

$$H(m_1, \dots, m_r) = \prod_{i \sim j} \left( \frac{m_i}{m_j} \right).$$

*Proof.* Property (i) follows immediately from the definition of  $H(m_1, \dots, m_r)$  and Proposition 3.1. Property (ii) follows from combining the definition of  $H(m_1, \dots, m_r)$ , and the facts

$$H(1, \dots, P^{k_i}, \dots, 1) = a(0, \dots, k_i, \dots, 0; |P|) = 1 \quad \text{and} \quad \left( \frac{1}{P} \right) = \left( \frac{P}{1} \right) = 1,$$

for all monic irreducibles  $P$ . □

We define the **Weyl group multiple Dirichlet series**  $Z(s_1, \dots, s_r)$  by

$$Z(s_1, \dots, s_r) = \sum_{m_1, \dots, m_r \text{ monic}} \frac{H(m_1, \dots, m_r)}{|m_1|^{s_1} \cdots |m_r|^{s_r}},$$

where the sum is over all monics in  $\mathbb{F}_q[t]$ . Note that by property (i) of Proposition 4.1,  $Z(s_1, \dots, s_r)$  converges locally absolutely uniformly on the region  $\Lambda = \{(s_1, \dots, s_r) \in \mathbb{C}^r : \operatorname{Re}(s_i) > 1 + C, 1 \leq i \leq r\}$  by viewing it as a Dirichlet series in one variable whose coefficients are in  $r - 1$  variables and then viewing the coefficients in the same way. In order to study  $Z(s_1, \dots, s_r)$  we will also need to consider twists of it by a set of Hilbert symbols. For each  $1 \leq i \leq r$ , let  $\psi_i$  be a Hilbert symbol. As we are working over function fields,  $\psi_i = \psi$  or  $\psi_i = \chi_1$ . Now define the **Weyl group multiple Dirichlet series**  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  twisted by  $\psi_1, \dots, \psi_r$  as

$$Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r) = \sum_{m_1, \dots, m_r \text{ monic}} \frac{\psi_1(m_1) \cdots \psi_r(m_r) H(m_1, \dots, m_r)}{|m_1|^{s_1} \cdots |m_r|^{s_r}}.$$

Since the Hilbert symbols are given by quadratic Dirichlet characters, it follows that  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  converges locally absolutely uniformly in the same region as  $Z(s_1, \dots, s_r)$ . Note that if  $\psi_1 = \cdots = \psi_r = \chi_1$ , then  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r) = Z(s_1, \dots, s_r)$ .

## 5. CORRECTION POLYNOMIALS

We will now deduce expressions for subsums of  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$ . For this, we always work in the region of local absolute uniform convergence. To begin, fix an index  $1 \leq j \leq r$ . Also, for any  $r$ -tuple  $m = (m_1, \dots, m_r)$ , set

$$\widehat{m} = (m_1, \dots, m_{j-1}, m_{j+1}, \dots, m_r).$$

To begin, summing over the index  $j$  in  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  first gives

$$Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r) = \sum_{\widehat{m} \text{ monic}} \frac{\prod_{i \neq j} \psi_i(m_i)}{\prod_{i \neq j} |m_i|^{s_i}} \sum_{m_j \text{ monic}} \frac{\psi_j(m_j) H(m_1, \dots, m_j, \dots, m_r)}{|m_j|^{s_j}}.$$

The idea is to express the inner sum over  $m_j$  as the product of an  $L$ -function and a Dirichlet polynomial up to a constant. Set  $N_j = m_1 \cdots m_{j-1} m_{j+1} \cdots m_r$ . Then write  $m_j = nn_j$  where  $n_j \mid N_j$  and  $(n, n_j) = 1$ . Equivalently,  $n$  is the part of  $m_j$  that is relatively prime to  $N_j$ . So we also have  $(n, N_j) = 1$ . Then we may write

$$\begin{aligned} \sum_{m_j \text{ monic}} \frac{\psi_j(m_j) H(m_1, \dots, m_r)}{|m_j|^{s_j}} &= \sum_{nn_j \text{ monic}} \frac{\psi_j(nn_j) H(m_1, \dots, nn_j, \dots, m_r)}{|nn_j|^{s_j}} \\ &= \sum_{n_j \mid N_j^\infty} \sum_{(n, N_j)=1} \frac{\psi_j(nn_j) H(m_1, \dots, nn_j, \dots, m_r)}{|nn_j|^{s_j}} \\ &= \sum_{n_j \mid N_j^\infty} \frac{\psi_j(n_j)}{|n_j|^{s_j}} \sum_{(n, N_j)=1} \frac{\psi_j(n) H(m_1, \dots, nn_j, \dots, m_r)}{|n|^{s_j}}, \end{aligned}$$

where we recall that  $n_j \mid N_j^\infty$  means that the irreducible factors of  $n_j$  are a subset of the irreducible factors of  $N_j$ . Using twisted multiplicativity, we may pull a factor  $H(m_1, \dots, n_j, \dots, m_r)$  into the outer sum obtaining

$$\sum_{n_j \mid N_j^\infty} \frac{\psi_j(n_j) H(m_1, \dots, n_j, \dots, m_r)}{|n_j|^{s_j}} \sum_{(n, N_j)=1} \frac{\psi_j(n) H(1, \dots, n, \dots, 1)}{|n|^{s_j}} \prod_{i \sim j} \left( \frac{m_i}{n} \right).$$

