

## OPENNESS AND CONVEXITY FOR MOMENTUM MAPS

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**ABSTRACT.** The purpose of this paper is finding the essential attributes underlying the convexity theorems for momentum maps. It is shown that they are of a topological nature; more specifically, we show that convexity follows if the map is open onto its image and has the so-called local convexity data property. These conditions are satisfied in all the classical convexity theorems and hence they can, in principle, be obtained as corollaries of a more general theorem that has only these two hypotheses. We also prove a generalization of the so-called Local-to-Global Principle that only requires the map to be closed and to have a normal topological space as domain, instead of using a properness condition. This allows us to generalize the Flaschka-Ratiu convexity theorem to noncompact manifolds.

### 1. INTRODUCTION

The problem of describing the image of a momentum map defined on a symplectic manifold has generated a large amount of research in the past twenty years and it remains to this day one of the most active areas in symplectic geometry and its applications to Hamiltonian dynamics, especially bifurcation theory. In 1982 Atiyah [3] and, independently, Guillemin and Sternberg [11] proved the following result about the convexity of the image of the momentum map associated to the action of a torus  $T$  on a compact symplectic manifold.

**Theorem** (Atiyah-Guillemin-Sternberg). *Let  $M$  be a compact connected symplectic manifold on which a torus  $T$  acts in a Hamiltonian fashion with associated invariant momentum map  $J : M \rightarrow \mathfrak{t}^*$ . Here  $\mathfrak{t}$  denotes the Lie algebra of  $T$  and  $\mathfrak{t}^*$  is its dual; both are isomorphic as Abelian Lie algebras to  $\mathbb{R}^{\dim T}$ . Then the image  $J(M)$  of  $J$  is a compact convex polytope in  $\mathbb{R}^{\dim T}$ , called the  $T$ -momentum polytope. Moreover, it is equal to the convex hull of the image of the fixed point set of the  $T$ -action. The fibers of  $J$  are connected.*

The motivation for this result was the *Kostant linear convexity theorem* [25] which states that the projection of an adjoint orbit of a compact connected Lie group onto the Lie algebra of any of its maximal tori is the convex hull of the corresponding Weyl group orbit. This in turn is a generalization of a classical result of Schur [34] and Horn [16] (which in the case of the unitary group  $U(n)$  is Kostant's theorem) which states that the set of diagonals of an isospectral set of Hermitian matrices equals the convex hull of the  $n!$  points obtained by permuting all the eigenvalues.

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Another problem with important mathematical and physical consequences is to describe all possible eigenvalues of the sum  $A + B$  of two Hermitian matrices  $A$  and  $B$  as each one of them ranges over an isospectral set. The isospectral sets of Hermitian matrices are precisely the coadjoint orbits  $\mathcal{O}_\mu$  of  $U(n)$ , where  $\mu = (\mu_1, \mu_2, \dots, \mu_n)$  and  $\mu_i$  are the eigenvalues. If one requires, in addition, that the eigenvalues of the sum  $A + B$  be sorted in decreasing order, this problem amounts to describing the set  $J(\mathcal{O}_\mu \times \mathcal{O}_\lambda) \cap \mathfrak{t}_+^*$  where  $J(A, B) = A + B$  and  $\mathfrak{t}_+^*$  is a positive Weyl chamber in  $\mathfrak{t}^* = \{\text{real diagonal matrices}\}$ . This problem is a particular case of the following more general situation: a compact Lie group  $G$  acts on a compact symplectic manifold  $M$  with associated equivariant momentum map  $J : M \rightarrow \mathfrak{g}^*$ . Equivariance is not an assumption, since any momentum map of a compact group can be averaged to give an equivariant momentum map for the same canonical  $G$ -action.

Guillemin and Sternberg [12] proved that  $J(M) \cap \mathfrak{t}^*$  is a union of compact convex polytopes and Kirwan [20] showed that this set is connected, thereby concluding that  $J(M) \cap \mathfrak{t}_+^*$  is a compact convex polytope. We will refer to this as the  $G$ -momentum polytope.

