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NOTES ON THE CONGRUENCE $y^2 \equiv x^5 - a \pmod p$

by A. R. RAJWADE

1. INTRODUCTION

In a previous paper [3] we proved the following

THEOREM. *Let* $p \equiv 1 \pmod 5$ *be a rational prime and* g *a fixed primitive root* $\bmod p$. *Then the number of solutions of the congruence*

$$(1) \qquad y^2 \equiv x^5 - a \pmod p$$

is $p + \Delta_a$, *where* Δ_a *is equal to* [1)]

$$(2) \qquad \left(\frac{-4a}{\pi_1}\right)_{10} . \pi_3 \pi_4 + \left(\frac{-4a}{\pi_2}\right)_{10} . \pi_1 \pi_3 + \left(\frac{-4a}{\pi_3}\right)_{10} . \pi_2 \pi_4 + \left(\frac{-4a}{\pi_4}\right)_{10} . \pi_1 \pi_2 .$$

Here $p = \pi_1 \pi_2 \pi_3 \pi_4 = \pi_1 . \sigma\pi_1 . \sigma^3 \pi_1 . \sigma^2 \pi_1$, with $\sigma : \zeta \to \zeta^2$, is the decomposition of p in $Q(\zeta)$, $\zeta^5 = 1$, $\zeta \neq 1$ and π_1 is chosen to satisfy $(g/\pi_1)_5 = \zeta$, so that $(g/\pi_i)_5 = \zeta^i$, and the π_j are normalized so that the products $S = \pi_1 \pi_2$, $\bar{S} = \pi_3 \pi_4$, $T = \pi_1 \pi_3$, $\bar{T} = \pi_2 \pi_4$ (all polynomials in ζ) satisfy

$$\begin{aligned} &1. \quad S(\zeta) . S(\zeta^{-1}) \equiv [S(1)]^2 \pmod 5, \\ &2. \quad S(\zeta) \equiv S(1) \pmod{(1-\zeta)^2}, \\ &3. \quad S(1) \equiv 4 \pmod 5. \end{aligned}$$

(and similarly for $\bar{S}$, T, $\bar{T}$).

In (2) the 4 products $\pi_i \pi_j$ are those 4 out of the 6 combinations $\pi_1 \pi_2$, $\pi_1 \pi_3$, $\pi_1 \pi_4$, $\pi_2 \pi_3$, $\pi_2 \pi_4$, $\pi_3 \pi_4$ for which $\bar{\pi}_i \neq \pi_j$. But there is no symmetrical way of coupling the residue symbol $\left(\frac{-4a}{\pi_i}\right)_{10}$ with $\pi_j \pi_k$. We ask: What do other expressions similar to Δ_a represent? For example the expression

1) See Appendix for the definitions of $(\alpha/\beta)_{10}$, $(\alpha/\beta)_5$, $(a/p)_Z$.

$$\left(\frac{-4a}{\pi_1}\right)_{10} . \pi_1 \pi_2 + \left(\frac{-4a}{\pi_2}\right)_{10} . \pi_2 \pi_4 + \left(\frac{-4a}{\pi_3}\right)_{10} . \pi_1 \pi_3 + \left(\frac{-4a}{\pi_4}\right)_{10} . \pi_3 \pi_4$$

being the trace of $(-4a/\pi_1)_{10} . \pi_1 \pi_2$, is a rational integer. What does it represent?

One could also remove the various restrictions on the π_i in the expression for Δ_a and ask what Δ_a then represents. The object of this note is to answer these questions and also to determine the set $\{\Delta_a \mid a = 1, 2, 3, \ldots, p-1\}$.

It is immediate that Δ_a can take only 10 distinct values. This follows by looking at (2) or directly from the congruence (1) as follows: Let $(e, p) = 1$, then we have

$$\Delta_a = \sum \left(\frac{x^5 - a}{p}\right) \text{ and so } \Delta_{ae^5} = (e/p)_{\mathbf{Z}} . \Delta_a .$$

It follows that the distinct values taken by the Δ_a, for $a = 1, 2, \ldots, p-1$ are just $\pm \Delta_g$, $\pm \Delta_{g^2}$, $\pm \Delta_{g^3}$, $\pm \Delta_{g^4}$, $\pm \Delta_{g^5}$. We shall determine these 10 values as a set. Which value is associated with which a will not be clear except when $4a$ is a quintic residue mod p.

