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COMPACT SUBSETS OF A TYCHONOFF SET

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The paper establishes a relation between the partial exponential law and the compactness of certain subsets of Tychonoff sets of multifunctions, and deduces consequences bearing on the Ascoli theorems established by Weston and Lin-Rose.

1. Introduction. The “Tychonoff set” is an abstraction of a class of sets arising in extensions of the classical Tychonoff theorem to multifunction context ([2],[5]). Extending the definition of the partial exponential law to multifunctions, we show that, when it is satisfied for a topology τ , certain subsets of a Tychonoff set are τ -compact. This approach — which is a non-trivial modification of the method introduced into function Ascoli theory by Noble [7] — will yield, in particular, sufficient conditions for compactness relative to the compact open topology.

In [6] Lin and Rose introduced a multifunction extension of the Kelley-Morse notion of even continuity, and proved a multifunction Ascoli theorem of the Weston type, without, however, showing that it contains the prototype [11, p. 20]. We deduce from our criterion a generalization of the Lin-Rose theorem. We show that this generalization contains the Weston Ascoli theorem and yields corollaries equivalent to the Tychonoff theorems for point-compact and point-closed multifunctions established in [2].

2. Multifunctions. We review the established definitions for multifunctions ([1],[9],[10]): Let X, Y be nonempty sets. A *multifunction* is a point to set correspondence $f: X \rightarrow Y$ such that, for all $x \in X, fx$ is a nonempty subset of Y . For $A \subseteq X, B \subseteq Y$ it is customary to write $f(A) = \bigcup_{x \in A} fx, f^-(B) = \{x: x \in X \text{ and } fx \cap B \neq \phi\}$ and $f^+(B) = \{x: x \in X \text{ and } fx \subseteq B\}$. If Y is a topological space, a multifunction $f: X \rightarrow Y$ is *point-compact* (*point-closed*) if fx is compact (closed) for all $x \in X$. If X, Y are topological spaces, a multifunction $f: X \rightarrow Y$ is *continuous* if $f^-(U), f^+(U)$ are open in X whenever U is open in Y . Henceforth the set of all continuous multifunctions (continuous functions) on a topological space X to a topological space Y will be denoted $\mathcal{C}(X, Y)(C(X, Y))$.

Let $\{Y_x\}_{x \in X}$ be a family of nonempty sets. The *m-product* $P\{Y_x: x \in X\}$ of the Y_x is the set of all multifunctions $f: X \rightarrow \bigcup_{x \in X} Y_x$

such that $fx \subseteq Y_x$ for all $x \in X$. In the case $Y_x = Y$ for all $x \in X$, the m -product of the Y_x , denoted Y^{mX} , is the set of all multifunctions on X to Y . For $x \in X$, the x -projection $pr_x: P\{Y_x: x \in X\} \rightarrow Y_x$ is the multifunction defined by $pr_x f = fx$. If the Y_x are topological spaces, the *pointwise topology* τ_p on $P\{Y_x: x \in X\}$ is defined to be the topology having as open subbase the sets of the forms $pr_x^-(U_x), pr_x^+(U_x)$, where U_x is open in $Y_x, x \in X$ ([5], [8]).

For $F \subseteq Y^{mX}, x \in X$, we write $F[x] = \bigcup_{f \in F} fx$. Let Y be a topological space. We say that a subset F of Y^{mX} is *pointwise bounded* if $F[x]$ has compact closure in Y for all $x \in X$. We say that a subset T of Y^{mX} is *Tychonoff* if, for every pointwise bounded subset F of T , $T \cap P\{\overline{F[x]}: x \in X\}$ is τ_p -compact. The following subsets of Y^{mX} are Tychonoff:

- (1) Y^X , by the classical Tychonoff theorem.
- (2) Y^{mX} , by the theorem of Lin [5, p. 400].
- (3) The set of all point-closed members of Y^{mX} , by Corollary 2 of [2].
- (4) The set of all point-compact members of Y^{mX} , by Corollary 3 of [2].