**Theorem** (Guillemin-Kirwan-Sternberg). *Let  $M$  be a compact connected symplectic manifold on which the compact connected Lie group  $G$  acts in a Hamiltonian fashion with associated equivariant momentum map  $J : M \rightarrow \mathfrak{g}^*$ . Here  $\mathfrak{g}$  denotes the Lie algebra of  $G$  and  $\mathfrak{g}^*$  is its dual. Let  $T$  be a maximal torus of  $G$ ,  $\mathfrak{t}$  its Lie algebra,  $\mathfrak{t}^*$  its dual, and  $\mathfrak{t}_+^*$  the positive Weyl chamber relative to a fixed ordering of the roots. Then  $J(M) \cap \mathfrak{t}_+^*$  is a compact convex polytope, called the  $G$ -momentum polytope. The fibers of  $J$  are connected.*

Important results about the description of the  $U(n)$ -momentum polytope were obtained by Knutson and Tao [24].

Sjamaar [35] has given another proof of the convexity theorems, based on ideas coming from Kähler and algebraic geometry. His proof, even though it gives the most complete information on these polytopes, uses strongly the symplectic form and it is not known how to generalize his technique to other manifolds and other types of actions, such as Poisson actions of Poisson-Lie groups.

The case of compact symplectic manifolds is rich but quite particular. For non-compact manifolds, the previous results no longer hold and a counterexample was given by Prato [33]. Conditions under which the  $T$  or  $G$ -momentum polytopes are convex were given by Condevaux, Dazord, and Molino [7] and later by Hilgert, Neeb, and Plank [14]. These papers show that the proof of the convexity of the image of the momentum map rests on the following result which we give here in the formulation due to the second group of authors:

**Theorem** (Local-to-Global Principle). *Let  $\Psi : X \rightarrow V$  be a locally fiber connected map from a connected locally connected Hausdorff topological space  $X$  to a finite dimensional vector space  $V$ , with local convexity data  $(C_x)_{x \in X}$  such that all convex cones  $C_x$  are closed in  $V$ . Suppose that  $\Psi$  is a proper map. Then  $\Psi(X)$  is a closed locally polyhedral convex subset of  $V$ , the fibers  $\Psi^{-1}(v)$  are all connected, and  $\Psi : X \rightarrow \Psi(X)$  is an open mapping.*

We elaborate now on the hypotheses of this theorem. A map  $\Psi : X \rightarrow V$  is said to have **local convexity data** if for each  $x \in X$  there exists an arbitrarily small open neighborhood  $U_x$  of  $x$  and a convex cone  $C_x$  with vertex  $\Psi(x)$  in  $V$  such that

$\Psi(U_x)$  is a neighborhood of the vertex  $\Psi(x)$  in  $C_x$  and such that  $\Psi|_{U_x} : U_x \rightarrow C_x$  is an open map, where  $C_x$  is endowed with the subspace topology inherited from  $V$ . A map  $\Psi : X \rightarrow V$  is said to be **locally fiber connected** if for each  $x \in X$  there is an open neighborhood  $U_x$  of  $x$  such that  $\Psi^{-1}(\Psi(u)) \cap U_x$  is connected for all  $u \in U_x$ . In Definitions 2.7 and 2.15 we will elaborate on these conditions. A continuous map between two topological spaces with Hausdorff domain is said to be **proper** if it is closed and all its fibers are compact subsets of its domain.

In spite of its generality this theorem cannot be applied to situations where the fibers  $\Psi^{-1}(v)$  are either not compact or the map  $\Psi$  is not closed because both conditions are necessary for  $\Psi$  to be a proper map. This is, for example, one of the difficulties in the (direct) proof of the convexity theorem due to Flaschka and Ratiu [10] that contains as an important particular instance the case of Poisson-Lie group actions on compact symplectic manifolds. Alekseev [2] reproved the Poisson-Lie group action result mentioned above by other means, reducing it to the case covered by the Guillemin-Sternberg-Kirwan convexity result. His method strongly uses the structure of Poisson-Lie groups and it is not known how to extend it to other types of actions.

