TOPOLOGICAL STABILITY OF $p$-ADIC COMPACTOIDS UNDER CONTINUOUS INJECTIONS

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Abstract. Let $A$ be an absolutely convex bounded subset of a locally convex space $(E, \tau)$ over a complete non-archimedean valued field $K$. The equivalence of (a) and (β) below is proved (Theorems A&A').

(a) $A$ is a compactoid.

(β) If $\tau'$ is a locally convex topology on $E$, weaker than $\tau$, and if there exists a $\tau$-neighbourhood base of $0$ in $E$ consisting of absolutely convex $\tau'$-closed sets then $\tau = \tau'$ on $A$.

In the same spirit connections are derived between complete compactoidity ($c$-compactness) of $A$ and a stronger version of (β) (Theorems B&B', Theorem 3.2), yielding also alternative proofs (Corollary 2.5 and Proposition 4.6) of two theorems of Gruson [2].
Preliminaries. Throughout $K$ is a non-archimedean nontrivially valued complete field with valuation $| |$. For fundamentals on Banach spaces and locally convex spaces over $K$ we refer to [4], [8]. We shall use the notations and terminology of [6]. For a subset $X$ of a locally convex space $E$ over $K$ we denote its absolutely convex hull by $\text{co} X$, its $K$-linear hull by $[X]$. The closure of a set $Y \subseteq E$ is denoted $\overline{Y}$. Instead of $\text{co} X$ we shall write $\text{co} X$.

Introduction. The well-known concepts of compactoidity and $c$-compactness (see Definition 1.1) are 'convexified' versions of (pre)compactness. Although (and because $| |$) for non-locally compact $K$ convex (pre)compact sets are trivial, one may put the general question as to whether 'convexified' versions of classical properties of (pre)compact sets hold for compactoids or $c$-compact sets. See, for example [7] for several fundamental compact-like properties of $c$-compact sets. In this paper we consider the convexified form of 'a continuous injection $f$ on a compact space $X$ is a homeomorphism of $X$ onto $f(X)'$. For an outline of the results see the abstract above. Facts of a more general nature, needed in this paper, have been put together in an Appendix (§4).
§ 1. STABILITY OF COMPACTOIDS

We recall the fundamental notions ([4],[7]).

1.1 DEFINITION. A subset $X$ of a locally convex space $E$ over $K$ is (a) compactoid if for each neighbourhood $U$ of 0 in $E$ there exists a finite set $F \subseteq E$ such that $X \subseteq U + \text{co}F$. An (absolutely) convex subset $A$ of $E$ is $c$-compact if every collection of nonempty relatively closed convex subsets of $A$, having the finite intersection property, has a nonempty intersection.

(For a connection between these concepts see Proposition 4.6.) Our aim in this section is to prove the Theorems A&B.

1.2 LEMMA. Let $B$ be a closed absolutely convex subset of a locally convex space $E$ over $K$, let $a \in [B]$. Further, let $\lambda \in K$, where $|\lambda| > 1$ if the valuation of $K$ is dense, $\lambda = 1$ if the valuation of $K$ is discrete.

(i) If $(x_i)_{i \in I}$ is a net in $B + Ka$ converging to 0 then $x_i \in \lambda B$ for large $i$.

(ii) The closure of $B + \text{co}\{a\}$ is contained in $\lambda B + \text{co}\{a\}$.

Proof. (i) $C = \{\mu \in K : \mu a \in B\}$ is a nonzero absolutely convex subset of $K$. We may assume $C \neq K$ so that $r_1 = \text{diam} C \in (0,\infty)$. We have

$$\{\mu \in K : |\mu| < r_1\} \subseteq C \subseteq \{\mu \in K : |\mu| \leq r_1\}$$

where, if the valuation of $K$ is discrete, the second inclusion is an equality and $r_1 \in |K|$. For each $i \in I$ we have a decomposition

$$(*)\quad x_i = b_i + \lambda_i a\quad (b_i \in B, \lambda_i \in K)$$
To prove (i) we derive a contradiction from the following assumption.

There exists an $a \in K$, $|a| > r$ and a directed cofinal $J \subset I$ such that $|\lambda_j| \geq |a|$ for all $j \in J$.