2. Determination of Δ_a without the normalization restrictions on the π_j

Write $p = \pi . \pi^{\sigma} . \pi^{\sigma^3} . \pi^{\sigma^2}$ (with $(g/\pi)_5 = \zeta$) $= \pi_1 \pi_2 \pi_3 \pi_4$ say. Since the restrictions on π are going to be removed, we denote Δ_a by $\Delta_a(\pi)$. We write (2) in a more convenient form viz

(3) $$\Delta_a(\pi) =$$

$$\left(\frac{-a}{p}\right)_{\mathbf{Z}} . \left[\left(\frac{4a}{\pi_1}\right)_5 . \pi_1 \pi_3 + \left(\frac{4a}{\pi_2}\right)_5 . \pi_1 \pi_2 + \left(\frac{4a}{\pi_3}\right)_5 . \pi_3 \pi_4 + \left(\frac{4a}{\pi_4}\right)_5 . \pi_2 \pi_4\right].$$

Thus $\Delta_a(\pi) = \mathrm{Tr}\left[(-a/p)_{\mathbf{Z}} (4a/\pi)_5 \, \pi \, \pi^{\sigma^3}\right]$.

Let the condition $(g/\pi)_5 = \zeta$ be retained first so that we only change π to an associate $\eta \pi$ where $\eta = \zeta^i \varepsilon \,(0 \leqslant i \leqslant 4)$ with ε a real fundamental unit, say $\pm \left(\frac{1+\sqrt{5}}{2}\right)^j$, $j \in \mathbf{Z}$, of $Q(\sqrt{5})$. We have the following

THEOREM 1. *$\Delta_a(\zeta^i \varepsilon . \pi) = \Delta_{ab}(\pi)$ where $(b/\pi)_5 = \zeta^{5-i}$ and $(b/p)_{\mathbf{Z}} \neq N_{Q(\sqrt{5})/Q}(\varepsilon)$.*

Proof. Step 1.

$$\begin{aligned} \Delta_a(\zeta\pi) &= \mathrm{Tr}\left[(-a/p)_Z (4a/\zeta\pi)_5 (\zeta\pi)(\zeta\pi)^{\sigma^3}\right] \\ &= \mathrm{Tr}\left[(-a/p)_Z (4a/\pi)_5 \,.\, \zeta^4 \,.\, \pi\pi^{\sigma^3}\right] \\ &= \mathrm{Tr}\left[(-au/p)_Z (4au/\pi)_5 \,.\, \pi\pi^{\sigma^3}\right], \end{aligned}$$

where $(u/p)_Z = 1$, $(u/\pi)_5 = \zeta^4$, and this $= \Delta_{au}(\pi)$. It follows that $\Delta_a(\zeta^i\pi) = \Delta_{au}(\pi)$, where $(u/p)_Z = 1$ and $(u/\pi)_5 = \zeta^{5-i}$ $(i=0, 1, 2, 3, 4)$.

Step 2.

$$\begin{aligned} \Delta_a(\varepsilon\pi) &= \mathrm{Tr}\left[(-a/p)_Z (4a/\varepsilon\pi)_5 \,.\, \varepsilon\pi \,.\, (\varepsilon\pi)^{\sigma^3}\right] \\ &= \mathrm{Tr}\left[(-a/p)_Z (4a/\pi)_5 \,.\, N_{Q(\sqrt{5})/Q}(\varepsilon) \,.\, \pi\pi^{\sigma^3}\right] \\ &= \Delta_{av}(\pi), \end{aligned}$$

where $(v/p)_Z = N_{Q(\sqrt{5})/Q}(\varepsilon)$, $(v/\pi)_5 = 1$.