The main purpose of this paper is finding the essential features underlying all the results mentioned above that ensure convexity. As we will see these properties are of a topological nature; more specifically, we will show that convexity is rooted on the map being open onto its image and having local convexity data. These conditions happen to be satisfied in all the classical convexity theorems that we discussed previously and hence they can in principle be obtained as corollaries of the following general theorem that can be found in Section 2:

**Theorem.** *Let  $f : X \rightarrow V$  be a continuous map from a connected Hausdorff topological space  $X$  to a Banach space  $V$  that is open onto its image and has local convexity data. Then the image  $f(X)$  is locally convex. If, in addition,  $f(X)$  is closed in  $V$ , then it is convex.*

Note first that  $V$  is allowed to be infinite dimensional. Second, unlike the local convexity data condition that can be found in [7, 14], we do not assume the cones  $C_x$  to be closed since it is not a reasonable assumption in infinite dimensions.

In the light of the result above, the convexity problem reduces to giving necessary and sufficient conditions for a map that has local convexity data to be open onto its image. In the paper (Section 3) we will provide those characterizations for the momentum maps associated to compact Lie group actions on symplectic manifolds. We will split the problem into two cases: when the map has connected fibers and when it has only the locally fiber connectedness property. We shall also show that the openness of the momentum map can be determined just by looking at its image and we will illustrate this with two examples.

It is worth noting at this stage that Montaldi and Tokieda [30] proved that the openness of the momentum map (relative to its image endowed with the subspace topology) implies persistence of extremal relative equilibria under every perturbation of the value of the momentum map, provided the isotropy subgroup of this value is compact. So the openness property of the momentum map onto its image has interesting dynamical consequences.

Section 2 contains a generalization of the Local-to-Global Principle in [7, 14] that only requires the map to be closed and to have a normal topological space as domain, instead of using the properness condition. This degree of generality is

needed to obtain convexity directly from the Local-to-Global Principle in some of the examples that we present and that generalize various results in the literature. For instance, in Theorem 3.5 we extend a result of Prato [33] where we only require the properness of a single component of the momentum map to conclude convexity. Additionally, using our generalization of the Local-to-Global Principle we are able to drop in Section 4 the compactness hypothesis on the manifold in the Flaschka-Ratiu convexity result [10].

It is worth mentioning that the generalization of the Local-to-Global Principle presented in the paper includes infinite dimensional situations. This suggests that one could, in principle, use this tool in dealing with convexity problems such as those in the papers of Bloch, Flaschka, and Ratiu [4] or of Neumann [31]. The implementation of this idea is not free of difficulties and remains an open problem. This is due to the lack of a Marle-Guillemin-Sternberg normal form in the infinite dimensional setting which makes the local convexity data property very difficult to check.

## 2. OPENNESS AND LOCAL CONVEXITY

In this section we will study topological properties of maps that have *local convexity data*, a notion that we will introduce below. This property holds typically for momentum maps and, under certain supplementary topological conditions on the map and on its domain of definition, it implies that the map is open onto its image. We will also show that local convexity of the image of a map that has local convexity data is implied by openness of that map.

**The Klee Theorem.** The passage from local convexity to convexity is given by a classical result of Klee [21] which we now present.

**Definition 2.1.** Let  $V$  be a topological vector space. If  $x, y \in V$ , the **straight line segment**, or simply **segment**,  $[x, y]$  is defined by  $[x, y] := \{(1 - \lambda)x + \lambda y \mid 0 \leq \lambda \leq 1\}$ . A subset  $X \subset V$  is said to be **convex** if for any  $x, y \in X$  we have  $[x, y] \subset X$ . A subset  $Y \subset V$  is called **locally convex** if each point  $y \in Y$  has a neighborhood  $V_y$  whose intersection with  $Y$  is convex. A **polygonal path** is a continuous path that is the union of segments. A subset  $X \subset V$  is said to be **polygonally connected** if any two points can be joined by a polygonal path lying entirely in  $X$ .