From (*) we obtain

$$aa = \lambda_j^{-1}ax_j - \lambda_j^{-1}ab_j.$$  \hspace{1cm} (j \in J)

As $|\lambda_j^{-1}a| \leq 1$ we have $\lim_{j \to \infty} \lambda_j^{-1}ax_j = 0$ and $\lambda_j^{-1}ab_j \in B$ for each $j \in J$ so that $aa \in \overline{B}$. On the other hand, $|a| > r$ so, $a \notin C$, a contradiction.

(ii) Let $x \in \overline{B + \text{co}(a)}$. There is a net

$$i \mapsto x^i = b_i + \lambda_i^a \quad (b_i \in B, \lambda_i \in K, |\lambda_i| \leq 1)$$

converging to $x$. The net $(i,j) \mapsto x^i_j - x_j$ is in $B + \text{co}(a)$ and converges to 0. By (i) there is an $i_0 \in I$ such that $x^i_j - x_j \in \lambda B$ for $i, j \geq i_0$. In particular

$$x^i_{i_0} \in x_{i_0} + \lambda B.$$ \hspace{1cm} ($i \geq i_0$)

The set $x_{i_0} + \lambda B$ is closed so that

$$x = \lim_{i \to \infty} x^i_{i_0} \in x_{i_0} + \lambda B.$$  

We see that $x \in b_{i_0} + \lambda^a + \lambda B \subset \lambda B + \lambda^a \subset \lambda B + \text{co}(a)$.

Remark. $B + \text{co}(a)$ is not always closed, see [5], 6.25.

1.3 LEMMA. Let $B, \lambda$ be as in Lemma 1.2. Let $a_1, \ldots, a_n \in [B]$. If $(x^i_{i \in I})$ is a net in $B + \text{co}(a_1, \ldots, a_n)$ converging to 0 then $x^i \in \lambda B$ for large $i$.

Proof. Let $\mu \in K$, $1 < |\mu|^{2n-1} \leq |\lambda|$ if the valuation of $K$ is dense, $\mu = 1$ otherwise. We have
so that by Lemma 1.2 (i)

\[ x_i \in \overline{B + \text{co}(a_1, \ldots, a_{n-1}) + \text{co}(a_n)} \quad (i \in I) \]

for large \( i \). By Lemma 1.2 (ii)

\[ x_i \in \mu(B + \text{co}(a_1, \ldots, a_{n-1})) \]

so that

\[ x_i \in \mu^2(B + \text{co}(a_1, \ldots, a_{n-2})) + \text{co}(a_{n-1}) \]

for large \( i \). Again by Lemma 1.2 (i)

\[ x_i \in \mu^3(B + \text{co}(a_1, \ldots, a_{n-2})), \text{ etc.} \]

Inductively we arrive at

\[ x_i \in \mu^{2n-1}B \subset \lambda B \]

for large \( i \).

1.4 THEOREM A. Let \( X \) be a compactoid in a locally convex space \((E, \tau)\) over \( K \). Let \( \tau' \) be a locally convex topology on \( E \), weaker than \( \tau \). Suppose there is a \( \tau \)-neighbourhood base of 0 in \( E \) consisting of absolutely convex \( \tau' \)-closed sets. Then \( \tau = \tau' \) on \( X \).

Proof. We shall prove that \( \tau = \tau' \) on \( A := \text{co} X \). To this end, it suffices, as \( A \) is an additive group, to show that for a net \( \{x_i\}_{i \in I} \) in \( A \),

\[ \tau'-\lim_{i} x_i = 0 \] implies \( \tau-\lim_{i} x_i = 0. \)
Let $U$ be an $\tau$-neighbourhood of 0 in $E$. There exists, by assumption, an absolutely convex $\tau$-closed $\tau$-neighbourhood $U$ of 0 with $U \subseteq V$.

Let $\lambda \in K$, $|\lambda| > 1$. By compactoidity there exist $a_1, \ldots, a_n \in E$ such that

$$x \subseteq \lambda^{-1}U + \text{co}(a_1, \ldots, a_n).$$

Then, by absolute convexity of $\lambda^{-1}U + \text{co}(a_1, \ldots, a_n)$, we have also

$$A \subseteq \lambda^{-1}U + \text{co}(a_1, \ldots, a_n).$$

As $\lambda^{-1}U$ is $\tau'$-closed and $a_1, \ldots, a_n \in [\lambda^{-1}U]$ we may apply Lemma 1.3 and conclude that $x_i \in \lambda\lambda^{-1}U \subseteq V$ for large $i$. It follows that

$$\tau' \lim_{i \to \infty} x_i = 0.$$

1.5 COROLLARY. Let $(E, \tau)$ be a locally convex space over a spherically complete field $K$. Then, on $\tau$-compactoids, the weak topology and the initial topology $\tau$ coincide.

