EPSILON STABILITY OF p-ADIC CHARACTERS

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Abstract. The following problem is solved (see Theorem 1.1 below). Let $G$ be an abelian group, written additively, and let $K$ be an algebraically closed nonarchimedean valued field which is complete for the valuation $| |$. Let $f : G \rightarrow T_K := \{ \lambda \in K : |\lambda| = 1 \}$ be an $\varepsilon$-character i.e.

$$|f(x+y) - f(x)f(y)| \leq \varepsilon \quad (x, y \in G)$$

where $0 \leq \varepsilon < 1$. Does there exist a character $\alpha : G \rightarrow T_K$ for which $|\alpha(x) - f(x)| \leq \varepsilon \quad (x \in G)$? Is it unique?

Notes. The results of this Report will be used in a future paper on p-adic almost periodic functions [4]. The expression 'epsilon stability' is taken from [1], p.11, where a closely related problem is discussed.
§1 THE THEOREM

Throughout, let $G, K, T_K$ be as above. For trivially valued fields $K$ the above problem has a trivial solution. So from now on we assume that the valuation of $K$ is non-trivial. The residue class field of $K$ is $k$. The characteristic of a field $L$ is denoted $\text{char} L$.

Let $0 < \varepsilon < 1$. A function $f : G \to T_K$ is an $\varepsilon$-character if $|f(x+y)-f(x)f(y)| \leq \varepsilon$ for all $x, y \in G$. As usual, we shall say 'character' instead of '0-character'.

Consider the following statements (E) and (U).

(E) For each $\varepsilon \in [0,1)$ and each $\varepsilon$-character $f : G \to T_K$ there exists a character $\alpha : G \to T_K$ for which $|f(x)-\alpha(x)| \leq \varepsilon$ $(x \in G)$.

(U) For each $\varepsilon \in [0,1)$ and each $\varepsilon$-character $f : G \to T_K$ there exists at most one character $\alpha : G \to T_K$ for which $|f(x)-\alpha(x)| \leq \varepsilon$ $(x \in G)$.

The purpose of this note is to prove the following Theorem.

THEOREM 1.1.

(i) Let $\text{char} k = 0$. Then (E) holds for any $G$, (U) holds if and only if $G$ is a torsion group.

(ii) Let $\text{char} K = 0$, $\text{char} k = p \neq 0$. Then (E) holds if and only if $G$ has no subgroups of order $p$, (U) holds if and only if $G$ has no subgroups of index $p$.

(iii) Let $\text{char} K = p \neq 0$. Then (E) holds if and only if $G$ has no subgroups of order $p$, (U) holds if and only if no subgroup of $G/G_p$, where $G_p := \{ x \in G : p^n x = 0 \text{ for some } n \in \mathbb{N} \}$, has index $p$. 

We have the following trivial corollary.

COROLLARY 1.2.

(i) Let char \( k = 0 \). Then both (E) and (U) hold if and only if \( G \) is a torsion group.

(ii) Let char \( k = p \neq 0 \). Then both (E) and (U) hold if and only if \( G \) has neither subgroups of order \( p \), nor subgroups of index \( p \).

REMARK. The statement '\( G \) has no subgroups of order \( p \)' is obviously equivalent to 'the map \( x \mapsto px \ (x \in G) \) is injective'. It is not hard to see that '\( G \) has no subgroups of index \( p \)' is equivalent to 'the map \( x \mapsto px \ (x \in G) \) is surjective'.

EXAMPLES. If \( G \) is \( p \)-free (i.e. if \( H_1 \subset H_2 \) are subgroups then the index \([H_2 : H_1]\), whenever finite, is not divisible by \( p \)) then \( x \mapsto px \) is a bijection. But this conclusion holds also for the additive group of the \( p \)-adic numbers \( \mathbb{Q}_p \). On \( \mathbb{Z}_p := \{x \in \mathbb{Q}_p : |x|_p \leq 1\} \) the map \( x \mapsto px \) is injective but not surjective, on \( \mathbb{Q}_p/\mathbb{Z}_p \) the map \( x \mapsto px \) is surjective but not injective.

§2 PRELIMINARIES

LEMMA 2.1. (Elementary properties of \( \varepsilon \)-characters). Let \( 0 < \varepsilon < 1 \).

