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p-ADIC L-FUNCTIONS ATTACHED TO CHARACTERS OF p-POWER ORDER

par Kenneth A. RIBET

SOMMAIRE. - L'objet de ce papier (rédigé en anglais) est d'étudier la fonction L p-adique (p impair) attachée à un caractère ε d'ordre une puissance de p dont le conducteur n'est pas une puissance de p. On donne un critère pour la non-trivialité de cette fonction. On trouve aussi que, si l'on remplace ε par le produit de ε et une puissance paire et non triviale du caractère de Teichmüller mod p, la fonction L qu'on obtient est toujours non triviale.

1. As is well known, the values at negative integers of the L-series attached to a function $\varepsilon : \mathbb{Z}/f\mathbb{Z} \longrightarrow \mathbb{C}$ are given by universal formulas as rational linear combinations of the values of ε. This fact permits us to define, when ε is a periodic function on $\mathbb{Z}$ with values in a $\mathbb{Q}$-vector space V, elements $L(1-k, \varepsilon) \in V$, for $k \geqslant 1$. One is especially interested in the case where V is a number field or, after completion, a p-adic field.

If ε is a character $(\mathbb{Z}/f\mathbb{Z})^* \longrightarrow \bar{\mathbb{Q}}_p^*$ (extended by 0 to a function on $\mathbb{Z}/f\mathbb{Z}$), there are well known necessary and sufficient conditions for the integrality of a number $L(1-k, \varepsilon) \in \bar{\mathbb{Q}}_p$ ([C], [F], [Le]). In this paper, we shall recall a proof of the sufficiency of the conditions in the case $p \neq 2$. At the same time, we find a criterion for the valuation of certain numbers $L(1-k, \varepsilon)$ to be strictly positive.

Our tools are the "Kummer congruences" as given by MAZUR [M] (and [K], [L]), and the (consequent) theory of p-adic L-functions. These can be used to prove as well some "trivial divisibilities" of L-values for $p = 2$ (cf. [Gr]), and also, of course, the necessity of the conditions for integrality, not merely their sufficiency. Our motivation in recalling the deduction of integrality theorems for the $L(1-k, \varepsilon)$ from the Kummer congruences was that these L-values occur as the constant terms in the q-expansions of certain Eisenstein series $G_{k,\varepsilon}$ for congruence subgroups of $SL_2\,\mathbb{Z}$. One can ask if more generally modular forms of the same "type" as a $G_{k,\varepsilon}$ will have constant terms enjoying the same integrality properties as the corresponding $L(1-k, \varepsilon)$ if their non-constant terms are integral. An example given in the last paragraph shows that this is not the case.

2. Given a periodic function $\varepsilon : \mathbb{Z} \longrightarrow V$ as in § 1 and an element $c \in \hat{\mathbb{Z}}^*$, we let ε_c be the function $x \longmapsto \varepsilon(cx)$. For $k \geqslant 1$, we set

$$\Delta_c(1-k, \varepsilon) = L(1-k, \varepsilon) - c_p^k\, L(1-k, \varepsilon_c) \in V,$$

where c_p is the image of c under the projection $\hat{\mathbb{Z}}^* \longrightarrow \mathbb{Z}_p^*$.

The Kummer congruences that we need may be stated as follows. Let $\varepsilon_1, \ldots, \varepsilon_t$

be periodic functions on $\underset{\sim}{Z}$ with values in $\underset{\sim}{Q}_p$, and let $k_1, \dots, k_t \geq 1$. Suppose that, for $n \geq 1$, we have

$$\sum_{i=1}^{t} \varepsilon_i(n) n^{k_i - 1} \in \underset{\sim}{Z}_p .$$

Then we have

$$\sum_{i=1}^{t} \Delta_c(1 - k_i , \varepsilon_i) \in \underset{\sim}{Z}_p .$$

Equivalently, we may regard periodic functions on $\underset{\sim}{Z}$ as the <u>locally constant</u> functions on $\hat{Z}$. The Kummer congruences state that the map $\varepsilon \longmapsto \Delta_c(0 , \varepsilon)$ is a measure μ_c on $\underset{\sim}{\hat{Z}}$ with values in $\underset{\sim}{Z}_p$ such that

$$\int \varepsilon(x) x_p^{k-1} \, d\mu(x) = \Delta_c(1 - k , \varepsilon) ,$$

for all $k \geq 1$, and all locally constant ε . (Here again, x_p is the projection function $\underset{\sim}{\hat{Z}} \longrightarrow \underset{\sim}{Z}_p$.)