Proof. By [9], for absolutely convex sets, the properties 'weakly closed' and 'compact' are identical. Now apply Theorem A.

Remark. The conclusion of Corollary 1.5 holds also for polar locally convex spaces over a nonspherically complete field $K$. ([6], Theorem 5.12.)

1.6 THEOREM B. Let $A$ be an absolutely convex bounded $\tau$-compact subset of a Hausdorff locally convex space $(E, \tau)$ over $K$. Let $\tau'$ be a Hausdorff locally convex topology on $E$, weaker than $\tau$. Then $\tau = \tau'$ on $A$. 
Proof. Let \((x_i)_{i \in I}\) be a net in \(A\) converging to 0 for \(\tau'\), let \(U\) be a \(\tau\)-neighbourhood of 0 in \(E\). We prove that \(x_i \in U\) for large \(i\). Let \(\lambda \in K, |\lambda| > 1\). There exists an absolutely convex \(\tau\)-neighbourhood \(V\) of 0 such that \(\lambda^2 V \subset U\). By proposition 4.6 \(A\) is a \(\tau\)-compactoid, so according to Katsaras' theorem ([3] or [6], Lemma 8.1) there exist \(a_1, \ldots, a_n \in A\) such that
\[
\lambda^{-1} A \subset V + \text{co}\{a_1, \ldots, a_n\}.
\]
Then also
\[
(*) \quad \lambda^{-1} A \subset V \cap A + \text{co}\{a_1, \ldots, a_n\}.
\]

By [7] \(V \cap A\), being an absolutely convex \(\tau\)-closed subset of \(A\), is \(c\)-compact for \(\tau\), hence for \(\tau'\) so that \(V \cap A\) is \(\tau'\)-closed.

From (*) and Lemma 1.3 we have, for large \(i\),
\[
\lambda^{-1} x_i \in \lambda(V \cap A) \subset \lambda V.
\]
We see that \(x_i \in \lambda^2 V \subset U\) for large \(i\).

Remark. Theorem B is only of interest if \(K\) is spherically complete.

See, however, §3.
§ 2. 'CHARACTERIZATIONS OF COMPACTOIDS BY STABILITY

In this section we shall prove 'converses' to Theorems A&B (Theorems A'&B').

Remark. If, in Theorem A', (see 2.3) we add the assumption that K is spherically complete or that E is a polar space over a nonsphe-

rically complete K, we may obtain a short proof of Theorem A' by choosing for τ' the weak topology.

For convenience we introduce the following terminology. Let τ₁, τ₂ be locally convex topologies on a K-vector space E. We say that τ₁ is closedly related to τ₂ if τ₁ ≤ τ₂ and if there exists a τ₂-

neighbourhood base of 0 in E consisting of absolutely convex τ₁-
closed sets.

2.1 LEMMA. Let τ₁, τ₂ be locally convex topologies on a K-vector space E. The following are equivalent.

(a) τ₁ is closedly related to τ₂.

(b) The set P consisting of all τ₂-continuous q for which

\[ q = \sup \{ p : p \text{ is a } \tau_1 \text{-continuous seminorm}, p \leq q \} \]

is a base of continuous seminorms for the topology τ₂.

Proof. (a) ⇒ (b). Let U be a τ₂-neighbourhood base of 0 consisting of absolutely convex τ₂-open and τ₁-closed sets. For each U ∈ U, define

\[ U^ε = \begin{cases} U & \text{if the valuation of } K \text{ is discrete} \\ \cap \lambda U & \text{if the valuation of } K \text{ is dense.} \end{cases} \]
Of course, \( U' = \{U^e : U \in U\} \) is again a \( \tau_2 \)-neighbourhood base of 0 consisting of absolutely convex \( \tau_2 \)-open and \( \tau_1 \)-closed sets. But in addition we have for each \( U \in U' \)

\[ U = \{z \in E : p_U(z) \leq 1\} \]

where \( p_U \) is the Minkowski function of \( U \). Set

\[ P' = \{p_U : U \in U'\}. \]