Set  $M = \prod_{i \sim j} m_i$  and let  $M_0$  be the square-free part of  $M$ . Since  $(n, N_j) = 1$ , the inner product is  $\chi_M(n) = \chi_{M_0}(n)$ . But as  $H(1, \dots, n, \dots, 1) = 1$ , these two facts imply

$$\sum_{(n, N_j)=1} \frac{\psi_j(n) H(1, \dots, n, \dots, 1)}{|n|^{s_j}} \prod_{i \sim j} \left( \frac{m_i}{n} \right) = L^{(N_j)}(s_j, \psi_j \chi_{M_0}),$$

where we recall that  $L^{(N_j)}(s_j, \psi_j \chi_{M_0})$  is  $L(s_j, \psi_j \chi_{M_0})$  with the local factors at the irreducibles dividing  $N_j$  removed. This  $L$ -function may be factored outside of the double sum so that in total we obtain

$$\sum_{m_j \text{ monic}} \frac{\psi_j(m_j) H(m_1, \dots, m_r)}{|m_j|^{s_j}} = L^{(N_j)}(s_j, \psi_j \chi_{M_0}) \sum_{n_j \mid N_j^\infty} \frac{\psi_j(n_j) H(m_1, \dots, n_j, \dots, m_r)}{|n_j|^{s_j}}. \quad (6)$$

We will now examine the sum in the right-hand side of Equation (6). We will show that it factors as a product over primes dividing  $N_j$ . To see this, let  $P$  be a prime dividing  $N_j$ . Then we may write

$$\begin{aligned} \sum_{n_j \mid N_j^\infty} \frac{\psi_j(n_j) H(m_1, \dots, n_j, \dots, m_r)}{|n_j|^{s_j}} &= \sum_{\substack{n_j \mid N_j^\infty \\ (n_j, P)=1}} \sum_{k_j \geq 0} \frac{\psi_j(n_j P^{k_j}) H(m_1, \dots, n_j P^{k_j}, \dots, m_r)}{|n_j P^{k_j}|^{s_j}} \\ &= \sum_{\substack{n_j \mid N_j^\infty \\ (n_j, P)=1}} \frac{\psi_j(n_j)}{|n_j|^{s_j}} \sum_{k_j \geq 0} \frac{\psi_j(P^{k_j}) H(m_1, \dots, n_j P^{k_j}, \dots, m_r)}{|P^{k_j}|^{s_j}}. \end{aligned}$$

Now let  $P^{\beta_i} \parallel m_i$  and let  $m_i^{(P)}$  be the part of  $m_i$  relatively prime to  $P$  for  $1 \leq i \leq r$ . Then by twisted multiplicativity we may pull out a factor  $H(m_1^{(P)}, \dots, n_j, \dots, m_r^{(P)})$  obtaining

$$\sum_{\substack{n_j | N_j^\infty \\ (n_j, P)=1}} \frac{\psi_j(n_j) H(m_1^{(P)}, \dots, n_j, \dots, m_r^{(P)})}{|n_j|^{s_j}} \sum_{k_j \geq 0} \frac{\psi_j(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}} \prod_{i \sim j} \left( \frac{m_i^{(P)}}{P^{k_j}} \right) \left( \frac{P^{\beta_i}}{n_j} \right) \\ \cdot \prod_{\substack{i \sim \ell \\ i, \ell \neq j}} \left( \frac{m_i^{(P)}}{P^{\beta_\ell}} \right) \left( \frac{P^{\beta_i}}{m_\ell^{(P)}} \right).$$

Since reciprocity is perfect,

$$\prod_{\substack{i \sim \ell \\ i, \ell \neq j}} \left( \frac{m_i^{(P)}}{P^{\beta_\ell}} \right) \left( \frac{P^{\beta_i}}{m_\ell^{(P)}} \right) = \prod_{\substack{i \sim \ell \\ i, \ell \neq j}} \left( \frac{m_i^{(P)}}{P^{\beta_\ell}} \right) \left( \frac{m_\ell^{(P)}}{P^{\beta_i}} \right) = \prod_{\substack{i \sim \ell \\ i, \ell \neq j}} \left( \frac{(m_i m_\ell)^{(P)}}{P^{\beta_i + \beta_\ell}} \right).$$