(i) Let \( f : G \to T_K \) be an \( \varepsilon \)-character. Then

(a) \(|f(0)| \leq \varepsilon \).

(b) If \( x_1, \ldots, x_n \in G \) then \(|f(x_1 + \ldots + x_n) - f(x_1)f(x_2)\ldots f(x_n)| \leq \varepsilon \).

(c) If \( g : G \to K, |g(x)| \leq \varepsilon \) for all \( x \in G \), then \( f+g \) is an \( \varepsilon \)-character.

(ii) \( B_1(\varepsilon) := \{\lambda \in K : |1-\lambda| \leq \varepsilon \} \) is a subgroup of \( T_K \). Let \( \pi : T_K \to T_K/B_1(\varepsilon) \) be the quotient map. Then \( f : G \to T_K \) is an \( \varepsilon \)-character if and only if \( \pi \circ f : G \to T_K/B_1(\varepsilon) \) is a homomorphism.

Proof. Straightforward.
PROPOSITION 2.2. (Extension of $\varepsilon$-characters) Let $H$ be a subgroup of $G$ and let, for some $\varepsilon \in (0,1)$, $f : H \rightarrow T_k$ be an $\varepsilon$-character. Then $f$ can be extended to an $\varepsilon$-character $\tilde{f} : G \rightarrow T_k$.

Proof. By lemma 2.1 (i) (c) it suffices to find an $\varepsilon$-character $\tilde{f} : G \rightarrow T_k$ for which $|\tilde{f}(h) - f(h)| \leq \varepsilon$ ($h \in H$). With the notations as in Lemma 2.1 (ii) we have that $\pi \circ f$ is a homomorphism $H \rightarrow T_k/B_1(\varepsilon)$. As $K$ is algebraically closed the group $T_K$, hence $T_k/B_1(\varepsilon)$, is divisible. Therefore, $\pi \circ f$ can be extended to a homomorphism $g : G \rightarrow T_k/B_1(\varepsilon)$. Choose any $\rho : T_k/B_1(\varepsilon) \rightarrow T_k$ for which $\pi \circ \rho$ is the identity. Then $\tilde{f} := \rho \circ g$ has the required properties.

We quote a lemma needed for the proof of Proposition 3.2.

LEMMA 2.3. Let char $k = p \neq 0$. Let $a, b \in T_k$ such that $0 < |a - b| < \varepsilon < 1$. Then $|a^p - b^p| \leq \tau e$ where $\tau := \max(\varepsilon, |p|)$. In particular, $|a^p - b^p| < |a - b|$. Proof. [2], Lemma 32.1.

§3 EXISTENCE

In this section we prove the 'existence part' of Theorem 1.1 i.e. the statements involving (E).

For the case char $k = 0$ we have quite standard methods:

PROPOSITION 3.1. Let char $k = 0$. Then, for any $G$, for each $\varepsilon \in (0,1)$ and each $\varepsilon$-character $f : G \rightarrow T_k$ there exists a character $\alpha : G \rightarrow T_k$ for which $|f(x) - \alpha(x)| \leq \varepsilon$ ($x \in G$).

Proof. We start the construction of $\alpha$ by setting $\alpha(0) := 1$. Then, by Lemma 2.1 (i) (a), $|f - \alpha| \leq \varepsilon$ on the zero group. Now suppose we have a subgroup $H$ of $G$ and a character $\alpha : H \rightarrow T_k$ such that $|f(h) - \alpha(h)| \leq \varepsilon$ for all $h \in H$. Let $x \in G \setminus H$. We prove that $\alpha$ can be extended to a character $\tilde{\alpha}$ defined on the group $H'$ generated by $H$ and $\{x\}$ such that $|f(h') - \tilde{\alpha}(h')| \leq \varepsilon$ for all $h' \in H$. (A simple application of Zorn's Lemma then may complete the proof.)
If $H'/H \cong \mathbb{Z}$ we define $\tilde{\alpha}$ by

$$\tilde{\alpha}(nx+h) := f(x)^{n} \alpha(h) \quad (n \in \mathbb{Z}, h \in H)$$

One proves easily, by using Lemma 2.1(i)(b), that $\tilde{\alpha}$ satisfies the requirements. If $H'/H \cong \mathbb{Z}/q\mathbb{Z}$ for some $q \in \mathbb{N}, q > 1$ we set