Clearly \( P' \) is a base of continuous seminorms for \( \tau_2 \). We shall prove that \( P' \subseteq P \). (Then (β) follows.) Let \( U \in U' \). From Proposition 4.2 it follows that for each \( x \in E \setminus U \) there exists a \( \tau_1 \)-continuous seminorm \( q^x \) such that \( q^x(x) > 1 \), \( q^x \leq 1 \) on \( U \), \( q^x(z) < 1 \) if \( z \in E \setminus U \). (If the valuation of \( K \) is discrete we may obtain \( q^x \) by multiplying \( p \) of Proposition 4.2 by a suitable constant, if the valuation of \( K \) is dense there is, by definition of \( U^e \), a \( \lambda \in K \), \( |\lambda| < 1 \) such that \( \forall x \in U \).) Now set

\[ q = \sup_{x \in E \setminus U} \{q^x : x \in E \setminus U\}. \]

One verifies directly that \( q = p_U \) which finishes the first part of the proof.

(β) ⇒ (α). For each \( p \in P \) set

\[ U_p = \{x \in E : p(x) \leq 1\} \]

and

\[ U = \{U_p : p \in P\} \]

One proves in a standard way that \( U \) is a \( \tau_2 \)-neighbourhood base of 0 consisting of \( \tau_1 \)-closed sets.
2.2 LEMMA. Let \( \tau \) be a locally convex topology on a K-vector space \( E \), let \( D \) be a linear subspace of \( E \), let \( \tau_D \) be the restriction of \( \tau \) to \( D \). If \( \tau_D' \) is a locally convex topology on \( D \) closedly related to \( \tau_D \), then there is a locally convex topology \( \tau' \) on \( E \) closedly related to \( \tau \) such that \( \tau'|_D = \tau'_D \).

Proof. Let \( \Gamma \) be the collection of all \( \tau \)-continuous seminorms on \( E \), let \( \Gamma^*_D(\Gamma'_D) \) be the collection of all \( \tau_D^- (\tau'_D^-) \)-continuous seminorms on \( D \). Define \( \tau' \) to be the locally convex topology on \( E \) generated by

\[
\Gamma' := \{ p \in \Gamma : p|_D \in \Gamma'_D \}.
\]

Obviously \( \tau' \leq \tau \), \( \tau'|_D = \tau'_D \) (Proposition 4.1), and \( \Gamma' \) is the set of all \( \tau' \)-continuous seminorms. To complete the proof that \( \tau' \) is closedly related to \( \tau \) we shall construct a base \( P_E \) of continuous seminorms for \( \tau \) such that each \( p \in P_E \) is a supremum of \( \tau' \)-continuous seminorms (Lemma 2.1). To this end, let

\[
P_D := \{ p \in \Gamma_D : p = \sup \{ q \in \Gamma_D' : q \leq p \} \}
\]

and

\[
P_E := \{ p \in \Gamma : p|_D \in P_D \}.
\]

By assumption and Lemma 2.1, \( P_D \) is a base of continuous seminorms for \( \tau_D \). To prove that \( P_E \) is a base for \( \tau \), let \( p \in \Gamma \). Then \( p|_D \in \Gamma'_D \).

There is an \( s \in P_D \) with \( p \leq s \) on \( D \). As \( s \in P_D \) it extends to a \( \tau \in \Gamma \).

Set \( q := \max (t, p) \). Then \( q \in \Gamma \), \( q|_D = s \in P_D \) (so that \( q \in P_E \)) and \( p \leq q \).

Finally we prove that

\[
p = \sup \{ q \in \Gamma' : q \leq p \}
\]

by constructing, for each \( x \in E \), a \( q \in \Gamma' \), \( q \leq p \) such that \( q(x) \) is close
to \( p(x) \). We distinguish two cases.

(i) \( p(x-d) \geq p(x) \) for all \( d \in D \). Then we take for \( q \) the quotient semi-norm of \( p \\
q(y) = \inf \{ p(y-d) : d \in D \} \quad (y \in E) \\
We have \( q \leq p \), \( q(x) = p(x) \) and \( q \in \Gamma' \) (since \( q = 0 \) on \( D \)).