The following lemma is due to Kakutani and Tukey and will be used in the proof of Klee's Theorem that insures the passage from local to global convexity.

**Lemma 2.2.** *In a topological vector space  $V$ , a connected locally convex set  $X$  is polygonally connected.*

*Proof.* Let  $p$  be an arbitrary point of  $X$  and let  $X_p$  be the set of all points of  $X$  which can be joined to  $p$  by a polygonal path. The strategy is to prove that  $X_p$  is both an open and closed subset of  $X$ . The result then follows by connectivity of  $X$ .

(i)  $X_p$  is open in  $X$ : Take an arbitrary point  $x \in X_p$  and a neighborhood  $U_x$  of  $x$  in  $X$  chosen such that  $U_x \cap X$  is convex. This is possible since  $X$  is locally convex. Each  $y \in U_x \cap X$  can be joined to  $p$  by the polygonal path obtained by adding to the polygonal path joining  $p$  to  $x$  the straight line segment from  $x$  to  $y$  that is guaranteed to lie entirely in  $U_x \cap X$ . Thus  $p$  can be joined to  $y \in U_x$  by a polygonal path that lies entirely in  $X$ , which proves that  $y \in X_p$ . Since  $y \in U_x \cap X$

was arbitrary, this shows that the open set  $U_x \cap X$  in the relative topology of  $X$  lies in  $X_p$ , that is, that  $X_p$  is open in  $X$ .

(ii)  $X_p$  is closed in  $X$ : We will show that  $\overline{X_p} \cap X = X_p$ . To prove the non-trivial inclusion  $\overline{X_p} \cap X \subset X_p$ , take an element  $y \in \overline{X_p} \cap X$  and recall that for any neighborhood  $U_y$  of  $y$  in the topological vector space  $V$  we have  $U_y \cap X_p \neq \emptyset$ . We can choose, by hypothesis,  $U_y$  such that  $U_y \cap X$  is convex. Thus there is an element  $z \in U_y \cap X_p$  such that the straight line segment joining  $z$  to  $y$  lies entirely in  $U_y \cap X$ . However,  $z \in X_p$ , so there is a polygonal path that lies entirely in  $X$  joining  $p$  to  $z$ . Adding to this path the segment joining  $z$  to  $y$  yields a polygonal path lying entirely in  $X$  that joins  $p$  to  $y$ , which proves that  $y \in X_p$ .  $\square$

The next theorem is due to Klee [21] and gives the connection between local convexity and convexity.

**Theorem 2.3** (Klee). *Each closed connected and locally convex subset of a topological vector space is convex.*

*Remark 2.4.* A quick inspection of the proof of this result shows that one can relax the closedness condition by requiring that the subset is closed just in a convex subset of the vector space endowed with the relative topology. This remark will be used in Theorem 2.13.

**Maps with local convexity data.** Let  $f : X \rightarrow V$  be a continuous map defined on a connected Hausdorff topological space  $X$  with values in a locally convex vector space  $V$ . On the topological space  $X$  define the following equivalence relation: declare two points  $x, y \in X$  to be equivalent if and only if  $f(x) = f(y) = v$  and they belong to the same connected component of  $f^{-1}(v)$ . The topological quotient space will be denoted by  $X_f := X/R$ , the projection map by  $\pi_f : X \rightarrow X_f$ , and the induced map on  $X_f$  by  $\tilde{f} : X_f \rightarrow V$ . Thus,  $\tilde{f} \circ \pi_f = f$  uniquely characterizes  $\tilde{f}$ . The map  $\tilde{f}$  is continuous and if the fibers of  $f$  are connected, then it is also injective.

The following elementary topological fact will be used several times later on.