Combining steps 1 and 2 we get:

$$\begin{aligned} \Delta_a(\zeta^i\varepsilon\pi) &= \Delta_{au}(\varepsilon\pi) \text{ where } (u/p)_Z = 1,\ (u/\pi)_5 = \zeta^{5-i} \\ &= \Delta_{au.v}(\pi) \text{ where } (v/p)_Z = \text{Norm } \varepsilon,\ (v/\pi)_5 = 1, \\ &= \Delta_{ab}(\pi) \text{ where } b = uv \text{ satisfies the conditions of} \end{aligned}$$

theorem 1. This completes the proof of theorem 1.

We next remove the restriction $(g/\pi)_5 = \zeta$ and see what the Δ_a's mean then.

3. The restriction $(g/\pi)_5 = \zeta$ removed

Here we have to look at $\Delta_a(\pi^\sigma)$ (and similarly $\Delta_a(\pi^{\sigma^2})$ and $\Delta_a(\pi^{\sigma^3})$). We have the following

THEOREM 2. $\Delta_a(\pi^\sigma) = \Delta_a(\pi)$.

Proof. $\Delta_a(\pi^\sigma) = \mathrm{Tr}\left[(-a/p)_Z (4a/\pi^\sigma)_5 \,.\, \pi^\sigma \,.\, (\pi^\sigma)^{\sigma^3}\right]$.
Now $(4a/\pi^\sigma)_5 = (4a/\pi_2)_5$, and if $4a \equiv g^\nu \pmod p$ then this $= (g^\nu/\pi_2)_5 = (g/\pi_2)_5^\nu = \zeta^{2\nu} = (g^\nu/\pi_1)_5^2 = (4a/\pi_1)_5^2 = \sigma\left[(4a/\pi)_5\right]$. Hence

$$\begin{aligned} \Delta_a(\pi^\sigma) &= \mathrm{Tr}\left[(-a/p)_Z \,.\, \sigma(4a/\pi)_5 \,.\, \pi \,.\, \pi^{\sigma^3}\right] \\ &= \mathrm{Tr}\left[\sigma\left((-a/p)_Z (4a/\pi)_5 \,.\, \pi\pi^{\sigma^3}\right)\right] \\ &= \Delta_a(\pi) \text{ as required.} \end{aligned}$$

A clearer insight is gained into this by looking at the whole thing directly as follows.

Since the choice of g is arbitrary, we change g to another primitive root g^r with $(r, p-1) = 1$, $r = i \pmod 5$, $i = 1, 2, 3, 4$. This does not alter Δ_a (as Δ_a is independent of g) but replaces π by any desired π_i so that $\Delta_a(\pi) = \Delta_a$ (any other π). Note that such an r exists, for all we want is, for $i = 1, 2, 3, 4$, a λ such that $(i+5\lambda, p-1) = 1$. Now $i + 5\lambda$ takes infinitely many prime values as λ takes positive integer values since $(i, 5) = 1$; so λ may be chosen so that $i + 5\lambda$ is a prime avoiding the primes occuring in $p - 1$.

4. Expressions allied to $\Delta_a(\pi)$

We fix our π now with $(g/\pi)_5 = \zeta$ and normalize it too. It is clear that there are only 3 expressions allied to $\Delta_a(\pi)$ viz $(-a/p)_Z (4a/\pi)_5 \,.\, \pi \,.\, \pi^\sigma$ + conjugates, $(-a/p)_Z (4a/\pi)_5 \,.\, \pi^\sigma \,.\, \pi^{\sigma^2}$ + conjugates and $(-a/p)_Z (4a/\pi)_5 \,.\, \pi^{\sigma^2} \,.\, \pi^{\sigma^3}$ + conjugates. This is so because changing the first term of $\Delta_a(\pi)$ fixes the changes in the other terms (otherwise we will not even get a rational integer!). Let us look at the first of these (the others would be similar), which equals $\mathrm{Tr}\,[(-a/p)_Z (4a/\pi)_5 \,.\, \pi\, \pi^\sigma]$. We have the following theorem:

THEOREM 3. $\mathrm{Tr}\,[(-a/p)_Z (4a/\pi)_5 \,.\, \pi\, \pi^\sigma] = \Delta_{au} - 1\ (\pi)$, *where* $(u/p)_Z = 1$ *and* $(u/\pi)_5 = (4a/\pi)_5$.