(ii) There exists a \( d \in D \) with \( p(x-d) < p(x) \). Then \( p(x) = p(d) \neq 0 \) and there is a \( c \in (0,1) \) with \( p(x-d) = cp(x) \). Let \( c' \in (0,1) \), \( c' \geq c \). By definition \( p|_D \in P_D \) so there is a \( q_1 \in \Gamma_D \) with \( q_1 \leq p \) on \( D \) and \( q_1(d) > c'p(d) \). By Proposition 4.1, \( q_1 \) extends to a \( q \in \Gamma \) with \( q \leq p \) on \( E \). Then \( q \in \Gamma' \). We have

\[
q(d) = q_1(d) > c'p(d) = c'p(x)
\]

but also

\[
q(x-d) \leq p(x-d) = cp(d) \leq c'p(d) < q_1(d) = q(d)
\]

so that \( q(x) = q(d) > c'p(x) \). As we may take \( c' \) close to 1 this completes the proof.

2.3 THEOREM A'. Let \( A \) be a bounded absolutely convex subset of a locally convex space \((E,\tau)\) over \( K \). Suppose that for each locally convex topology \( \tau' \leq \tau \) on \( E \), for which there exists a \( \tau' \)-neighbourhood base of \( 0 \) consisting of absolutely convex \( \tau' \)-closed sets, we have \( \tau = \tau' \) on \( A \). Then \( A \) is a compactoid in \((E,\tau)\).

Proof. By Proposition 4.4 it suffices to prove that, for any countable subset \( X \) of \( A \), the set \( B : = \text{co} X \) is a compactoid in \( D : = [X] \), with the restriction topology \( \tau_D \) of \( \tau \). Now \( D \) is of countable type so
its weak topology $\tau_D$ is closely related to $\tau_D$ \([6],\) Proposition 5.2 (\(\gamma\)). By Lemma 2.2 $\tau'$ is the restriction of a locally convex topology $\tau'$ on $E$ that is closely related to $\tau$. By assumption $\tau = \tau'$ on $A$, hence $\tau_D = \tau_D'$ on $B$. Now $B$ is bounded, hence a compactoid for the weak topology $\tau_D'$. By Proposition 4.5 $B$ is also a $\tau_D'$-compactoid.

Remark. The example $E = A = K$ shows the relevance of the boundedness condition in Theorem A'. I do not know whether the absolute convexity of $A$ can be dropped.

2.4 THEOREM B'. Let $A$ be a closed bounded absolutely convex subset of a Hausdorff locally convex space $(E,\tau)$ over $K$. Suppose that for each locally convex Hausdorff topology $\tau' \leq \tau$ on $E$ we have $\tau = \tau'$ on $A$. Then $A$ is a complete compactoid in $(E,\tau)$.

Proof. Theorem A' yields compactoidity of $A$. Suppose $A$ is not $\tau$-complete; we construct a Hausdorff locally convex topology $\tau'$ on $E$ with $\tau' \leq \tau$ on $E$ and $\tau' \neq \tau$ on $A$. As $A$ is closed there exists a $\tau$-Cauchy net $(x_i)_{i \in I}$ in $A$ that does not converge in $(E,\tau)$. Let $\tau'$ be the locally convex topology generated by the set $P$ of all $\tau$-continuous seminorm $p$ for which $\lim_{i \to I} p(x_i) = 0$. Obviously $\tau' \leq \tau$ and $\tau' \neq \tau$ on $A$.

It remains to be shown that $\tau'$ is Hausdorff. The net $(x_i)_{i \in I}$ converges to an $x$ in the completion $(E,\tau)^{\sim}$ of $(E,\tau)$, and $x \notin (E,\tau)$. Then for each $a \in E$, $a \neq 0$ the elements $a, x$ are linearly independent and there exists a continuous seminorm $q$ on $(E,\tau)^{\sim}$ for which $q(x) = 0$, $q(a) \neq 0$ (consider the quotient map $(E,\tau)^{\sim} \to (E,\tau)/Kx$). Hence, $q|E \in P$. It follows that $P$ separates the points of $E$. 
2.5 COROLLARY. Let $A$ be a closed bounded absolutely convex subset of a Hausdorff locally convex space $(E, \tau)$ over a spherically complete field $K$. The following are equivalent.

(a) $A$ is $c$-compact.