Suppose that ε is a character of conductor $f \geq 1$ with values in $\bar{\underset{\sim}{Q}}_p^*$, where p is an odd prime. Let K be the finite extension of $\underset{\sim}{Q}_p$ generated by the values of ε , and let R be the integer ring of K . When is a value $L(1 - k , \varepsilon)$ an element of R (i. e., integral)? Using the fact that the values of ε lie in R (which is a free $\underset{\sim}{Z}_p$-module), we find by the Kummer congruenees the integrality

$$\Delta_c(1 - k , \varepsilon) = (1 - \varepsilon(c) c_p^k) . L(1 - k , \varepsilon) \in R$$

for each $c \in \underset{\sim}{\hat{Z}}^*$. This implies that $L(1 - k , \varepsilon)$ is itself integral, <u>except</u> perhaps in the special case where the product of ε and the k-th power of the Teichmüller character is a character of p-power order. (Recall that the Teichmüller character is the uhique character $\omega : (\underset{\sim}{Z}/p\underset{\sim}{Z})^* \longrightarrow \underset{\sim}{Z}_p^*$ which satisfies $\varepsilon(x) \equiv x \mod p$, for all $x \in (\underset{\sim}{Z}/p\underset{\sim}{Z})^*$.)

Said differently, if the order of ε is divisible by a prime other than p , we have

$$L(1 - k , \varepsilon\omega^{-k}) \in R$$

for $k \geq 1$. On the other hand, suppose that the order of ε is a power of p ; this implies, incidentally, that ε is an even character since p is odd. One then finds in the literature, the additional statement that a number $L(1 - k , \varepsilon\omega^{-k})$ lies in R if (and only if) the conductor of ε is divisible by some prime different from p .

3. The theory of p-adic L-functions provides a proof of the integrality. Indeed, let ε , once again, be a character of p-power order whose conductor f is not a p-power. Since ε is non-trivial, there is a continuous function $L_p(s , \varepsilon)$ on $\underset{\sim}{Z}_p$ whose value at $1 - k$ is

$$L^*(1 - k , \varepsilon\omega^{-k}) = L(1 - k , \varepsilon\omega^{-k})(1 - p^{k-1}(\varepsilon\omega^{-k})(p)) .$$

The factor multiplying $L(1 - k , \varepsilon^{-k})$ is trivial unless $p - 1 | k$; hence it is in all cases a unit. Thus the integrality of $L^*(1 - k , \varepsilon\omega^{-k})$ is equivalent to that of $L(1-k\ ,\ \varepsilon\omega^{-k})$.

Let $\langle x\rangle$ be the function $x \longmapsto x\omega(x)^{-1}$ on $\underset{\sim}{Z}_p^*$. We view it alternately as a function on $\hat{\underset{\sim}{Z}}^*$ via the projection $x \longmapsto x_p$. As we shall recall in § 5 , there is, for each $c \in \hat{\underset{\sim}{Z}}^*$, a power series $F_c(T) \in R[[T]]$ such that

$$F_c((1+p)^{-s}-1) = (1-\varepsilon(c)\langle c\rangle^{1-s})L_p(s\ ,\ \varepsilon)$$

for all $s \in \underset{\sim}{Z}_p$. (The appearance of the quantity $1+p$ in this representation arises from the choice of an isomorphism of $\underset{\sim}{Z}_p$-modules