**Lemma 2.5.** *Let  $f : X \rightarrow Y$  be a continuous map between two topological spaces. Assume that  $f$  has connected fibers and is open or closed. Then for every connected subset  $C$  of  $Y$  the inverse image  $f^{-1}(C)$  is connected.*

*Proof.* Suppose that  $f$  is an open map,  $C \subset Y$  is connected, and  $f^{-1}(C)$  is not connected. Then there exist two open sets  $U_1, U_2$  in  $X$  such that  $f^{-1}(C) = (U_1 \cap f^{-1}(C)) \cup (U_2 \cap f^{-1}(C))$ ,  $U_1 \cap f^{-1}(C) \neq \emptyset$ ,  $U_2 \cap f^{-1}(C) \neq \emptyset$ , and  $U_1 \cap U_2 \cap f^{-1}(C) = \emptyset$ . Note that  $C = f(f^{-1}(C)) = f((U_1 \cap f^{-1}(C)) \cup (U_2 \cap f^{-1}(C))) = f(U_1 \cap f^{-1}(C)) \cup f(U_2 \cap f^{-1}(C)) \subset (f(U_1) \cap C) \cup (f(U_2) \cap C)$ . Conversely, since  $f(U_1) \cap C \subset C$  and  $f(U_2) \cap C \subset C$  it follows that  $(f(U_1) \cap C) \cup (f(U_2) \cap C) \subset C$ , which proves that  $(f(U_1) \cap C) \cup (f(U_2) \cap C) = C$ . Also,  $f(U_1) \cap C \supset f(U_1 \cap f^{-1}(C)) \neq \emptyset$  and  $f(U_2) \cap C \supset f(U_2 \cap f^{-1}(C)) \neq \emptyset$ . By openness of  $f$ , the sets  $f(U_1)$  and  $f(U_2)$  are open in  $Y$  so that connectedness of  $C$  implies that  $f(U_1) \cap f(U_2) \cap C \neq \emptyset$ .

If  $c \in f(U_1) \cap f(U_2) \cap C$ , then  $f^{-1}(c) = (U_1 \cap f^{-1}(c)) \cup (U_2 \cap f^{-1}(c))$ . The inclusion  $\supset$  is obvious. To prove the reverse inclusion  $\subset$ , let  $x \in f^{-1}(c) \subset f^{-1}(C)$ . Thus  $x \in U_1 \cap f^{-1}(C)$  or  $x \in U_2 \cap f^{-1}(C)$ . Since  $x \in f^{-1}(c)$  by hypothesis, this implies that  $x \in U_1 \cap f^{-1}(c)$  or  $x \in U_2 \cap f^{-1}(c)$ , which proves the inclusion  $\subset$ . Note also that  $U_1 \cap f^{-1}(c) \neq \emptyset$  since  $c \in f(U_1)$ . Similarly,  $U_2 \cap f^{-1}(c) \neq \emptyset$ . Finally,

$U_1 \cap U_2 \cap f^{-1}(c) \subset U_1 \cap U_2 \cap f^{-1}(C) = \emptyset$ . Thus the fiber  $f^{-1}(c)$  can be written as the disjoint union of the two open nonempty sets  $U_1 \cap f^{-1}(c)$  and  $U_2 \cap f^{-1}(c)$ , which contradicts the connectedness hypothesis of the fibers of  $f$ .

The proof for  $f$  a closed map is identical to the one above by repeating the same argument for  $U_1$  and  $U_2$  closed subsets of  $X$ .  $\square$

**Definition 2.6.** Let  $V$  be a topological vector space. A set  $C \subset V$  is called a **cone** with **vertex**  $v_0$  if for each  $\lambda \geq 0$  and for each  $v \in C$ ,  $v \neq v_0$ , we have  $(1 - \lambda)v_0 + \lambda v \in C$ . If the set  $C$  is, in addition, convex, then  $C$  is called a **convex cone**. Note that, by definition, the vertex  $v_0 \in C$ .