Now set

$$\varepsilon_P(\widehat{m}) = \prod_{\substack{i \sim \ell \\ i, \ell \neq j}} \left( \frac{(m_i m_\ell)^{(P)}}{P^{\beta_i + \beta_\ell}} \right) \quad \text{and} \quad \varepsilon_j(\widehat{m}) = \prod_{P | N_j} \varepsilon_P(\widehat{m}).$$

Note that  $\varepsilon_P(\widehat{m})$  is the second product in our expression above. This factor is independent of both sums and so we may pull it outside. Further factoring out the sum over  $k_j$ , we obtain

$$\varepsilon_P(\widehat{m}) \sum_{k_j \geq 0} \frac{\psi_j(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}} \prod_{i \sim j} \left( \frac{m_i^{(P)}}{P^{k_j}} \right) \\ \cdot \sum_{\substack{n_j | N_j^\infty \\ (n_j, P)=1}} \frac{\psi_j(n_j) H(m_1^{(P)}, \dots, n_j, \dots, m_r^{(P)})}{|n_j|^{s_j}} \prod_{i \sim j} \left( \frac{P^{\beta_i}}{n_j} \right).$$

After repeating this process to

$$\sum_{\substack{n_j | N_j^\infty \\ (n_j, P)=1}} \frac{\psi_j(n_j) H(m_1^{(P)}, \dots, n_j, \dots, m_r^{(P)})}{|n|^{s_j}} \prod_{i \sim j} \left( \frac{P^{\beta_i}}{n_j} \right),$$

for all primes dividing  $N_j$ , the sum over  $n_j$  factors as

$$\varepsilon_j(\widehat{m}) \prod_{\substack{P | N_j \\ P^{\beta_i} \parallel m_i}} \sum_{k_j \geq 0} \frac{\psi_j(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}} \left( \frac{M^{(P)}}{P^{k_j}} \right),$$

where  $M^{(P)} = \prod_{i \sim j} m_i^{(P)}$  is the part of  $M$  relatively prime to  $P$ . Therefore, we have

$$\sum_{m_j \text{ monic}} \frac{\psi_j(m_j) H(m_1, \dots, m_r)}{|m_j|^{s_j}} = \varepsilon_j(\widehat{m}) L^{(N_j)}(s_j, \psi_j \chi_{M_0}) \\ \cdot \prod_{\substack{P | N_j \\ P^{\beta_i} \parallel m_i}} \sum_{k_j \geq 0} \frac{\psi_j(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}} \left( \frac{M^{(P)}}{P^{k_j}} \right). \quad (7)$$

Now write  $M = M_0 M_1^2 M_2^2$  with  $M_0$  square-free,  $M_2$  relatively prime to  $M_0 M_1$ , and such that every irreducible divisor of  $M_1$  divides  $M_0$ . In other words,  $M_0$  is the square-free part of  $M$ ,  $M_1$  is the square part of  $M$  whose irreducible factors divide  $M$  to odd power, and  $M_2$  is the square part of  $M$  whose

irreducible factors divide  $M$  to even power. We will inspect the sum over  $k_j$  in Equation (7) depending upon the order that  $P$  divides  $M$  to. We break this into three cases:

(i)  $P$  does not divide  $M$ : Suppose  $(M, P) = 1$ . Then  $M^{(P)} = M$  so that

$$\left(\frac{M^{(P)}}{P^{k_j}}\right) = \chi_{M^{(P)}}(P^{k_j}) = \chi_M(P^{k_j}) = \chi_{M_0}(P^{k_j}).$$

Moreover, from the definition of  $M$  we see that  $P$  is relatively prime to  $m_i$  provided  $i \sim j$ . Therefore  $\beta_i = 0$  for such  $i$ . But then  $H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r}) = a(\beta_1, \dots, k_j, \dots, \beta_r; |P|) = 1$  since  $\beta_i = 0$  if  $i \sim j$ . The sum over  $k_j$  reduces to

$$\sum_{k_j \geq 0} \frac{(\psi_j \chi_{M_0})(P^{k_j})}{|P^{k_j}|^{s_j}} = (1 - (\psi_j \chi_{M_0})(P)|P|^{-s_j})^{-1},$$

which is the local factor of  $L(s_j, \psi_j \chi_{M_0})$  at  $P$ .