$$\alpha :\ 1 + p\underset{\sim}{Z}_p \xrightarrow{\sim} \underset{\sim}{Z}_p$$

such that $x = (1+p)^{\alpha(x)}$ for all x in the multipli ative group $1 + p\underset{\sim}{Z}_p$. For simplicity, we write again $\alpha(x)$ for the function $\alpha(\langle x\rangle)$ on $\underset{\sim}{Z}_p^*$ (or $\hat{\underset{\sim}{Z}}^*$).)
Since we have on the other hand

$$1-\varepsilon(c)\langle c\rangle^{1-s} = 1-\varepsilon(c)\langle c\rangle(1+T)^{\alpha(c)}\big|_{T=(1+p)^{-s}-1}\ ,$$

we can "represent" $L_p(s\ ,\ \varepsilon)$ by a quotient of two power series with coefficients in R . Now the point is that, although the individual series representing the "fudge factors" $1-\varepsilon(c)\langle c\rangle^{1-s}$ are not invertible in $R[[T]]$, it is easy to see that their greatest common divisor in $R[[T]]$ is 1 ([CL], p. 540). Hence there is an $F \in R[[T]]$ such that

$$F((1+p)^{-s}-1) = L_p(s\ ,\ \varepsilon)\ .$$

In particular, the values $L_p(1-k\ ,\ \varepsilon)$ belong to R , which is what we wanted to show.

4. A different proof of the integrality may be given using the measures μ_c of § 2. We view $\varepsilon\omega^{-k}$ and ω^{-k} as characters of $(\underset{\sim}{Z}/fp\underset{\sim}{Z})^*$. These give rise to two functions on $\underset{\sim}{Z}/fp\underset{\sim}{Z}$, whose values are zero on the non-invertible elements. We regard them as functions φ_1 and φ_2 on $\hat{\underset{\sim}{Z}}$, which are constant mod pf . If $\mathfrak{P}$ is the maximal ideal of R , we have

$$\varphi_1(x) \equiv \varphi_2(x) \mod \mathfrak{P}$$

for all $x \in \hat{\underset{\sim}{Z}}$. Multiplying this congruence by x_p^{k-1} and integrating, we find the Kummer congruence

$$\Delta_c(1-k\ ,\ \varphi_1) \equiv \Delta_c(1-k\ ,\ \varphi_2) \mod \mathfrak{P}\ .$$

The first of these two numbers is simply $(1-\varepsilon(c)\langle c\rangle^{k})L^*(1-k\ ,\ \varepsilon\omega^{-k})$. The second is

$$(1-\langle c\rangle^{k})L^*(1-k\ ,\ \omega^{-k})\ \prod_{\ell | f,\ell\neq p}(1-\omega^{-k}(\ell)\ell^{k-1})$$

(the factors ℓ are understood to be primes) because in φ_2 we have artificially given ω^{-k} the value 0 on <u>all</u> primes dividing pf . Now it is clear that any $\ell \neq p$ which divides f is congruent to 1 mod p , and so in the product (which by hypothesis is non empty) every term is divisible by p . Since on the other hand the term multiplying the product is integral (again by a Kummer congruence, for example), the right hand side of the above Kummer congruence is divisible by $\mathfrak{P}$. Looking now at the left side of the congruence, we choose a c such that $\varepsilon(c)$ generates the group of values of ε. We then have $\mathfrak{P}\|(1-\varepsilon(c)\langle c\rangle^k)\|$, implying the integrality of $L^*(1-k\ ,\ \varepsilon\omega^{-k})$. We note that our congruence now reads $0 \equiv 0$; we cannot obtain from it the value of $L^*(1-k\ ,\ \varepsilon\omega^{-k}) \mod \mathfrak{P}$.