Proof. We have

$$\begin{aligned}
\Delta_a(\pi) &= \mathrm{Tr}\,[(-a/p_Z)(4a/\pi)_5 \,.\, \pi \,.\, \pi^{\sigma^3}] \\
&= \mathrm{Tr}\,[(-a/p)_Z (4a/\pi^\sigma)_5 \,.\, \pi^\sigma \,.\, \pi^{\sigma^3}] \text{ by 3 on letting } \pi \to \pi^\sigma, \\
&= \mathrm{Tr}\,[(-a/p)_Z (16a^2/\pi)_5 \,.\, \pi^\sigma \,.\, \pi] \text{ since } (4a/\pi^\sigma)_5 = (g^\nu/\pi_2)_5 \\
&\qquad\qquad = (g^\nu/\pi_1)_5^2 = (4a/\pi)_5^2 = (16a^2/\pi)_5, \\
&= \mathrm{Tr}\,[(-au/p)_Z (4(au)/\pi)_5 \,.\, \pi\, \pi^\sigma], \text{ where } (u/p)_Z = 1 \text{ and } (u/p)_5 \\
&\qquad\qquad = (4a/\pi)_5.
\end{aligned}$$

Now writing a for au we get the theorem.

It follows that the expressions allied to $\Delta_a(\pi)$ also represent the number of solutions of the congruence (1) for a suitable value of a.

5. The set $\{\Delta_a \mid a = 1, 2, 3, \ldots, p-1\}$

Dickson's paper on cyclotomy [1] includes the following Theorem (theorem 8 of [1]). Let $p \equiv 1 \pmod 5$ be a rational prime. Then the Diophantine equations

$$(4)\qquad \begin{aligned} &\text{i. } 16p = x^2 + 50u^2 + 50v^2 + 125w^2 \\ &\text{ii. } v^2 - 4uv - u^2 = xw \\ &\text{iii. } x \equiv 1 \pmod 5 \end{aligned}$$

have exactly 4 integral simultaneous solutions. If (x, u, v, w) is one solution then the remaining three are $(x, -u, -v, w)$, $(x, v, -u, -w)$, $(x, -v, u, -w)$.

Now let $f(x, u, v, w) = \frac{1}{4}(25w - x - 10u - 20v)$. We have the following

THEOREM 4. *The distinct* Δ_a *are the following* 10 *numbers:*

$$\pm x,\ \pm f(x, u, v, w),\ \pm f(x, -u, -v, w),\ \pm f(x, v, -u, -w),$$
$$\pm f(x, -v, u, -w).$$

Remark. If $4a$ is a quintic residue mod p then $\Delta_a = (-a/p)_Z \cdot x$.

Proof. In the notation of [2] we have

$$\Delta_a = (-a/p)_Z \left[\left(\frac{4a}{\pi_1}\right)_5 \cdot T + \left(\frac{4a}{\pi_2}\right)_5 + S \cdot \left(\frac{4a}{\pi_3}\right)_5 \cdot \bar{S} + \left(\frac{4a}{\pi_4}\right)_5 \cdot \bar{T} \right]$$

with $T = s_1\zeta + s_2\zeta^2 + s_3\zeta^3 + s_4\zeta^4$ and $S = s_3\zeta + s_1\zeta^2 + s_4\zeta^3 + s_2\zeta^4$. Let $4a \equiv g^\nu \pmod p$. We have to look at the five cases $\nu \equiv 0, 1, 2, 3, 4 \pmod 5$.