(ii)  $P$  divides  $M$  to odd order: Suppose  $P^{2\alpha+1} \parallel M$  for some  $\alpha \geq 1$ . Noticing that  $\left(\frac{M^{(P)}}{P^{k_j}}\right) = \chi_{M^{(P)}}(P^{k_j})$ , define

$$Q_{P^{2\alpha+1}}(s_j; \psi_j \chi_{M^{(P)}}) = \sum_{k_j \geq 0} \frac{(\psi_j \chi_{M^{(P)}})(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}}.$$

Then  $Q_{P^{2\alpha+1}}(s_j; \psi_j \chi_{M^{(P)}})$  is the sum over  $k_j$ . Now apply statement (ii) of Proposition 3.2 with  $x_j = (\psi_j \chi_{M^{(P)}})(P)|P|^{-s_j}$  and use the fact  $((\psi_j \chi_{M^{(P)}})(P))^2 = 1$  to produce the functional equation

$$Q_{P^{2\alpha+1}}(s_j; \psi_j \chi_{M^{(P)}}) = |P|^{\alpha(1-2s_j)} Q_{P^{2\alpha+1}}(1-s_j; \psi_j \chi_{M^{(P)}}).$$

(iii)  $P$  divides  $M$  to even order: Suppose  $P^{2\alpha} \parallel M$  for some  $\alpha \geq 1$ . Then  $\chi_{M^{(P)}}(P^{k_j}) = \chi_{M_0}(P^{k_j})$  which implies  $\left(\frac{M^{(P)}}{P^{k_j}}\right) = \chi_{M_0}(P^{k_j})$ . Now define

$$Q_{P^{2\alpha}}(s_j; \psi_j \chi_{M_0}) = (1 - (\psi_j \chi_{M_0})(P)|P|^{-s_j}) \sum_{k_j \geq 0} \frac{(\psi_j \chi_{M_0})(P^{k_j}) H(P^{\beta_1}, \dots, P^{k_j}, \dots, P^{\beta_r})}{|P^{k_j}|^{s_j}}.$$

Then  $(1 - (\psi_j \chi_{M_0})(P)|P|^{-s_j})^{-1} Q_{P^{2\alpha}}(s_j; \psi_j \chi_{M_0})$  is the sum over  $k_j$ . Using statement (i) of Proposition 3.2 with  $x_j = (\psi_j \chi_{M^{(P)}})(P)|P|^{-s_j}$  again and using the fact  $((\psi_j \chi_{M^{(P)}})(P))^2 = 1$  yields the functional equation

$$Q_{P^{2\alpha}}(s_j; \psi_j \chi_{M_0}) = |P|^{\alpha(1-2s_j)} Q_{P^{2\alpha}}(1-s_j; \psi_j \chi_{M_0}).$$

Upon setting

$$Q_M(s_j; \psi_j) = \prod_{P^\alpha \parallel M_1} Q_{P^{2\alpha+1}}(s_j; \psi_j \chi_{M^{(P)}}) \cdot \prod_{P^\alpha \parallel M_2} Q_{P^{2\alpha}}(s_j; \psi_j \chi_{M_0}),$$

cases (ii) and (iii) combine to give the functional equation

$$Q_M(s_j; \psi_j) = |M_1 M_2|^{1-2s} Q_M(1-s_j; \psi_j).$$

This function equation implies that  $Q_M(s_j; \psi_j)$  is a Dirichlet polynomial (and hence  $Q_{P^{2\alpha+1}}(s_j)$  and  $Q_{P^{2\alpha}}(s_j)$  are as well). Actually, from the functional equation, the highest power of  $|P|^{-s_j}$  appearing  $Q_M(s_j; \psi_j)$  is at most  $2\alpha$  if  $P^\alpha \parallel M_1 M_2$ .  $Q_M(s_j; \psi_j)$  also satisfies a polynomial bound. If  $\text{Re}(s_j) > c_2$ , then statement (iii) of Proposition 3.2 and the definition of  $Q_M(s_j; \psi_j)$  together imply

$$|Q_M(s_j; \psi_j)| \ll c_1^{\omega(N_j)} |N_j|^{c_2},$$

where  $\omega(N_j)$  is the number of prime divisors of  $N_j$ . This implies the simplified estimate

$$|Q_M(s_j; \psi_j)| \ll |N_j|^{c_3},$$

for some  $c_3 > 0$ . Combining our three cases with Equation (7) results in

$$\sum_{m_j \text{ monic}} \frac{\psi_j(m_j)H(m_1, \dots, m_r)}{|m_j|^{s_j}} = \varepsilon_j(\widehat{m})L(s_j, \psi_j\chi_{M_0})Q_M(s_j; \psi_j), \quad (8)$$

which is a product of an  $L$ -function and a Dirichlet polynomial, up to a constant, as desired. We collect this work into two theorems. First, the Dirichlet polynomial:

**Theorem 5.1.** *Fix an index  $1 \leq j \leq r$  and an  $(r-1)$ -tuple of monics  $\widehat{m} = (m_1, \dots, m_{j-1}, m_{j+1}, \dots, m_r)$ . Set  $M = \prod_{i \sim j} m_i$  and let  $M = M_0 M_1^2 M_2^2$  be the square decomposition of  $M$  stratified into even and odd powers. Also set  $N_j = m_1 \cdots m_{j-1} m_{j+1} \cdots m_r$ . Then  $Q_M(s_j; \psi_j)$  is a Dirichlet polynomial supported on the prime dividing  $M$  to order larger than 1. It admits an Euler product*

$$Q_M(s_j; \psi_j) = \prod_{P^\alpha \parallel M_1} Q_{P^{2\alpha+1}}(s_j; \psi_j\chi_{M^{(P)}}) \cdot \prod_{P^\alpha \parallel M_2} Q_{P^{2\alpha}}(s_j; \psi_j\chi_{M_0}),$$

and satisfies a functional equation

$$Q_M(s_j; \psi_j) = |M_1 M_2|^{1-2s} Q_M(1-s_j; \psi_j).$$

Moreover, for  $\text{Re}(s_j) > c_2$ ,  $Q_M(s_j; \psi_j)$  satisfies the bound

$$|Q_M(s_j; \psi_j)| < |N_j|^{c_3},$$

for some  $c_3 > 0$ .

The Dirichlet polynomial  $Q_M(s_j; \psi_j)$  given in Theorem 5.1 is called a **correction polynomial**. It is the factor that  $L(s_j, \psi_j\chi_{M_0})$  is multiplied by, when  $M$  is not square-free, to allow the global Weyl group multiple Dirichlet series to admit functional equations. Our second theorem, is a decomposition of the subseries over  $s_j$  in terms of correction polynomials:

**Theorem 5.2.** *Fix an index  $1 \leq j \leq r$  and an  $(r-1)$ -tuple of monics  $\widehat{m} = (m_1, \dots, m_{j-1}, m_{j+1}, \dots, m_r)$ . Set  $M = \prod_{i \sim j} m_i$  and let  $M = M_0 M_1^2 M_2^2$  be the square decomposition of  $M$  stratified into even and odd powers. Then the subseries of  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  over  $s_j$  corresponding to  $\widehat{m}$  admits the decomposition*

$$\sum_{m_j \text{ monic}} \frac{\psi_j(m_j)H(m_1, \dots, m_r)}{|m_j|^{s_j}} = \varepsilon_j(\widehat{m})L(s_j, \psi_j\chi_{M_0})Q_M(s_j; \psi_j),$$

where  $\varepsilon_j(\widehat{m}) = \pm 1$ .

As a consequence of Theorem 5.2, we immediately get the following representations of  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  for every  $1 \leq j \leq r$ :

$$Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r) = \sum_{\widehat{m} \text{ monic}} \frac{\prod_{i \neq j} \psi_i(m_i)}{\prod_{i \neq j} |m_i|^{s_i}} \varepsilon_j(\widehat{m})L(s_j, \psi_j\chi_{M_0})Q_M(s_j; \psi_j). \quad (9)$$

We refer to Equation (9) as **the interchange** for  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$ .

## 6. FUNCTIONAL EQUATIONS

We can now prove functional equations for  $Z(s_1, \dots, s_r)$ . For  $\mathbf{s} = (s_1, \dots, s_r)$ , it will be convenient to set

$$Z_{\psi_1, \dots, \psi_r}(\mathbf{s}) = Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r),$$

so, in particular,  $Z(\mathbf{s}) = Z(s_1, \dots, s_r)$ . One can actually prove functional equations for all of the twisted Weyl group multiple Dirichlet series  $Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  but we will not need this level of generality. So we assume  $\psi_1 = \cdots = \psi_r = \chi_1$  is the trivial character. We will also write  $Q_M(s_j) = Q_M(s_j; \chi_1)$ . Letting



$x_i = q^{-s_i}$  for  $1 \leq i \leq r$ , the  $W$ -action on  $\mathbf{s} = (s_1, \dots, s_r)$  is easily checked to be given component-wise on simple reflections by

$$(\sigma_i \mathbf{s})_j = \begin{cases} s_i + s_j - \frac{1}{2} & \text{if } i \sim j, \\ 1 - s_j & \text{if } i = j, \\ s_j & \text{otherwise.} \end{cases}$$

We will deduce a functional equation of shape  $\mathbf{s} \rightarrow \sigma_j \mathbf{s}$  for every  $1 \leq j \leq r$ . In accordance with Theorem 5.2, define

$$L(s_j, \chi_M; \widehat{m}) = \sum_{m_j \text{ monic}} \frac{H(m_1, \dots, m_r)}{|m_j|^{s_j}} = \varepsilon_j(\widehat{m}) L(s_j, \chi_{M_0}) Q_M(s_j).$$