As a variant, let us replace ε by $\varepsilon\omega^i$, where $i \not\equiv 0 \pmod{p-1}$ is even. We obtain as above the congruence

$$(1-\varepsilon(c)\omega^i(c)\langle c\rangle^k)L^*(1-k\ ,\ \varepsilon\omega^{i-k}) \equiv 0 \mod \mathfrak{P}\ .$$

Since ω^i is non trivial, we may choose c so that the "fudge factor" is invertible mod $\mathfrak{P}$. This implies the ("trivial") divisibility by $\mathfrak{P}$ of the L^*-value. The passage from L to L^* just means multiplying by an Euler factor at p; as before we see that this factor is trivial for $k = 1$, and hence a unit for all k. The conclusion is that we have

$$\mathfrak{P}|L(1-k\ ,\ \varepsilon\omega^{i-k})|$$

for all $k \geqslant 1$.

5. We obtain a congruence mod $\mathfrak{P}$ for the numbers $L(1-k\ ,\ \varepsilon\omega^{-k})$ by combining the techniques of § 3 and § 4. The point is that we have a (term by term) congruence of <u>series</u> $F_c \equiv G_c \mod \mathfrak{P}$, where F_c is the series of § 3 representing

$$A(s) = (1-\varepsilon(c)\langle c\rangle^{1-s})L_p(s\ ,\ \varepsilon)\ ,$$

and G_c represents similarly the regularized p-adic zeta function

$$B(s) = [(1-\langle c\rangle^{1-s})\zeta_p(s)]\prod_{\ell|f,\ell\neq p}(1-\ell^{-s})$$

which has been stripped of its ℓ-Euler factors for primes $\ell|f$. (The idea of looking at such congruences of series was suggested by Lichtenbaum.) The congruence is easy to prove, once we remember that we can construct the series F_c and G_c by regarding $A(s)$ and $B(s)$ as p-adic Mellin transforms of measures. Indeed, we have

$$A(s) = \int_{\hat{\mathbb{Z}}}\langle x\rangle^{-s}\ \varepsilon(x)\omega^{-1}(x)\ d\mu_c(x)\ ,$$

with the convention that the integrand is given the value 0 for x such that $x_p \notin \mathbb{Z}_p^*$. (To prove this identity, we note that the integral is continuous in s and, by the defining properties of μ_c, coincides with $A(s)$ for $s = 1-k$, $k \geqslant 1$.) Similarly, we have

$$B(s) = \int\langle x\rangle^{-s}\ \psi(x)\omega^{-1}(x)\ d\mu_c(x)\ ,$$

where the integral is again taken over the subset S of $\hat{\mathbb{Z}}$ consisting of those x with $x_p \in \mathbb{Z}_p^*$, and where ψ is the characteristic function of $(\mathbb{Z}/fp\mathbb{Z})^*$ in $\mathbb{Z}/fp\mathbb{Z}$. For $x \in S$, the binomial theorem gives

$$\langle x\rangle^{-s} = \sum_{n\geq 0}\binom{\alpha(x)}{n}\gamma_s^n ,$$

where $\gamma_s = (1+p)^{-s} - 1$. Putting this into the integrals, we find

$$A(s) = \sum_{n\geq 0} a_n \gamma_s^n , \quad B(s) = \sum_{n\geq 0} b_n \gamma_s^n ,$$

where

$$a_n = \int \binom{\alpha(x)}{n}\varepsilon(x)\omega^{-1}(x)\, d\mu_c(x) , \quad b_n = \int \binom{\alpha(x)}{n}\psi(x)\omega^{-1}(x)\, d\mu_c(x) ;$$

both integrals are taken over S . Now $\varepsilon \equiv \psi \bmod \mathfrak{P}$, and hence $a_n \equiv b_n \bmod \mathfrak{P}$ for each n ; this is exactly the congruence required.