If $\nu \equiv 0 \pmod 5$, so that $(4a/\pi_i)_5 = 1$ for all i, then

$$\begin{aligned} \Delta_a &= (-a/p)_Z(T + \bar{T} + S + \bar{S}) = (-a/p)_Z[(s_1 + s_4)(\zeta + \zeta^4) \\ &\quad + (s_2 + s_3)(\zeta^2 + \zeta^3) + (s_2 + s_3)(\zeta + \zeta^4) + (s_1 + s_4)(\zeta^2 + \zeta^3)] \\ &= (-a/p)_Z[-(s_1 + s_2 + s_3 + s_4)] = (-a/p)_Z \cdot x \text{ (see equation (62) of [1]).} \end{aligned}$$

If $\nu \equiv 1, 2, 3, 4 \pmod 5$, we get respectively, as above

$$(5)\qquad \Delta_a(\pi) = (-a/p)_Z \begin{cases} 4s_4 - (s_1 + s_2 + s_3) & \text{if } \nu \equiv 1 \pmod 5, \\ 4s_3 - (s_1 + s_2 + s_4) & \text{if } \nu = 2 \pmod 5, \\ 4s_2 - (s_1 + s_3 + s_4) & \text{if } \nu \equiv 3 \pmod 5, \\ 4s_1 - (s_2 + s_3 + s_4) & \text{if } \nu \equiv 4 \pmod 5. \end{cases}$$

Now from equations (62) and (63) of [1] we get, on solving

$$\begin{aligned} 4s_1 &= 5w - x + 2u + 4v, \\ 4s_2 &= -5w - x + 4u - 2v, \\ 4s_3 &= -5w - x - 4u + 2v, \\ 4s_4 &= 5w - x - 2u - 4v. \end{aligned}$$

so that substitution in (5) gives

$$\Delta_a(\pi) = (-a/p)_Z \cdot \begin{cases} \frac{1}{4}(25w - x - 10u - 20v) & \text{if } v \equiv 1 \pmod 5, \\ \frac{1}{4}(-25w - x - 20u + 10v) & \text{if } v \equiv 2 \pmod 5, \\ \frac{1}{4}(-25w - x + 20u - 10v) & \text{if } v \equiv 3 \pmod 5, \\ \frac{1}{4}(25w - x + 10u + 20v) & \text{if } v \equiv 4 \pmod 5. \end{cases}$$

But letting $(x, u, v, w) \to (x, -u, -v, w), (x, v, -u, -w), (x, -v, u, -w)$ in the case $v \equiv 1 \pmod 5$ gives just the cases $v \equiv 2, 3, 4 \pmod 5$ respectively. This completes the proof of theorem 4.

6. A relation and an example

THEOREM 5. $(\Delta_g)^2 + (\Delta_{g^2})^2 + (\Delta_{g^3})^2 + (\Delta_{g^4})^2 + (\Delta_{g^5})^2 = 20 \,.\, p$

Proof. The left hand side

$$= [f(x, u, v, w)]^2 + [f(x, -u, -v, w)]^2 + [f(x, v, -u, -w)]^2 + [f(x, -v, u, -w)]^2 + x^2$$

$$= \frac{1}{16}[4 \,.\, 625w^2 + 4 \,.\, x^2 + 1000(u^2 + v^2)] + x^2$$

on simplifying

$$= \frac{5}{4}(125w^2 + x^2 + 50u^2 + 50v^2) = \frac{5}{4} \,.\, 16 \,.\, p \quad (\text{by } i \text{ of } (4))$$

$$= 20 \,.\, p$$

as required.

An example. Let $p = 11$. The 4 solutions of (4) are

$$(1, 0, 1, 1),\ (1, 0, -1, 1),\ (1, 1, 0, -1),\ (1, -1, 0, -1)$$

and so by theorem 4 the set Δ_a is given by $\pm 1, \pm 4, -9, \pm 11, \pm 1$, so that $1^2 + 4^2 + 9^2 + 11^2 + 1^2 = 220 = 20 \,.\, \text{p}$.