($\beta$) $A$ is a complete compactoid.

($\gamma$) If $\tau'$ is a Hausdorff locally convex topology, weaker than $\tau$, then $\tau = \tau'$ on $A$.

Proof. Proposition 4.6, Theorems B&B'.

Remark. There exists noncomplete absolutely convex compactoids for which ($\gamma$) is true. (Let $K$ be the spherical completion of $\mathbb{C}_p$ and set

$$A = \{ (\xi_1, \xi_2, \ldots) \in \mathbb{C}_0 : \sup_1 \xi_i |p^i| < 1 \}.$$

$$B = \{ (\xi_1, \xi_2, \ldots) \in \mathbb{C}_0 : \sup_1 \xi_i |p^i| \leq 1 \}.$$

$B$ is $c$-compact, $pB \subset A \subset B$ so ($\gamma$) holds for $A$. However, $A$ is not closed.)
§ 3. 'THEOREM B FOR NONSPHERICALLY COMPLETE K

Contrary to the Theorems A, A', B', Theorem B is a triviality for nonspherically complete K. The hope that absolutely convex complete compactoids are topologically stable under continuous linear injections (inspired by Theorem B') is too optimistic as the following example shows.

3.1 EXAMPLE. Let K be not spherically complete, let A be the 'closed' unit ball of $c_0$. Then A is a complete compactoid for the weak topology $\sigma$. However, for the topology $\sigma'$ of coordinatewise convergence we have $\sigma' \leq \sigma$ but $\sigma \neq \sigma'$ on A.

Proof. As $c_0$ is reflexive ([4], Theorem 4.17) and A is weakly closed the first statement follows from [6], Theorem 9.6. The sequence $e_1, e_2, \ldots$ of the standard unit vectors does not converge weakly ([6], Proposition 4.11) but does converge coordinatewise (to 0).

On the positive side we have the following theorem (see also the remarks below).

3.2 THEOREM. Let A be an absolutely convex complete metrizable compactoid in a Hausdorff locally convex space $(E, \tau)$ over K. Let $\tau'$ be a Hausdorff locally convex topology on E, weaker than $\tau$. Then $\tau = \tau'$ on A.

Proof. Without loss of generality we may assume $E = [A]$ (then, by Proposition 4.3, $(E, \tau)$ is of countable type) and that A is edged
i.e. that, if the valuation of \( K \) is dense, \( A = \bigcap_{\lambda \geq 1} \lambda A. \)

Let \( E'_A \) be the dual space of \( (E, \tau) \) equipped with the topology of uniform convergence on \( A \). This topology is induced by the single norm \( f \mapsto \sup \{|f(x)| : x \in A\} \).

We first prove (i), (ii) below.

(i) \( E'_A \) is strongly polar ([6], Definition 3.5). Proof. By [6], Proposition 8.2 there is a sequence \( e_1, e_2, \ldots \) in \( \lambda A \) for some \( \lambda \in K, |\lambda| > 1 \) with \( \lim_{n \to \infty} e_n = 0 \) such that \( A \subseteq \text{co}\{e_1, e_2, \ldots\} \subseteq \lambda A \). The formula

\[
 f \mapsto (f(e_1), f(e_2), \ldots) \quad (f \in E')
\]

defines a linear homeomorphism of \( E'_A \) into \( c_0 \). Now \( c_0 \) is of countable type hence ([6], Proposition 4.4) strongly polar, so are its subspaces ([6], Proposition 4.1) and, therefore, \( E'_A \).

(ii) The canonical map \( E \to (E'_0)' \) is surjective. Proof. By [6], Lemma 7.1 (ii) the map \( E \to (E'_0)' \) is bijective (where \( E'_0 \) is \( E'_A \), with the topology of pointwise convergence), so we shall prove that \( (E'_0)' = (E'_0)' \). To this end we shall check that the covering \( \{\lambda A : \lambda \in K\} \) of \( E \) satisfies the conditions of [6], Proposition 7.4.

Each \( \lambda A \) is edged and a complete compactoid for \( \tau \) and by [6], Theorem 5.13, also a complete compactoid for the weak topology \( \sigma(E, E') \).