Let c be an element of $\hat{\mathbb{Z}}^*$ such that $\langle c\rangle = 1 + p$, i. e., such that $\alpha(c) = 1$. The first factor in the expression for $B(s)$, namely $(1 - \langle c\rangle^{1-s})\zeta_p(s)$, may be written in the form $H_c(\gamma_s)$, for some series H_c with coefficients in R . It is easy to see that H_c is invertible, for we have more precisely the congruence

$$H_c(0) = -p\zeta_p(0) = -pL(0 , \omega^{-1}) \equiv +1 \bmod p .$$

The remaining factors in the expression for $B(s)$ are also represented by power series : we have

$$G_c(T) = H_c(T)\prod[1 - (1+T)^{\alpha(\ell)}] ,$$

with the product as usual taken over the primes ℓ dividing f and different from p . Since $\langle c\rangle = 1 + p$ and $\varepsilon(c) \equiv 1 \bmod \mathfrak{P}$, we have

$$F_c(T) = [1 - \langle c\rangle\varepsilon(c)(1+T)]F(T) \equiv -TF(T) \bmod \mathfrak{P} .$$

Hence, we obtain finally

$$-TF(T) \equiv H_c(T)\prod[1 - (1+T)^{\alpha(\ell)}] \bmod \mathfrak{P} .$$

This formula shows that not all coefficients of $F(T)$ are divisible by $\mathfrak{P}$ (we have "$\mu = 0$") and enables one to compute the Weierstrass degree of F .

More precisely, we find that $F(T)$ is the product of an invertible power series with a distinguished polynomial $W(T)$ of degree

$$\lambda = -1 + \sum_{\ell | f'}\left\{\frac{\ell - 1}{p}\right\}_{p'} ,$$

where $\{n\}_p$ means the p-part of an integer n , and f' is the prime to p part of f . In particular, we have $\lambda > 0 \Longleftrightarrow p^2 | \varphi(f')$, where φ is the Euler function. Another way to say that $W(T)$ is of positive degree is to say that $F(0)$ is divisible by $\mathfrak{P}$. It is exactly divisible by $\mathfrak{P}$ if and only if $W(T)$ is an Eisenstein polynomial. (Observe that if $W(T)$ is an Eisenstein polynomial and $\lambda > 1$, then the roots of $W(T)$ do not lie in K . This is rather the opposite of what occurs in the familiar situation of a p-adic L-function attached to a power of ω , where in all examples so far we have $\lambda = 0$ or 1. I have no conjecture concerning the precise values of the roots.) A final remark is that we have the congruence

$$F(0) \equiv L_p(s , \varepsilon) \bmod p$$

for all $s \in \underset{\sim}{Z}_p$. A number $L(1-k\ ,\ \varepsilon\omega^{-k})$ is thus divisible by $\wp$ if and only if $p^2 | \varphi(f')$. For comparison, we recall that the numbers $L(1-k\ ,\ \varepsilon\omega^{i-k})$ (i even and $i \not\equiv 0 \mod p-1$) are <u>always</u> divisible by $\wp$.

The number $F(0) = L(0\ ,\ \varepsilon\omega^{-1})$ occurs in the formula for the relative class number of the (imaginary) abelian field corresponding to the kernel of $\varepsilon\omega^{-1}$. Provided that the degree of this field is no bigger than 256, we can decide the power of $\wp$ dividing $F(0)$ by consulting the table [SR]. For $p = 3$ and

$$f = 19\ ,\ 37\ ,\ 73\ ,\ 91\ (= 7 \times 13)\ ,\ 109\ ,\ 127\ ,\ \text{or}\ \ 133\ (= 7 \times 19)\ ,$$

we have $\wp \| F(0) \|$, except in the case where $f = 133$ and ε is of order 9 , in which case $\wp^3 | F(0)$. This extra divisibility cah be explained by an argument similar to the above, which begins with the observation that ε is congruent mod $\wp^3$ to a character of order 9 mod 19 . As far as I can see, it is only an accident that one gets exactly the divisibilities which are <u>a priori</u> predictable. In an analogous series of examples, we take $p = 5$ and look at values $L(0\ ,\ \varepsilon\omega)$, with ε of order 5 and conductor $f = 11\ ,\ 31\ ,\ 41\ ,\ 61$. Here we find a trivial divisibility $\wp | L(0\ ,\ \varepsilon\omega)$ and no further divisibility <u>except</u> in the case $f = 31$, when $\wp^2 | L(0\ ,\ \varepsilon\omega)$. This extra divisibility seems "irregular".