A direct computation gives the following values

$$\begin{array}{rcl} a & = & 1, \quad 2, \quad 3, \quad 4, \quad 5, \quad 6, \quad 7, \quad 8, \quad 9, \quad 10 \\ \Delta_a & = & 4, \ -9, \ -1, \ -11, \ -1, \ 1, \ 11, \ 1, \ 9, \ -4 \end{array}$$

The fifth powers are $4a = 1, 10$ that is $a = 3, 8$ and for these $\Delta_3 = (-3/p)_Z \cdot x = -x = -1$ and $\Delta_8 = (-8/p)_Z \cdot x = x = 1$ as required.

I should like to thank Professor Frohlich sincerely for his suggestion to look at these Δ_a.

APPENDIX

1. For the convenience of the reader we give here the definition of $(\alpha/\beta)_{10}$, the tenth power residue symbol and some of its properties.

First let π be a prime factor of a rational prime $p \equiv 1 \pmod 5$. The residue classes mod π, in $\mathbf{Z}[\zeta]$, form a field of norm $\pi = p$ elements. The non-zero classes form a cyclic group (multiplicative) $1, \rho, \ldots, \rho^{p-2}$ of $p - 1$ elements. This group has in it just 10 elements or order dividing 10 viz. $\rho^{j(p-1)/10}$ $(j = 0, 1, \ldots, 9)$. These are represented (mod π) by $\pm 1, \pm\zeta, \ldots, \pm \zeta^4$, since these are distinct mod π and have order dividing 10. Now let α be any non-zero residue mod π. Then $\alpha^{(p-1)/10}$ has order dividing 10 and so is congruent to one of $\pm 1, \pm \zeta, \ldots, \pm \zeta^4 \pmod \pi$. We define $(\alpha/\pi)_{10} = \pm 1, \pm \zeta, \ldots, \pm \zeta^4$ according as $\alpha^{(p-1)/10}$ is congruent to $\pm 1, \pm \zeta, \ldots, \pm \zeta^4 \pmod \pi$. It follows that

$$(\alpha/\pi)_{10} \equiv \alpha^{(N\pi-1)/10} \pmod{\pi}.$$

It is immediately verified that $(\alpha\beta/\pi)_{10} = (\alpha/\pi)_{10} \cdot (\beta/\pi)_{10}$, and we define $(\alpha/\pi_1\pi_2)_{10} = (\alpha/\pi_1)_{10} \cdot (\alpha/\pi_2)_{10}$. The following properties may be easily verified directly from the definition.

(i). If $p \equiv 2, 3 \pmod 5$, so that p stays prime in $\mathbf{Z}[\zeta]$, and if $n \in \mathbf{Z}$, then $(n/p)_{10} = 1$.

(ii). If π is a prime factor of a $p \equiv 4 \pmod 5$, so that $p = \pi\bar{\pi}$ is the prime decomposition of p in $\mathbf{Z}[\zeta]$, and $n \in \mathbf{Z}$, then

$$(n/\pi)_{10} = 1.$$

(iii). If π is a prime factor of a $p \equiv 1 \pmod 5$, so that $p = \pi_1 \pi_2 \bar{\pi}_2 \bar{\pi}_1$ is the prime decomposition of p in $\mathbf{Z}[\zeta]$, then

$$(n/\pi)_{10} \cdot (n/\bar{\pi})_{10} = 1.$$

(iv). If π is a complex prime factor of a $p \equiv 1, 4 \pmod 5$ and σ of a $q \equiv 1, 4 \pmod 5$, then $\overline{(\pi/\sigma)_{10}} = (\bar{\pi}/\bar{\sigma})_{10}$.

2. The symbol $(\alpha/\beta)_5$ is defined in the same way and has similar properties.

3. The symbol $(a/p)_{\mathbf{Z}}$ is simply the ordinary Legendre symbol, the subscript $\mathbf{Z}$ is used to distinguish it from the symbol $(\alpha/\beta)_2$ which denotes the quadratic character of α modulo β in a given ring, e.g. if $\alpha, \beta \in \mathbf{Z}[i]$

then $(\alpha/\beta)_{\mathbf{Z}[i]} = \begin{cases} 1 \text{ if } x^2 \equiv \alpha \pmod{\beta} \text{ is solvable in } \mathbf{Z}[i], \\ -1 \text{ otherwise.} \end{cases}$

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