$$\tilde{\alpha}(nx+h) := \theta^{n} \alpha(h) \quad (n \in \{0,1,\ldots,q-1\}, h \in H)$$

where $\theta \in K$ is chosen such that $\theta^q = \alpha(qx)$ (then $\tilde{\alpha}$ is a character) and such that $|\theta-f(x)| \leq \varepsilon$ (then $|\tilde{\alpha}(h')-f(h')| \leq \varepsilon$ for all $h' \in H'$). To see such a $\theta$ exists consider the polynomial $p = x^q - \alpha(qx) \in K[x]$. We have $|p(f(x))| \leq \varepsilon$, $|p'(f(x))| = |q||f(x)q^{-1}| = 1$ (here we use the assumption $\text{char } k = 0$). By Hensel's Lemma there exists a $\theta \in K$ with $p(\theta) = 0$ and $|\theta-f(x)| \leq \varepsilon$.

REMARKS.

1. The algebraic closedness of $K$ has not been used in the above proof.
2. Let $B_1(\varepsilon)$, $\pi$ be as in Lemma 2.1. Then any $\rho : T_K/B_1(\varepsilon) \to T_K$ for which $\pi \circ \rho$ is the identity, is an $\varepsilon$-character of $T_K/B_1(\varepsilon)$. Proposition 3.1 tells that there exists a homomorphism $\tilde{\rho} : T_K/B_1(\varepsilon) \to T_K$ such that $\pi \circ \tilde{\rho}$ is the identity. As a corollary we obtain that if $\text{char } k = 0$ then $B_1(\varepsilon)$ is a factor in $T_K$.

Next we turn to the case where $\text{char } k = p \neq 0$. To cover also groups like $\mathbb{Q}/p\mathbb{Q}$ we shall use a technique different from the above one.

PROPOSITION 3.2. Let $\text{char } k = p \neq 0$. Suppose $x \mapsto px$ is a bijection $G \to G$.

Then for each $\varepsilon \in [0,1)$ and each $\varepsilon$-character $f : G \to T_K$ there exists a character $\alpha : G \to T_K$ such that $|f(x) - \alpha(x)| \leq \varepsilon$ $(x \in G)$.
Proof. For each \( n \in \mathbb{N} \) let \( x \mapsto p^{-n}x \) \((x \in G)\) be the inverse of \( x \mapsto p^n x \).

For any \( n \in \mathbb{N} \), \( x \in G \) we have

\[
|f(p^{-n-1}x)p^n - f(p^{-n}x)| \leq \varepsilon
\]

so that, by Lemma 2.3,

\[
|f(p^{-n-1}x)p^{n+1} - f(p^{-n}x)p^n| \leq \tau^n \varepsilon.
\]

By completeness of \( K \)

\[
a(x) := \lim_{n \to \infty} f(p^{-n}x)p^n
\]

exists (uniformly in \( x \in G \)). For each \( n \in \mathbb{N} \), \( x \in G \) we have

\[
|f(x) - f(p^{-n}x)p^n| \leq \varepsilon
\]

hence also

\[
|f(x) - a(x)| \leq \varepsilon
\]

To see that \( a \) is a character, let \( x, y \in G \), \( n \in \mathbb{N} \). We have

\[
|f(p^{-n}(x+y)) - f(p^{-n}x)f(p^{-n}y)| \leq \varepsilon
\]

Again by Lemma 2.3,

\[
|f(p^{-n}(x+y))p^n - f(p^{-n}x)p^n f(p^{-n}y)p^n| \leq \tau^n \varepsilon
\]

hence also

\[
|a(x+y) - a(x)a(y)| \leq 0.
\]

Proposition 3.2 is a stepping stone for
PROPOSITION 3.3. Let \( \text{char } k = p \neq 0 \). Suppose \( x \mapsto px \) is an injection \( G \to G \). Then the conclusion of Proposition 3.2 holds.

