

# Pacific Journal of Mathematics

**THE CLASS NUMBER OF  $\mathcal{O}(\sqrt{-p})$  MODULO 4, FOR  $p \equiv 3 \pmod{4}$  A PRIME**

KENNETH S. WILLIAMS

THE CLASS NUMBER OF  $Q(\sqrt{-p})$  MODULO 4,  
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**If  $p$  is a prime congruent to 3 modulo 4, it is well-known that the class number  $h(-p)$  of the imaginary quadratic field  $Q(\sqrt{-p})$  is odd. In this paper we determine  $h(-p)$  modulo 4.**

The class number of  $Q(\sqrt{-p})$  is odd, if  $p$  is a prime congruent to 3 modulo 4 (see for example [3: p. 413]. D.H. Lehmer [4: p. 9] has posed the problem of determining the Jacobi symbol  $(-1/h(-p)) = (-1)^{h(-p)-1}/2$ , that is, of determining  $h(-p)$  modulo 4. In this paper we evaluate  $h(-p)$  modulo 4 in terms of the class number  $h(p)$  and the fundamental unit  $\epsilon_p = T + U\sqrt{p}$  of the corresponding real quadratic field  $Q(\sqrt{p})$ . It is known that  $T$  and  $U$  are positive integers which satisfy  $T \equiv 0 \pmod{2}$ ,  $U \equiv 1 \pmod{2}$ ,  $N(\epsilon_p) = T^2 - pU^2 = +1$ . We prove

**THEOREM.** *If  $p > 3$  is a prime congruent to 3 modulo 4 then*

$$(1) \quad h(-p) \equiv h(p) + U + 1 \pmod{4}.$$

It is easily checked that (1) does not hold for  $p = 3$  ( $h(-3) = h(3) = U = 1$ ). ( $p = 3$  is a special case as this is the only value of  $p \equiv 3 \pmod{4}$  for which the ring of integers of  $Q(\sqrt{-p})$  has more than 2 units.) The method of proof is purely analytic in nature, it uses Dirichlet's class number formula (in various forms) for both real and imaginary quadratic fields and also some results from cyclotomy. It would be of interest to give a purely algebraic proof.

*Proof.* Let  $p > 3$  be a prime congruent to 3 modulo 4 and set  $\rho = \exp(2\pi i/p)$ . For  $z$  a complex variable, we let

$$(2) \quad F_+(z) = \prod_{\substack{j=1 \\ (j/p) = +1}}^{p-1} (z - \rho^j), \quad F_-(z) = \prod_{\substack{j=1 \\ (j/p) = -1}}^{p-1} (z - \rho^j),$$

so that

$$(3) \quad F_+(z)F_-(z) = F(z),$$

where  $F(z)$  is the cyclotomic polynomial of index  $p$ , that is,

$$(4) \quad F(z) = \prod_{j=1}^{p-1} (z - \rho^j) = \frac{z^p - 1}{z - 1} = z^{p-1} + z^{p-2} + \cdots + z + 1.$$

$F_+$  and  $F_-$  are polynomials in  $z$  of degree  $(p-1)/2$  with coefficients in the ring of integers of  $\mathbb{Q}(\sqrt{-p})$  (see for example [6: p.215]). Hence we can write

$$(5) \quad F_+(z) = \frac{1}{2} (Y(z) - Z(z)\sqrt{-p}), \quad F_-(z) = \frac{1}{2} (Y(z) + Z(z)\sqrt{-p}),$$

where  $Y$  and  $Z$  are polynomials with rational integral coefficients. From (3) and (5) we have

$$(6) \quad Y(z)^2 + pZ(z)^2 = 4F(z).$$

It is also known [6: p.216] or [7: p.209] that  $Y$  and  $Z$  have the symmetry properties expressed by

$$(7) \quad Y(z) = \sum_{n=0}^{(p-3)/4} a_n (z^{(p-1)/2-n} - z^n), \quad Z(z) = \sum_{n=0}^{(p-3)/4} b_n (z^{(p-1)/2-n} + z^n),$$

where the  $a_n$  and  $b_n$  are integers with

$$a_0 = 2, a_1 = 1, a_2 = (3-p)/4, \dots$$

and

$$b_0 = 0, b_1 = 1, b_2 = \frac{1}{2} \left( 1 + \left( \frac{2}{p} \right) \right), \dots$$

(see [7] for further values of  $a_n$  and  $b_n$ : see [6] for a table of values of  $Y$  and  $Z$  for  $p \leq 29$ ).