LEMMA 2.1. *If F is a pointwise bounded subset of a Tychonoff set T , then the τ_p -closure of F is compact.*

Proof. Let \bar{F} denote the τ_p -closure of F . Since $P\{\overline{F[x]}: x \in X\} \cap T$ is a τ_p -compact subset of T , it suffices to show that $\bar{F} \subseteq P\{\overline{F[x]}: x \in X\}$. Let $f \in \bar{F}$. We must show that, for $x \in X, y \in fx$ and an open neighbourhood V of $y, F[x] \cap V \neq \emptyset$. Since $M = \{h: h \in T \text{ and } hx \cap V \neq \emptyset\}$ is a τ_p -neighborhood of f , there exists $h' \in M \cap F$. Then $h'x \cap V \neq \emptyset$ and $h'x \subseteq F[x]$, so $F[x] \cap V \neq \emptyset$.

Let X, Y be topological spaces. The multifunction $(f, x) \rightarrow fx$ on $Y^{mX} \times X$ to Y , or any restriction, will be denoted by the symbol ω . Let $F \subseteq Y^{mX}$. A topology τ on F is said to be *jointly continuous* if $\omega: (F, \tau) \times X \rightarrow Y$ is continuous [8, p. 48]. The *compact open topology* τ_c on Y^{mX} is defined to be the topology having as open subbase the sets of the forms $\{f: f(K) \subseteq U\}, \{f: fx \cap U \neq \emptyset \text{ for all } x \in K\}$, where K is a compact subset of X and U is open in Y ([6, p. 742], [8, p. 47]). Obviously τ_c is larger than τ_p .

3. Partial exponential law. Let X, Y, Z be topological spaces. An element $f \in Z^{m(X \times Y)}$ determines the function $\tilde{f}: x \rightarrow f(x, \cdot)$ on X to Z^{mY} . The function $\mu: f \rightarrow \tilde{f}$, called the *exponential map*, is a bijection of $Z^{m(X \times Y)}$ onto $(Z^{mY})^X$. It is clear that if $f \in \mathcal{C}(X \times Y, Z)$, then $\tilde{f}(x) = f(x, \cdot) \in \mathcal{C}(Y, Z)$ for all $x \in X$. When τ is a topology on

Z^{m^Y} , we say that (X, Y, Z, τ) satisfies the partial exponential law if $\mu(\mathcal{C}(X \times Y, Z)) \subseteq C(X, (\mathcal{C}(Y, Z), \tau))$.

We establish now the main theorem of the paper:

THEOREM 3.1. *Let T be a Tychonoff set of multifunctions on a topological space X to a topological space Y , and let τ be a topology on Y^{m^X} such that (K, X, Y, τ) satisfies the partial exponential law for all compact spaces K . Then a subset F of T is τ -compact if*

- (a) F is τ -closed in T ,
- (b) F is pointwise bounded, and
- (c) τ_p is jointly continuous on the τ_p -closure of F in T .

Proof. Let \bar{F} denote the τ_p -closure of F in T and let $\omega: (\bar{F}, \tau_p) \times X \rightarrow Y$. By (c), ω is continuous, so $\bar{F} \subseteq \mathcal{C}(X, Y)$. Since T is a Tychonoff set, (b) implies, by Lemma 2.1, that \bar{F} is τ_p -compact. Then $\tilde{\omega}: (\bar{F}, \tau_p) \rightarrow (\mathcal{C}(X, Y), \tau)$ is continuous. Since $\tilde{\omega}$ is the inclusion map, $\bar{F} = \tilde{\omega}(\bar{F})$ is τ -compact. Since, by (a), F is τ -closed in \bar{F} , it follows that F is τ -compact.

The application of this theorem to τ_c depends on the following generalization to multifunctions of Lemma 1 of R. H. Fox [3, p. 430]:

LEMMA 3.2. (X, Y, Z, τ_c) satisfies the partial exponential law.

Proof. Let $f \in \mathcal{C}(X \times Y, Z)$. Let $x \in X$. Since $f(x, \cdot) = f \circ j$, where $j(y) = (x, y)$ ($y \in Y$), $f(x, \cdot)$ is continuous [9, p. 35]. Thus \tilde{f} maps X into $\mathcal{C}(Y, Z)$. It remains to show that $\tilde{f}: X \rightarrow (\mathcal{C}(Y, Z), \tau_c)$ is continuous.