Proof. \( G \) can be embedded into a divisible group \( D \). Set \( G_1 := D/D_p \) (for \( D_p \) see Theorem 1.1(iii)). Then \( G + D + G_1 \) is injective and \( x \mapsto px \) is a bijection \( G_1 \to G \). We may assume \( G \subseteq G_1 \). By Proposition 2.2 \( f \) can be extended to an \( \varepsilon \)-character \( \tilde{f} \) on \( G_1 \). By Proposition 3.2 there is a character \( \tilde{a} : G_1 \to T_K \) for which \( |\tilde{f}(x) - \tilde{a}(x)| \leq \varepsilon \) (\( x \in G_1 \)). Set \( a := \tilde{a}|G \).

We now prove the converse to Proposition 3.3.

PROPOSITION 3.4. Let \( \text{char } k = p \neq 0 \). Suppose \( x \mapsto px \) (\( x \in G \)) is not injective. Then there exists an \( \varepsilon \in (0,1) \) and an \( \varepsilon \)-character \( f : G + T_K \) such that for every character \( \alpha : G + T_K \) there exists an \( x \in G \) with \( |f(x) - \alpha(x)| > \varepsilon \).

Proof. Choose an element \( x \in G \) of order \( p \) and a \( b \in K \) with \( 0 < |1-b| < 1 \).

If \( \text{char } K = 0 \) we assume in addition that \( |1-b| < |1-\theta| \) where \( \theta \) is a primitive \( p \)th root of unity. Consider the map

\[
g : nx \mapsto b^n \quad (n \in \{0,1,\ldots,p-1\})
\]

defined on the group generated by \( x \). For \( n,m \in \{0,1,\ldots,p-1\} \) we have

\[
|g(nx+mx) - g(nx)g(mx)| = \begin{cases} 0 & \text{if } n+m \leq p-1 \\ |b^{n+m-p}b^m| & \text{if } n+m > p \end{cases}
\]

so we see that \( g \) is an \( \varepsilon \)-character where \( \varepsilon = |b^{-p-1}| = |b^{p-1}| \).

By Proposition 2.2 \( g \) extends to an \( \varepsilon \)-character \( f : G + T_K \). Now let \( \alpha : G + T_K \) be a character. If \( \alpha = 1 \) on \( H \) we have \( |f(x) - \alpha(x)| = |b-1| > |b^{p-1}| = \varepsilon \) (Lemma 2.3). Otherwise we have \( \alpha(x) = \theta \) where \( \theta \) is a primitive \( p \)th root of unity (and \( \text{char } K = 0 \)). Then we have, since \( |1-b| < |1-\theta| \),

\[
|f(x) - \alpha(x)| = |b-\theta| = \max(|b-1|,|1-\theta|) = |1-\theta| > |1-b| > \varepsilon.
\]
§4 UNIQUENESS

In this section we prove the 'uniqueness part' of Theorem 1.1 i.e. the statements involving (U).

PROPOSITION 4.1.

(i) Let \( \text{char } k = 0 \). Then (U) holds if and only if \( G \) is a torsion group.

(ii) Let \( \text{char } K = 0 \), \( \text{char } k = p \neq 0 \). Then (U) holds if and only if \( G \) has no subgroup of index \( p \).

(iii) Let \( \text{char } K = p \neq 0 \). Then (U) holds if and only if each homomorphism \( G \to \mathbb{Z}_p \) is zero.

Proof. Statement (U) is equivalent to "if \( \alpha, \beta \) are distinct characters then \( \sup\{|\alpha(x) - \beta(x)| : x \in G\} = 1 \), which is by [3], Proposition 1.1, the same as "the characters form an orthogonal set with respect to the sup norm".

Now apply [3], Theorem 3.1, Theorem 2.2, Theorem 4.3 (where \( G \) has the discrete topology). Proposition 4.1 follows.

To complete the proof of Theorem 1.1 the following lemma remains to be shown.

LEMMA 4.2. Let \( p \) be a prime number. The following are equivalent.

(a) Any homomorphism \( G \to \mathbb{Z}_p \) is zero.

(b) If \( H \) is a subgroup of \( G/p \), then \( H \) does not have index \( p \).

The heart of the proof is contained in

LEMMA 4.3. Let \( x \mapsto px \ (x \in G) \) be injective but not surjective. Then there exists a nonzero homomorphism \( G \to \mathbb{Z}_p \).