**Definition 2.7.** The continuous map  $f : X \rightarrow V$  defined on a connected locally connected Hausdorff topological space  $X$  with values in a locally convex topological vector space  $V$  is said to have **local convexity data** if for each  $x \in X$  and every sufficiently small neighborhood  $U_x$  of  $x$  there exists a convex cone  $C_{x,f(x),U_x}$  in  $V$  with vertex at  $f(x)$  such that

(VN):  $f(U_x) \subset C_{x,f(x),U_x}$  is a neighborhood of the vertex  $f(x)$  in the cone  $C_{x,f(x),U_x}$  and

(SLO):  $f|_{U_x} : U_x \rightarrow C_{x,f(x),U_x}$  is an open map and for any neighborhood  $U'_x$  of  $x$ ,  $U'_x \subset U_x$ , the set  $f(U'_x)$  is a neighborhood of the vertex  $f(x)$  in the cone  $C_{x,f(x),U_x}$ ,

where the cone  $C_{x,f(x),U_x}$  is endowed with the subspace topology induced from  $V$ . If the associated cones  $C_{x,f(x),U_x}$  are such that  $C_{x,f(x),U_x} \cap f(X)$  is closed in  $f(X)$ , then we say that  $f$  has **local convexity data with closed cones**.

*Remark 2.8.* We are using the (VN) condition as an abbreviation for “vertex neighborhood condition” and the (SLO) condition as an abbreviation for “strong local openness condition”. Note that in the case when the associated cones  $C_{x,f(x),U_x}$  are closed in  $f(X)$  the second condition in (SLO) is automatically implied by the openness of  $f|_{U_x} : U_x \rightarrow C_{x,f(x),U_x}$ .

*Remark 2.9.* Let  $V$  be a locally convex topological vector space,  $C_1$  and  $C_2$  two cones in  $V$  with vertex at zero, and  $V_0$  a neighborhood of zero in  $V$ . Suppose that  $C_1 \cap C_2 \cap V_0$  is a neighborhood of zero in  $C_2$ . Then  $C_2 \subset C_1$ .

Indeed, since scalar multiplication is a continuous operation with respect to the subspace topology on  $C_2$  induced by the topology of  $V$  and since  $V$  is a locally convex topological space, we obtain that for every  $x \in C_2$  there exists some  $\lambda > 0$  such that  $\lambda x \in C_1 \cap C_2 \cap V_0 \subset C_1$ . Since  $C_1$  is a cone, it follows that  $t\lambda x \in C_1$  for every  $t > 0$  and hence  $x \in C_1$ .

By translation, the same property holds if the common vertices of the cones  $C_1$  and  $C_2$  are at some other point of  $V$ . We shall use this observation several times in the remarks that follow.

*Remark 2.10.*  $C_{x,f(x),U_x}$  does not depend on the neighborhood  $U_x$  in the sense that if  $U'_x \subset U_x$  is another neighborhood of  $x$ , then  $C_{x,f(x),U'_x} = C_{x,f(x),U_x}$ .

Indeed, we have  $f(U'_x) \subset C_{x,f(x),U'_x}$  is a neighborhood of the vertex  $f(x)$  in  $C_{x,f(x),U'_x}$ ,  $f(U_x) \subset C_{x,f(x),U_x}$  is a neighborhood of the vertex  $f(x)$  in  $C_{x,f(x),U_x}$ , and  $f(U'_x) = V'_{f(x)} \cap C_{x,f(x),U'_x} \subset f(U_x) = V_{f(x)} \cap C_{x,f(x),U_x}$ , where  $V'_{f(x)}$  and  $V_{f(x)}$  are two open neighborhoods of  $f(x)$  in  $V$ . By the argument used in Remark 2.9

it follows that  $C_{x,f(x),U'_x} \subset C_{x,f(x),U_x}$ . The (SLO) condition shows that  $f(U'_x) = f(U'_x) \cap C_{x,f(x),U'_x} \cap C_{x,f(x),U_x}$  is a neighborhood of the vertex  $f(x)$  in  $C_{x,f(x),U_x}$ . Again Remark 2.9 implies that  $C_{x,f(x),U_x} \subset C_{x,f(x),U'_x}$ .

Thus, since  $C_{x,f(x),U'_x}$  is independent of the neighborhood  $U_x$ , we shall write  $C_{x,f(x)}$  for the cone in Definition 2.7.