6. As mentioned just above, our trivial divisibilities for L-values give divisibilities for relative class numbers of certain imaginary abelian fields. For example, if $p \geqslant 5$, and N is a product of distinct primes congruent to 1 mod p, the field of pN-th roots of 1 has a relative class number divisible by p .

On hearing of these results, LENSTRA, GREENBERG and GRAS each pointed out that there is a simple algebraic interpretation. In the example of pN-th roots of 1 , the ideal classes generated by the (ramified) primes dividing N in $\underset{\sim}{Q}(\mu_{pN})$ are non trivial and highly independent. GRAS suggests that the existence of these ideal classes may be predicted by Chevalley's theory of ambiguous classes in cyclic extensions ([Ch], p. 402-406), which has recently been refined in [G].

7. The connection with modular forms is the following. Let ε be a character mod f with values in $\bar{\underset{\sim}{Q}}{}_p^*$, and let $g = \sum_{n\geqslant 0} a_n q^n$ be a modular form of weight k and character $\varepsilon\omega^{-k}$ with coefficients in $\bar{\underset{\sim}{Q}}_p$. Suppose that the a_n , with $n > 0$, are (p-adically) integral. Then for each $c \geqslant 1$ prime to pf one can show that

$$(1 - \varepsilon(c)\omega^{-k}(c)c^k)a_0$$

is integral (cf. [Ka]). As in § 2, it follows from this "Kummer congruences" that a_0 is integral if ε is not of p-power order. If ε has p-power order and p-power conductor, then a_0 will not, in general, be integral ; this is seen from the example of the Eisenstein series

$$G_{k,\eta} = \frac{L(1-k\ ,\ \eta)}{2} + \sum_{n\geqslant 1}\left(\sum_{d|n} \eta(d)d^{k-1}\right)q^n\ ,$$

where $\eta = \varepsilon\omega^{-k}$.

The remaining case is that where ε has p-power order but not p-power conductor. Then as we have seen, the constant term of $G_{k,\varepsilon}$ is integral, and this integrality can be directly traced to Kummer congruences. This leads one to speculate that, more generally, the term a_0 might always be integral.

Here is an example where this is not true. We take $p = 3$ and $k = 2$, so that in particular we will have $\varepsilon = \varepsilon\omega^{-k}$. Let f be a prime congruent to 1 mod 3 but not mod 9 . Let ε be one of the two characters mod f of order 3 , with values in $K = \mathbb{Q}_3(\mu_3)$. Let g be the difference between $G_{2,\varepsilon}$ and the ("other") Eisenstein series

$$H_{2,\varepsilon} = \sum_{n\geq 1}(\sum_{d|n} \varepsilon(\tfrac{n}{d})d)q^n$$

of weight 2 and character ε . By the results of § 5, the constant coefficient $L(-1, \varepsilon)/2$ of g is a unit in K since $9 \nmid \varphi(f)$. (This can also be checked directly by using the formula for an $L(-1)$.) On the other hand, we shall see that the higher coefficients of the q-expansion of g are divisible by the maximal ideal $\mathfrak{P}$ of the integer ring of K .

To prove this, since both $G_{2,\varepsilon}$ and $H_{2,\varepsilon}$ are eigenforms for the Hecke operators, it is enough to check the congruence

$$1 + \varepsilon(\ell)\ell \equiv \ell + \varepsilon(\ell) \mod \mathfrak{P}$$

for each prime ℓ . This is of course a consequence of the congruence $\varepsilon \equiv 1 \mod \mathfrak{P}$, except when $\ell = f$, in which case $\varepsilon(\ell) = 0$. But in the case $\ell = f$, the congruence to be proved reads $1 \equiv f$; it is true mod $\mathfrak{P}$ because true mod 3 .

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