Since  $Q_M(s_j)$  is a Dirichlet polynomial it admits analytic continuation to  $\mathbb{C}$ . This implies  $L(s_j, \chi_M; \widehat{m})$  admits meromorphic continuation to  $\mathbb{C}$  with a simple pole at  $s = 1$  if and only if  $\chi_{M_0}$  is the trivial character. That is, if and only if  $M$  is a perfect square. Now  $L(s_j, \chi_{M_0})$  satisfies a functional equation and by Theorem 5.1 we know that  $Q_M(s_j)$  does as well. We can combine these functional equations to deduce a functional equation for  $L(s_j, \chi_M; \widehat{m})$ . Define the completed  $L$ -function

$$L(s_j, \chi_M; \widehat{m}) = \varepsilon_j(\widehat{m}) L^*(s_j, \chi_{M_0}) Q_M(s_j).$$

Then we have the functional equation

$$L^*(s_j, \chi_M; \widehat{m}) = \begin{cases} q^{2s_j-1} |M|^{\frac{1}{2}-s_j} L^*(1-s_j, \chi_M; \widehat{m}) & \text{if } \deg(M) \text{ is even,} \\ q^{s_j-\frac{1}{2}} |M|^{\frac{1}{2}-s_j} L^*(1-s_j, \chi_M; \widehat{m}) & \text{if } \deg(M) \text{ is odd.} \end{cases}$$

At last, we can obtain a functional equation for  $Z(s_1, \dots, s_r)$ . By Theorem 5.2 we know

$$Z(s_1, \dots, s_r) = \sum_{\widehat{m} \text{ monic}} \frac{L(s_j, \chi_M; \widehat{m})}{\prod_{i \neq j} |m_i|^{s_i}}.$$

Now define

$$Z_j^\pm(s_1, \dots, s_r) = \frac{Z(s_1, \dots, s_r) \pm Z_\psi(s_1, \dots, s_r)}{2},$$

where  $Z_\psi(s_1, \dots, s_r) = Z_{\psi_1, \dots, \psi_r}(s_1, \dots, s_r)$  is such that  $\psi_i = \psi$  if  $i \sim j$  and  $\psi_i = \chi_1$  otherwise (we are slightly abusing notation with the even and odd parts of  $f \in \mathbb{C}(\mathbf{x}, u)$  with respect to  $\varepsilon_i$  given in the description of the Chinta-Gunnells action). By the construction of  $Z_\psi(s_1, \dots, s_r)$ , we have

$$Z_j^+(s_1, \dots, s_r) = \sum_{\substack{\widehat{m} \text{ monic} \\ M \text{ even}}} \frac{L(s_j, \chi_M; \widehat{m})}{\prod_{i \neq j} |m_i|^{s_i}} \quad \text{and} \quad Z_j^-(s_1, \dots, s_r) = \sum_{\substack{\widehat{m} \text{ monic} \\ M \text{ odd}}} \frac{L(s_j, \chi_M; \widehat{m})}{\prod_{i \neq j} |m_i|^{s_i}},$$

are the subsums of  $Z(s_1, \dots, s_r)$  whose functional equations for  $L(s_j, \chi_M; \widehat{m})$  have a fixed gamma factor. The subsums  $Z_j^+(s_1, \dots, s_r)$  and  $Z_j^-(s_1, \dots, s_r)$  admit functional equations, and as  $Z(s_1, \dots, s_r)$  is a linear combination of these two series, we obtain a functional equation for  $Z(s_1, \dots, s_r)$ :

**Theorem 6.1.** *Fix some  $1 \leq j \leq r$ . Then  $Z(\mathbf{s})$  admits the functional equation*

$$Z(\mathbf{s}) = \frac{1}{2} \left( \frac{q^{2s_j-1}(1-q^{-s_j})}{1-q^{s_j-1}} \right) Z(\sigma_j \mathbf{s}) + \frac{1}{2} \left( \frac{q^{2s_j-1}(1-q^{-s_j})}{1-q^{s_j-1}} \right) Z_\psi(\sigma_j \mathbf{s}).$$

*Proof.* The functional equation for  $L^*(s_j, \chi_M; \widehat{m})$  implies the functional equations

$$Z_j^+(\mathbf{s}) = \frac{q^{2s_j-1}(1-q^{-s_j})}{1-q^{s_j-1}} Z_j^+(\sigma_j \mathbf{s}) \quad \text{and} \quad Z_j^-(\mathbf{s}) = q^{2s_j-1} Z_j^-(\sigma_j \mathbf{s}).$$

As  $Z(\mathbf{s}) = Z_j^+(\mathbf{s}) + Z_j^-(\mathbf{s})$ , the functional equations just stated give

$$Z(\mathbf{s}) = \frac{q^{2s_j-1}(1-q^{-s_j})}{1-q^{s_j-1}} Z_j^+(\sigma_j \mathbf{s}) + q^{2s_j-1} Z_j^-(\sigma_j \mathbf{s}).$$

The desired functional equation for  $Z(\mathbf{s})$  follows by expressing  $Z_j^+(\mathbf{s})$  and  $Z_j^-(\mathbf{s})$  in terms of  $Z(\mathbf{s})$  and  $Z_\psi(\mathbf{s})$ .  $\square$

Theorem 6.1 says that  $Z(\mathbf{s})$  admits a functional equation for each simple reflection  $\sigma_j$ . But since the action of these simple reflections is a  $W$ -action on  $\mathbb{C}^r(\mathbf{s}; u)$  (where  $x_i = q^{-s_i}$ ), it follows immediately that  $Z(\mathbf{s})$  posses a group of functional equations isomorphic to  $W$ .