Proof. Let \( \pi : G \to G/pG \) be the quotient map. As \( pG \neq G \) the group \( G/pG \) is in a natural way a nonzero vector space over the field of \( p \) elements.

So there exists an indexed set \( \{e_i : i \in I\} \) in \( G \) where \( I \neq \emptyset \) such that \( \{\pi(e_i) : i \in I\} \) is a base of the vector space \( G/pG \). It follows that for
each \( x \in G \) there exist unique \( \lambda^{(1)}_i, i \in \mathcal{I} \) where \( \lambda^{(1)}_i \in \{0,1,\ldots,p-1\} \subset \mathbb{Z} \) and \( \{i \in \mathcal{I} : \lambda^{(1)}_i \neq 0\} \) is finite such that \( x - \sum \lambda^{(1)}_i e_i = px_1 \) where \( x_1 \in G \). By injectivity of \( x \) also \( x_1 \) is unique. By treating \( x_1 \) in the same way as we did for \( x \) we find unique \( \lambda^{(2)}_i, i \in \mathcal{I} \) \( \in \{0,1,\ldots,p^2-1\} \subset \mathbb{Z} \), \( \{i \in \mathcal{I} : \lambda^{(2)}_i \neq 0\} \) is finite such that \( x - \sum \lambda^{(2)}_i e_i = p^2x_2 \) where \( x_2 \in G \) etc.

Thus, for each \( n \in \mathbb{N} \) there exist unique maps \( \phi^{(n)}_i : G \to \{0,1,\ldots,p^n-1\} \subset \mathbb{Z} \) with \( \{i \in \mathcal{I} : \phi^{(n)}_i(x) \neq 0\} \) finite for each \( x \in G \) such that

\[
\phi^{(n)}_i(x) \equiv \phi^{(n)}_i(x) \mod p^n \quad (x \in G)
\]

By uniqueness, for each \( i \in \mathcal{I} \), \( n \in \mathbb{N} \)

\[
\phi^{(n+1)}_i(x) \equiv \phi^{(n)}_i(x) \mod p^n \quad (x \in G)
\]

We see that, for any \( j \in \mathcal{I} \), the \( p \)-adic limit

\[
\phi_j(x) = \lim_{n \to \infty} \phi^{(n)}_j(x) \quad (x \in G)
\]

exists and defines a map \( \phi_j : G \to \mathbb{Z}_p \). As \( \phi_j(e_j) = 1 \) this map is not zero.

To see that \( \phi_j \) is a homomorphism observe that for each \( n \in \mathbb{N} \), \( x,y \in G \)

\[
\sum_i (\phi^{(n)}_i(x+y) - \phi^{(n)}_i(x) - \phi^{(n)}_i(y)) e_i \in p^n G
\]

By what we have proved above

\[
\phi^{(n)}_j(x+y) - \phi^{(n)}_j(x) - \phi^{(n)}_j(y) \equiv 0 \mod p^n
\]

i.e.

\[
|\phi^{(n)}_j(x+y) - \phi_j(x) - \phi_j(y)|_p \leq p^{-n}
\]

which means for \( \phi_j \) that

\[
|\phi_j(x+y) - \phi_j(x) - \phi_j(y)| \leq 0
\]
Proof of Lemma 4.2. (a) $\Rightarrow$ (b). Suppose we had a subgroup $H$ of $G/G_p$ of index $p$. Then, since $G/G_p$ has no elements of order $p$, the map $x \mapsto px$ is injective but not surjective on $G/G_p$, so Lemma 4.3 gives us a nontrivial homomorphism $\phi : G/G_p \to \mathbb{Z}_p$. But then $G + G/G_p \phi : G_p$ is a nontrivial homomorphism $G \to \mathbb{Z}_p$ which conflicts (a). To prove (b) $\Rightarrow$ (a), suppose we had a nontrivial homomorphism $\phi : G \to \mathbb{Z}_p$. Then we may assume $1 \in \text{Im}\phi$. It is easy to see that $H := \phi^{-1}(p\mathbb{Z}_p)$ has index $p$ and contains $G_p$. This violates (a).

PROBLEM. Generalize Theorem 1.1 to topological abelian groups $G$ and continuous ($\epsilon$-)characters.

REFERENCES