Differentiating the expressions in (7) and (6) with respect to  $z$ , we obtain respectively

$$(8) \quad Y'(z) = \sum_{n=0}^{(p-3)/4} a_n \left( \left( \frac{p-1}{2} - n \right) z^{(p-3)/2-n} - n z^{n-1} \right),$$

$$Z'(z) = \sum_{n=0}^{(p-3)/4} b_n \left( \left( \frac{p-1}{2} - n \right) z^{(p-3)/2-n} + n z^{n-1} \right),$$

and

$$(9) \quad Y(z)Y'(z) + pZ(z)Z'(z) = 2F'(z).$$

Taking  $z = i$  in (7) and (8) we obtain

$$(10) \quad Y(i) = \begin{cases} A_3(1-i), & \text{if } p \equiv 3 \pmod{8}, \\ A_7(1+i), & \text{if } p \equiv 7 \pmod{8}, \end{cases}$$

$$Z(i) = \begin{cases} -B_3(1+i), & \text{if } p \equiv 3 \pmod{8}, \\ B_7(1-i), & \text{if } p \equiv 7 \pmod{8}, \end{cases}$$

and

$$(11) \quad \begin{aligned} Y'(i) &= \begin{cases} C_3 + 2D_3i, & \text{if } p \equiv 3 \pmod{8}, \\ C_7 + 2D_7i, & \text{if } p \equiv 7 \pmod{8}, \end{cases} \\ Z'(i) &= \begin{cases} E_3 + 2F_3i, & \text{if } p \equiv 3 \pmod{8}, \\ E_7 + 2F_7i, & \text{if } p \equiv 7 \pmod{8}, \end{cases} \end{aligned}$$

where  $A_3, \dots, F_7$  are rational integers (given in terms of the  $a_n$  and  $b_n$ ). Using (10) and (11) in (6) and (9) with  $z = i$ , we obtain

$$(12) \quad \begin{cases} A_3^2 - pB_3^2 = -2, & \text{if } p \equiv 3 \pmod{8}, \\ A_7^2 - pB_7^2 = +2, & \text{if } p \equiv 7 \pmod{8}, \end{cases}$$

and

$$(13) \quad \begin{cases} A_3C_3 + 2pB_3F_3 = -1, & 2A_3D_3 - pB_3E_3 = p, & \text{if } p \equiv 3 \pmod{8}, \\ A_7C_7 + 2pB_7F_7 = p, & 2A_7D_7 - pB_7E_7 = 1, & \text{if } p \equiv 7 \pmod{8}. \end{cases}$$

Clearly from (12) and (13) we see that  $A_3, B_3, C_3, E_3, A_7, B_7, C_7$  and  $E_7$  are all odd. Now Liouville [5: p. 415] has shown that

$$(14) \quad Z(z)Y'(z) - Z'(z)Y(z) = \frac{2}{z-1} \sum_{j=1}^{p-1} \left(\frac{j}{p}\right) z^{p-1-j}.$$

Taking  $z = i$  in (14) we obtain

$$(15) \quad Z(i)Y'(i) - Z'(i)Y(i) = (L + M) + i(L - M),$$

where

$$L = \sum_{j=0}^{(p-1)/2} (-1)^j \left(\frac{2j}{p}\right), \quad M = \sum_{j=0}^{(p-1)/2} (-1)^j \left(\frac{2j+1}{p}\right).$$

Applying the transformation  $j \rightarrow (p-1)/2 - j$  to  $L$  or  $M$  we obtain  $L = M$ . Also we have

$$\begin{aligned} L &= \sum_{j=1}^{(p-3)/4} \left(\frac{4j}{p}\right) - \sum_{j=0}^{(p-3)/4} \left(\frac{4j+2}{p}\right) \\ &= \sum_{j=1}^{(p-3)/4} \left(\frac{j}{p}\right) - \sum_{j=(p+1)/4}^{(p-1)/2} \left(\frac{4((p-1)/2 - j) + 2}{p}\right) \\ &= \sum_{j=1}^{(p-3)/4} \left(\frac{j}{p}\right) + \sum_{j=(p+1)/4}^{(p-1)/2} \left(\frac{j}{p}\right) = \sum_{j=1}^{(p-1)/2} \left(\frac{j}{p}\right), \end{aligned}$$

so, by Dirichlet's class number formula (as  $p \equiv 3 \pmod{4}$ ,  $p < 3$ ) see for example [2: p. 346], we have

$$(16) \quad L = M = \left\{2 - \left(\frac{2}{p}\right)\right\} h(-p).$$

Hence from (15) and (16) we have

$$(17) \quad Z(i)Y'(i) - Z'(i)Y(i) = 2 \left\{ 2 - \left( \frac{2}{p} \right) \right\} h(-p).$$

Using (10) and (11) in (17), after equating real and imaginary parts, we obtain

$$(18) \quad \begin{cases} 3h(-p) = 2B_3D_3 - A_3E_3, & \text{if } p \equiv 3 \pmod{8}, \\ h(-p) = 2B_7D_7 - A_7E_7, & \text{if } p \equiv 7 \pmod{8}. \end{cases}$$

Now from (13) we have

$$(19) \quad \begin{cases} E_3 \equiv -2A_3B_3D_3 - B_3 \pmod{8}, & \text{if } p \equiv 3 \pmod{8}, \\ E_7 \equiv -2A_7B_7D_7 + B_7 \pmod{8}, & \text{if } p \equiv 7 \pmod{8}. \end{cases}$$

Using (19) in (18) we have

$$(20) \quad h(-p) \equiv \begin{cases} -A_3B_3 \pmod{4}, & \text{if } p \equiv 3 \pmod{8}, \\ -A_7B_7 \pmod{4}, & \text{if } p \equiv 7 \pmod{8}. \end{cases}$$