## 7. MEROMORPHIC CONTINUATION

In order to meromorphically continue  $Z(\mathbf{s})$  to  $\mathbb{C}^r$ , we will use Bochner's theorem. To state this theorem we only require a small definition. We say that a domain  $\Omega \subset \mathbb{C}^r$  is a **tube domain** if there is an open set  $\omega \subset \mathbb{R}^r$  such that

$$\Omega = \{\mathbf{s} \in \mathbb{C}^r : \operatorname{Re}(\mathbf{s}) \in \omega\}.$$

Now we can state Bochner's theorem (see [3] for a proof):

**Theorem 7.1** (Bochner's continuation theorem). *If  $\Omega$  is a connected tube domain, then any holomorphic function on  $\Omega$  can be extended to a holomorphic function on the convex hull  $\widehat{\Omega}$ .*

By clearing polar divisors, Bochner's continuation theorem implies that any meromorphic function on a connected tube domain possessing a finite amount of hyperplane polar divisors can be extended to a meromorphic function on the convex hull. This is the situation for  $Z(\mathbf{s})$ , but first we need to enlarge the region  $Z(\mathbf{s})$  is defined on. This is achieved by the Phragmén-Lindelöf convexity principal. Choose  $s_j$  such that  $\operatorname{Re}(s_j) > -c_2$ . The functional equation for  $L^*(s_j, \chi_M; \widehat{m})$  and Theorem 5.1 together imply the estimate

$$L(-\varepsilon, \chi_M; \widehat{m}) \ll |M|^{2c_2+1} |N_j|^{c_3}.$$

As this  $L$ -function has at most a simple pole at  $s_j = 1$ , the Phragmén-Lindelöf convexity principal implies the weak estimate

$$(s_j - 1)L(-\varepsilon, \chi_M; \widehat{m}) \ll |M|^{2c_2+1} |N_j|^{c_3},$$

for  $\operatorname{Re}(s_j) > -c_2$ . Using the interchange it follows that

$$\left( \prod_{1 \leq j \leq r} (s_j - 1) \right) Z(s_1, \dots, s_r),$$

is locally absolutely uniformly convergent on the region

$$\Lambda_0 = \Lambda \cup \bigcup_{1 \leq j \leq r} \{(s_1, \dots, s_r) : \operatorname{Re}(s_j) > -c_2, \operatorname{Re}(s_i) > 2c_2 + c_3 + 2 \text{ for } i \neq j\}.$$

Technically we only need  $\operatorname{Re}(s_i) > 2c_2 + c_3 + 2$  if  $i \sim j$  and  $\operatorname{Re}(s_i) > 1 + c_3$  otherwise. But this is unimportant since  $\Lambda_0$  is a sufficiently large region. Indeed,  $\Lambda_0$  is a connected tube domain and

$$\Lambda_W = \bigcup_{w \in W} w\Lambda_0,$$

is also a connected tube domain that is all of  $\mathbb{C}^r$  except for a compact subset about the origin. By Theorem 6.1, the possible polar divisors of  $Z(\mathbf{s})$  belong to the set

$$\{(w\mathbf{s})_j - 1 = 0 : w \in W, 1 \leq j \leq r\},$$

which is finite since  $W$  is finite. Therefore by Bochner's continuation theorem,  $Z(\mathbf{s})$  admits meromorphic continuation to  $\mathbb{C}^r$ . We collect this work as a theorem:

**Theorem 7.2.**  *$Z(\mathbf{s})$  admits meromorphic continuation to  $\mathbb{C}^r$  with possible polar divisors belonging to the set*

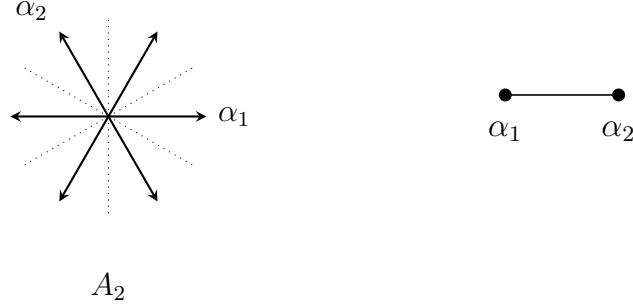
$$\{(w\mathbf{s})_j - 1 = 0 : w \in W, 1 \leq j \leq r\}.$$