Now we finish the proof as follows. Let \( \sigma (\sigma') \) be the weak topology of \( \tau (\tau') \). By Corollary 1.5 and the remark following it we have \( \sigma = \tau \) on \( A \), \( \sigma' = \tau' \) on \( A \) and \( \sigma' \leq \sigma \) on \( E \). We prove that \( \sigma = \sigma' \) on \( A \).

Let \( F : = (E, \sigma') \). Then \( F \subseteq E' \) and, as \( \sigma' \) is Hausdorff, \( F \) separates the points of \( E \).

We claim that \( F \) is dense in \( E'_A \). Indeed, if \( \phi \in (E'_0)' \), \( \phi = 0 \) on \( F \) then, by (ii) there exists an \( x \in E \) for which \( \phi(f) = f(x) \) for all \( f \in E' \) so
that \( f(x) = 0 \) for all \( f \in F \), i.e. \( x = 0 \). By (i) and [6], Corollary 4.9, the norm closure of \( F \) equals its weak closure which is \( E' \). Now let 

\( (x_i)_{i \in I} \) be a net in \( A \) converging to 0 for \( \sigma' \). Then \( \lim_{i} f(x_i) = 0 \) for all \( f \in F \). By the above, for each \( g \in E' \) there is a net in \( F \) converging to \( g \) uniformly on \( A \). But then \( \lim_{i} g(x_i) = 0 \) so that \( \lim_{i} x_i = 0 \) for \( \sigma \).

**Remark 1.** If \( K \) is spherically complete each locally convex space is strongly polar ([6], §4). So an obvious modification makes the above proof valid for a complete absolutely convex compactoid in a locally convex space over \( K \) yielding an alternative proof of Theorem B.

**Remark 2.** As a contrast to Theorem 3.2 we mention the following result of A. van Rooij ([5], Theorem 6.28). Let \( A \) be an absolutely convex subset of a Banach space \( E \) over a nonspherically complete field \( K \). If for each \( K \)-Banach space \( F \) and each \( T \in L(E,F) \) the set \( TA \) is closed then \( A \) is finite dimensional.

### 3.3 COROLLARY

Let \( A, B \) be absolutely convex compactoids in a Fréchet space \( (E, \tau) \) over \( K \).

(i) If \( A, B \) are closed and \( A \cap B = (0) \) then \( A+B \) is closed.

(ii) If \( \tau' \leq \tau \) is a Hausdorff locally convex topology on \( E \) then \( \tau = \tau' \) on \( A \).

**Proof.** (i) \( A \times B \) is a complete compactoid in \( E \times E \). As \( [A] \cap [B] = 0 \), addition is a continuous linear bijection:

\[
[A] \times [B] \rightarrow [A+B]
\]

sending \( A \times B \) onto \( A+B \). It follows from Theorem 3.2 that \( A+B \) is
complete, hence closed in $E$. For (ii) apply Theorem 3.2 to the closure of $A$.

PROBLEM. For a nonspherically complete field $K$, characterize the absolutely convex complete compactoids $A$ in a Hausdorff locally convex space $(E, \tau)$ over $K$ for which $\tau = \tau'$ on $A$ for any Hausdorff locally convex topology $\tau'$ on $E$ that is weaker than $\tau$. 
§ 4. APPENDIX

4.1 PROPOSITION. Let $D$ be a linear subspace of a $K$-vector space $E$. If $p$ is a seminorm on $E$ and $q$ is a seminorm on $D$ such that $q \leq p$ on $D$ then $q$ can be extended to a seminorm $\overline{q}$ on $E$ for which $\overline{q} \leq p$ on $E$.

Proof. Set $\overline{q}(x) = \inf_{d \in D} \max(p(x-d), q(d)) \ (x \in E)$.

4.2 PROPOSITION. Let $A$ be a closed absolutely convex subset of a locally convex space $E$ over $K$, let $x \in E \setminus A$. There exists a continuous seminorm $p$ with $p(a) < 1$ for each $a \in A$ and $p(x) = 1$. If the valuation of $K$ is discrete $p$ can be chosen such that $p(z) \in \mathbb{N}$ for each $z \in E$.