From (4) we have  $F(i) = i$ , and so taking  $z = i$  in (2) and (3) we obtain

$$\begin{aligned} -i\{F_-(i)\}^2 &= \frac{F_-(i)}{F_+(i)} = \prod_{j=1}^{p-1} (1 + i\rho^j)^{-(j/p)} \\ &= \exp \left( -\sum_{j=1}^{p-1} \left( \frac{j}{p} \right) \log(1 + i\rho^j) \right) \\ &= \exp \left( \sum_{n=1}^{\infty} \frac{(-i)^n}{n} \sum_{j=1}^{p-1} \left( \frac{j}{p} \right) \rho^{nj} \right) \\ &= \exp \left( i\sqrt{p} \sum_{n=1}^{\infty} \left( \frac{n}{p} \right) \frac{(-i)^n}{n} \right) \\ &= \exp \left( \sqrt{p} \sum_{m=0}^{\infty} \left( \frac{2m+1}{p} \right) \frac{(-1)^m}{2m+1} + \frac{i\sqrt{p}}{2} \left( \frac{2}{p} \right) \sum_{m=1}^{\infty} \left( \frac{m}{p} \right) \frac{(-1)^m}{m} \right) \\ &= \exp \left( h(p) \log(T + U\sqrt{p}) + \frac{\pi i}{2} \left( 1 - \left( \frac{2}{p} \right) \right) h(-p) \right) \\ &= (T + U\sqrt{p})^{h(p)} i^{(1-(2/p))h(-p)} \\ &= (-1)^{(p+1)/4} (T + U\sqrt{p})^{h(p)}, \end{aligned}$$

where we have made use of the Gauss sum

$$\sum_{j=1}^{p-1} \left( \frac{j}{p} \right) \rho^{nj} = \left( \frac{n}{p} \right) i\sqrt{p},$$

and the two results

$$\sum_{m=1}^{\infty} \binom{m}{p} \frac{(-1)^m}{m} = \frac{\pi}{\sqrt{p}} \left( \left( \frac{2}{p} \right) - 1 \right) h(-p)$$

and

$$\sum_{m=0}^{\infty} \binom{2m+1}{p} \frac{(-1)^m}{2m+1} = \frac{h(p)}{\sqrt{p}} \log(T + U\sqrt{p}),$$

which follow easily by standard arguments from Dirichlet's class number formula (see for example [2: p. 343]). Hence we have (using (10))

$$\begin{aligned} (T + U\sqrt{p})^{h(p)} &= (-1)^{(p-3)/4} i F_-(i)^2 \\ &= (-1)^{(p-3)/4} i \left\{ \frac{1}{2} (Y(i) + Z(i)i\sqrt{p}) \right\}^2 \\ &= \begin{cases} \frac{1}{2} (A_3 + B_3\sqrt{p})^2, & \text{if } p \equiv 3 \pmod{8}, \\ \frac{1}{2} (A_7 + B_7\sqrt{p})^2, & \text{if } p \equiv 7 \pmod{8}. \end{cases} \end{aligned}$$

This is essentially a result of Arndt [1].

Expanding  $(T + U\sqrt{p})^{h(p)}$  by the binomial theorem and equating coefficients of  $\sqrt{p}$ , we have as  $h(p) \equiv 1 \pmod{2}$ ,

$$\begin{aligned} U^{h(p)} p^{(h(p)-1)/2} + \binom{h(p)}{2} U^{h(p)-2} T^2 p^{(h(p)-3)/2} + \dots \\ = \begin{cases} A_3 B_3, & \text{if } p \equiv 3 \pmod{8}, \\ A_7 B_7, & \text{if } p \equiv 7 \pmod{8}. \end{cases} \end{aligned}$$

As  $T \equiv 0 \pmod{2}$ ,  $U \equiv 1 \pmod{2}$ , this gives

$$U(-1)^{(h(p)-1)/2} \equiv \begin{cases} A_3 B_3 \pmod{4}, & \text{if } p \equiv 3 \pmod{8}, \\ A_7 B_7 \pmod{4}, & \text{if } p \equiv 7 \pmod{8}, \end{cases}$$

so that

$$(21) \quad h(p) \equiv \begin{cases} A_3 B_3 - U + 1 \pmod{4}, & \text{if } p \equiv 3 \pmod{8}, \\ A_7 B_7 - U + 1 \pmod{4}, & \text{if } p \equiv 7 \pmod{8}. \end{cases}$$

Putting (20) and (21) together, we obtain (1) as required.

From (1) we have  $(-1/h(-p)) = (-1)^{(h(-p)-1)/2} = (-1)^{(h(p)+U)/2}$ . In particular whenever  $h(p) = 1$  (a common occurrence) we have  $(-1/h(-p)) = (-1)^{(U+1)/2}$ .

In [8] the author has treated, in a similar way, Lehmer's question [4: p. 10] regarding  $h(-2p)$  modulo 8, when  $p$  is a prime congruent to 5 modulo 8.

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