8. A WORKED EXAMPLE FOR  $A_2$ 

We will fully work out the Chinta-Gunnells average for the root system of type  $A_2$ . Let  $\Delta = \{\alpha_1, \alpha_2\}$  be a base. Then

$$\Phi = \{\pm\alpha_1, \pm\alpha_2, \pm(\alpha_1 + \alpha_2)\} \quad \text{and} \quad W = \langle \sigma_1, \sigma_2 : \sigma_1^2 = \sigma_2^2 = 1, \sigma_1\sigma_2\sigma_1 = \sigma_2\sigma_1\sigma_2 \rangle.$$

As a set is  $W = \{1, \sigma_1, \sigma_2, \sigma_1\sigma_2, \sigma_2\sigma_1, \sigma_0\}$  where  $\sigma_0 = \sigma_1\sigma_2\sigma_1 = \sigma_2\sigma_1\sigma_2$  is the longest element. The root system and its Dynkin diagram are displayed below:



The Chinta-Gunnells action on  $\mathbb{C}(x_1, x_2, u)$  gives rise to the following six terms:

$$\begin{aligned} (1|^{CG}1)(x_1, x_2; u) &= 1, \\ (1|^{CG}\sigma_1)(x_1, x_2) &= -\frac{1 - ux_1}{ux_1(1 - x_1)}, \\ (1|^{CG}\sigma_2)(x_1, x_2; u) &= -\frac{1 - ux_2}{ux_2(1 - x_2)}, \\ (1|^{CG}\sigma_1\sigma_2)(x_1, x_2; u) &= -\frac{u^2x_1^2x_2^3 + ux_1x_2^2(1 - u - ux_1) + x_2(ux_1 - x_1 - 1) + 1}{u^2x_1x_2^2(1 - x_2)(1 - ux_1^2x_2^2)}, \\ (1|^{CG}\sigma_2\sigma_1)(x_1, x_2; u) &= -\frac{u^2x_1^3x_2^2 + ux_1^2x_2(1 - u - ux_2) + x_1(ux_2 - x_2 - 1) + 1}{u^2x_1^2x_2(1 - x_1)(1 - ux_1^2x_2^2)}, \\ (1|^{CG}\sigma_0)(x_1, x_2; u) &= -\frac{u^3x_1^2x_2^2(1 - x_1x_2) + u^2x_1^2x_2^2(x_1 + x_2 - 2) + u(2x_1x_2 - x_1 - x_2) - x_1x_2 + 1}{u^3x_1^2x_2^2(1 - x_1)(1 - x_2)(1 - ux_1^2x_2^2)}. \end{aligned}$$

The associated  $j(\sigma, x_1, x_2)$  factors are

$$\begin{aligned} j(1, x_1, x_2) &= 1, \\ j(\sigma_1, x_1, x_2) &= -ux_1^2, \\ j(\sigma_2, x_1, x_2) &= -ux_2^2, \\ j(\sigma_1\sigma_2, x_1, x_2) &= u^3x_1^2x_2^4, \\ j(\sigma_2\sigma_1, x_1, x_2) &= u^3x_1^4x_2^2, \\ j(\sigma_0, x_1, x_2) &= -u^4x_1^4x_2^4. \end{aligned}$$

One can then compute

$$Z_W(x_1, x_2; u) = \frac{(1 - x_1x_2)(1 - ux_1^2)(1 - ux_2^2)(1 - u^2x_1^2x_2^2)}{(1 - x_1)(1 - x_2)(1 - ux_1^2x_2^2)},$$

and so

$$Z_\Phi(x_1, x_2; u) = \frac{1 - x_1x_2}{(1 - x_1)(1 - x_2)(1 - ux_1^2x_2^2)}.$$

Notice that

$$Z_{\Phi}(q^{1-s_1}, q^{1-s_2}; q^{-1}) = \frac{1 - q^{2-s_1-s_2}}{(1 - q^{1-s_1})(1 - q^{1-s_2})(1 - q^{3-2s_1-2s_2})},$$

is the global  $A_2$  multiple Dirichlet series  $Z(s_1, s_2)$ .

#### REFERENCES

- [1] Gautam Chinta, Solomon Friedberg, and Paul E. Gunnells. On the p-parts of quadratic weyl group multiple dirichlet series. *Journal für die reine und angewandte Mathematik*, 2008(623):1–23, 2008.
- [2] Gautam Chinta and Paul E. Gunnells. Weyl group multiple dirichlet series constructed from quadratic characters. *Inventiones mathematicae*, 167(2):327–353, 2007.
- [3] Lars Hörmander. *An introduction to complex analysis in several variables*. Number 7 in North-Holland mathematical library. North-Holland, 3., rev. ed., 3. impr edition, 2000.
- [4] Michael I. Rosen. *Number theory in function fields*. Number 210 in Graduate texts in mathematics. Springer, 2002.