Proof. Let $U$ be an open absolutely convex set that is maximal with respect to the properties $A \subset U$, $x \notin U$. Let $q$ be the Minkowski function of $U$. Then $q$ is continuous and

$$\{z \in E : q(z) < 1\} \subset U \subset \{z \in E : q(z) \leq 1\}.$$

If $q(x) > 1$ then $p := q(x)^{-1}q$ satisfies the requirements, so assume $q(x) = 1$. Set $p := q$. Obviously, $p(z) \in \mathbb{N}$ for all $z \in E$ for a discretely values field $K$; we prove that $p(u) < 1$ for each $u \in U$. Suppose $p(u) = 1$ for some $u \in U$. The set $Ku + U$ is absolutely convex and it properly contains $U$ so, by maximality, it contains $x$. There is a $\lambda \in K$ for which $x - \lambda u \in U$. As $x \notin U$ we must have $|\lambda| > 1$. As $p(x - \lambda u) \leq 1$ and $p(\lambda u) > 1$ we arrive at $p(x) > 1$, a contradiction.

4.3 PROPOSITION. If $A$ is a compactoid in a locally convex space $E$ over $K$ then $[A]$ is of countable type ([6], Definition 4.3).
Proof. Set $E = [A]$. For each continuous seminorm $p$, let $\pi_p$ be the canonical map of $E$ onto the normed space $E_p = E/\text{Kerp}$. Then $\pi_p(A)$ is a compactoid in $E_p$, and absorbing. By [6], Proposition 8.2 there exist $e_1, e_2, \ldots \in E_p$ with $\pi_p(A) \subseteq \overline{\text{co}}\{e_1, e_2, \ldots\}$ so that $E_p = [e_1, e_2, \ldots]$ is of countable type. Then so is $\Pi E_p$ ([6], Proposition 4.12 (iii)) and is $E$ (being linearly homeomorphic to a subspace of $\Pi E_p$).

4.4 PROPOSITION. Let $A$ be an absolutely convex subset of a locally convex space $E$ over $K$. If each countable subset of $A$ is a compactoid then $A$ is a compactoid.

Proof. For Banach spaces $E$ this is proved in [4], Theorem 4.37. From [1], Lemma 1.3 it follows that the statement is true for normed spaces $E$. Now let $E$ be locally convex. With $\pi_p$, $E_p$ as in the proof of Proposition 4.3 we have that each $\pi_p(A)$ is a compactoid in $E_p$. But then $\Pi P \pi_p(A)$ is a compactoid ([1], Proposition 1.7) and so is $A$ (being linearly homeomorphic to a subset of $\Pi P \pi_p(A)$).

4.5 PROPOSITION. Let $A$ be an absolutely convex subset of a $K$-vector space $E$. Let $\tau_1, \tau_2$ be locally convex topologies on $E$ such that $\tau_1 = \tau_2$ on $A$. Then $A$ is a $\tau_1$-compactoid if and only if $A$ is a $\tau_2$-compactoid.

Proof. Suppose $A$ is a $\tau_1$-compactoid. Let $U$ be a $\tau_2$-neighbourhood of 0. Let $\lambda \in K$, $0 < |\lambda| < 1$. There is an absolutely convex $\tau_2$-neighbourhood $U'$ of 0 with $U' \subseteq \lambda U$. There is an absolutely convex $\tau_2$-neighbourhood $V$ of 0 with $V \cap A \subseteq U' \cap A$. By Katsaras' theorem ([3], or [6], Lemma 8.1) there exist $a_1, \ldots, a_n \in A$ such that $\lambda A \subseteq V + \text{co} \{a_1, \ldots, a_n\}$. Then also $\lambda A \subseteq V \cap A + \text{co} \{a_1, \ldots, a_n\}$. We see that $A \subseteq \lambda^{-1}(V \cap A) + \text{co} \{\lambda a_1, \ldots, \lambda a_n\}$. It follows that $A$ is a $\tau_2$-compactoid.
4.6 PROPOSITION. Let $A$ be a bounded absolutely convex subset of a Hausdorff locally convex space $E$ over a spherically complete field $K$. The following are equivalent.

(a) $A$ is $c$-compact.

(b) $A$ is a complete compactoid.

Proof. [2], Proposition 4, p.93. A more elementary proof for Banach spaces $E$ is given in [5], Theorem 6.15. From this the general statement can be obtained in a straightforward way by using the embedding $E \rightarrow \mathbb{E}^{\sim}$ (where $\mathbb{E}^{\sim}$ is the completion of $\mathbb{E}$) and the properties of $c$-compact sets proved in [7].
REFERENCES.