Let $M = \{h: h \in \mathcal{C}(Y, Z) \text{ and } h(K) \subseteq U\}$, where K is a compact subset of Y and U is open in Z . Let $x_0 \in \tilde{f}^{-1}(M)$. Then $f(x_0, \cdot) \in M$, so $\{x_0\} \times K \subseteq f^+(U)$. By the theorem of Wallace [4, p. 142], there is a neighbourhood V of x_0 such that $V \times K \subseteq f^+(U)$. Let $x \in V$. Then, for all $y \in K$, $\tilde{f}(x)y = f(x, y) \subseteq U$, so $\tilde{f}(x)(K) \subseteq U$. Thus $x \in \tilde{f}^{-1}(M)$, and we have shown that $\tilde{f}^{-1}(M)$ is open in X .

Let $M = \{h: h \in \mathcal{C}(Y, Z) \text{ and } hy \cap U \neq \emptyset \text{ for all } y \in K\}$, where K is a compact subset of Y and U is open in Z . Let $x_0 \in \tilde{f}^{-1}(M)$. Then $f(x_0, \cdot) \in M$, so $\{x_0\} \times K \subseteq f^-(U)$. There is a neighbourhood V of x_0 such that $V \times K \subseteq f^-(U)$. Let $x \in V$. Then, for all $y \in K$, $\tilde{f}(x)y \cap U \neq \emptyset$, so $\tilde{f}(x) \in M$, that is, $x \in \tilde{f}^{-1}(M)$, and we have shown that $\tilde{f}^{-1}(M)$ is open in X .

4. Even continuity. Let X, Y be topological spaces and let $F \subseteq Y^{m^X}$. Following [6], we say that F is *evenly continuous* if, for each

$(x, y) \in X \times Y$ and each neighborhood V of y , there exist neighbourhoods U, W of x, y , respectively, such that

- (a) $f \in F$ and $fx \cap W \neq \emptyset$ imply $U \subseteq f^{-}(V)$, and
- (b) $f \in F$, $fx \cap W \neq \emptyset$ and $fx \subseteq V$ imply $f(U) \subseteq V$.

LEMMA 4.1. *Let X, Y be topological spaces and let $F \subseteq Y^{m \times}$. If F is evenly continuous, τ_p on F is jointly continuous.*

Proof. Let $\omega: (F, \tau_p) \times X \rightarrow Y$. Suppose that $(f, x) \in \omega^{-}(V)$, where V is open in Y . Choose $y \in fx \cap V$. Then there exist open neighbourhoods U, W of x, y , respectively, such that $g \in F$ and $gx \cap W \neq \emptyset$ imply $U \subseteq g^{-}(V)$. Write $M = \{h: h \in F \text{ and } hx \cap W \neq \emptyset\}$. Then $M \times U$ is a neighbourhood of (f, x) , which is contained in $\omega^{-}(V)$. Now suppose that $(f, x) \in \omega^{+}(V)$, where V is open in Y . Then $fx \subseteq V$. Choose $y \in fx$. There exist open neighbourhoods U, W of x, y , respectively, such that $g \in F$, $gx \cap W \neq \emptyset$ and $gx \subseteq V$ imply $g(U) \subseteq V$. Write $M = \{h: h \in F, hx \cap W \neq \emptyset \text{ and } hx \subseteq V\}$. Then $M \times U$ is a neighbourhood of (f, x) , which is contained in $\omega^{+}(V)$.

COROLLARY 4.2. *Let X, Y be topological spaces and let $F \subseteq Y^{m \times}$. If F is evenly continuous, then each member of F is continuous.*

The following result, which generalizes the Ascoli theorem of Lin and Rose [6, p. 746], contains also the Weston Ascoli theorem [11, p. 20]:

THEOREM 4.3. *Let T be a Tychonoff set of multifunctions on a topological space X to a topological space Y . Then a subset F of T is τ_c -compact if*

- (a) F is τ_c -closed,
- (b) F is pointwise bounded, and
- (c) F is evenly continuous.

Proof. By Lemma 3.2, this theorem will follow as a corollary of Theorem 3.1 if we show that τ_p is jointly continuous on the τ_p -closure \bar{F} of F . By (c) and Lemma 4.1, τ_p on F is jointly continuous. By (a), $F = \bar{F}$, where \bar{F} is the τ_c -closure of F . Finally, by (c) and Lemma 3.1 of [6, p. 744], $\bar{F} = F$.

COROLLARY 4.4. *Let $(Y^{m \times})_0((Y^{m \times})_1)$ be the set of all point-compact (point-closed) multifunctions on a topological space X to a*

topological space Y . Then a subset F of $(Y^{m^X})_0((Y^{m^X})_1)$ is τ_c -compact if

- (a) F is τ_c -closed,
- (b) F is pointwise bounded, and
- (c) F is evenly continuous.

5. REMARKS. The Lin-Rose Ascoli theorem [6, p. 746], depends, apart from Lemma 3.1 of [6], on the Tychonoff theorem of Lin [5, p. 400]. Consequently, the Corollary 4.4 can be proved by the Lin-Rose argument, using the Tychonoff theorems of [2]. We will prove the converse implication: Let $\{Y_x\}_{x \in X}$ be a family of compact spaces. We will deduce from Corollary 4.4 that $F = (P\{Y_x : x \in X\})_0$ is τ_p -compact.

We may suppose the Y_x disjoint. Assign to X the discrete topology and let $Y = \bigcup_{x \in X} Y_x$ have the sum topology. We have $F \subseteq (Y^{m^X})_0$ and, since X is discrete, F is evenly continuous [6, p. 743]. Since $F[x] = Y_x$ and Y_x is closed in Y , F is pointwise bounded. If we show that F is τ_p -closed, it will follow from Corollary 4.4 that F is τ_c -compact and therefore τ_p -compact. Let $\{f_\alpha\}$ be a net in F which is τ_p -convergent to an element $f \in (Y^{m^X})_0$. Let $x \in X$. Let $y \in fx$, and let V be an open neighborhood of y . Since $\{h : h \in (Y^{m^X})_0$ and $hx \cap V \neq \emptyset\}$ is a τ_p -neighborhood of f , $f_\alpha x \cap V \neq \emptyset$ eventually. Since $f_\alpha x \subseteq Y_x$, $Y_x \cap V \neq \emptyset$. This shows that $y \in \bar{Y}_x = Y_x$, proving that $f \in F$.

We prove similarly the same implication for $F = (P\{Y_x : x \in X\})_1$.

REFERENCES

1. C. Berge, *Topological Spaces*, The MacMillan Company, New York (1965).
2. G. Fox and P. Morales, *A general Tychonoff theorem for multifunctions*, to appear in *Canad. Math. Bull.*
3. R. H. Fox, *On topologies for function spaces*, *Bull. Amer. Math. Soc.*, **51** (1945), 429-432.
4. J. Kelley, *General Topology*, D. Van Nostrand, New York (1965).
5. Y. F. Lin, *Tychonoff's theorem for the space of multifunctions*, *Amer. Math. Monthly*, **74** (1967), 399-400.
6. Y. F. Lin and D. A. Rose, *Ascoli theorem for spaces of multifunctions*, *Pacific J. Math.*, **34** (1970), 741-747.
7. N. Noble, *Ascoli theorems and the exponential map*, *Trans. Amer. Math. Soc.*, **143** (1969), 393-411.
8. R. E. Smithson, *Topologies on sets of relations*, *J. Nat. Sci. and Math. (Lahore)*, **11** (1971), 43-50.
9. ———, *Multifunctions*, *Nieuw. Arch. Wisk.*, **20** (1972), 31-53.
10. W. L. Strother, *Continuous multi-valued functions*, *Bol. Soc. Mat. São Paulo*, **10** (1955), 87-120.
11. J. D. Weston, *A generalization of Ascoli's theorem*, *Mathematika*, **6** (1959), 19-24.

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