*Remark 2.11.* In Remark 2.12 we shall need the following statement (see e.g. [6] or [15]): a topological space is connected if and only if every open covering  $\{U_\alpha \mid \alpha \in \mathcal{A}\}$  has the property that for each pair of points  $x, y$  there exists a finite sequence  $\{\alpha_1, \dots, \alpha_k\} \subset \mathcal{A}$  such that  $x \in U_{\alpha_1}, y \in U_{\alpha_k}$ , and  $U_{\alpha_i} \cap U_{\alpha_{i+1}} \neq \emptyset$  for all  $i = 1, \dots, k - 1$ . This finite family of open sets  $\{U_{\alpha_1}, \dots, U_{\alpha_k}\}$  is called a **finite chain** linking  $x$  to  $y$ . A topological space that has the property that for each open cover and arbitrary points  $x, y$  there is a finite chain formed by elements of this open cover linking  $x$  to  $y$  is also called **well-chained**. The statement above asserts hence that a topological space is connected if and only if it is well-chained.

*Remark 2.12.*  $C_{x,f(x)}$  depends only on the connected components of  $f^{-1}(f(x))$ , that is, if  $y$  is in the same connected component of  $f^{-1}(f(x))$ , then  $C_{x,f(x)} = C_{y,f(y)}$ .

Let  $U_x$  be the open neighborhood of  $x \in X$  guaranteed by Definition 2.7. Let  $y \in f^{-1}(f(x))$  be in the same connected component of  $f^{-1}(f(x))$  as  $x$  and  $y \in U_x$ . For this  $y$ , let  $U_y$  be the open neighborhood of  $y$  in Definition 2.7, which we can choose such that  $U_y \subset U_x$ . The fact that  $f(U_y) \subset f(U_x)$  and  $f(U_y)$  is a neighborhood of  $f(x)$  in  $C_{y,f(x)}$  and  $f(U_x)$  is a neighborhood of  $f(x)$  in  $C_{x,f(x)}$  implies that  $C_{y,f(x)} \subset C_{x,f(x)}$ . For the reverse inclusion observe that  $f(U_y) \subset C_{y,f(x)}$  is a neighborhood of  $f(x)$  and by the (SLO) condition we also have that  $f(U_y)$  is open in  $C_{x,f(x)}$ , which shows that  $f(U_y) \cap C_{x,f(x)} = f(U_y) \cap C_{x,f(x)} \cap C_{y,f(x)}$  is an open neighborhood of  $f(x)$  in  $C_{x,f(x)}$ . By Remark 2.9, we obtain  $C_{x,f(x)} \subset C_{y,f(x)}$ . Thus for any  $y \in U_x$  that also lies in the same connected component of  $f^{-1}(f(x))$  as  $x$ , we have  $C_{x,f(x)} = C_{y,f(x)}$ .

So, on the connected component  $E_x$  of the fiber  $f^{-1}(f(x))$  containing  $x$ , using Remark 2.11, we obtain  $C_{x,f(x)} = C_{y,f(x)}$  for any  $y \in E_x$ . Thus, if the fibers  $f^{-1}(f(x))$  are connected we can erase  $x$  from  $C_{x,f(x)}$ .

Our strategy to prove local convexity for the image of a map that has local convexity data is to prove that it is open onto its image.

**Theorem 2.13.** *Let  $X$  be a connected Hausdorff topological space,  $V$  a locally convex topological vector space, and  $f : X \rightarrow V$  a continuous map that has local convexity data. If  $f$  is open onto its image, then  $f(X)$  is a locally convex subset of  $V$ . Moreover, if  $f(X)$  is closed in a convex subset of  $V$ , then it is convex.*

*Proof.* Let  $v \in f(X)$  be arbitrary and take  $x \in f^{-1}(v)$ . By the condition (VN), there exists a neighborhood  $U_x \subset X$  of  $x$  such that  $f(U_x) \subset C_{x,f(x)}$  is open in  $f(X)$ ;  $C_{x,f(x)}$  is the convex cone with vertex at  $v = f(x)$  given in Definition 2.7. Thus, shrinking  $U_x$  if necessary, using condition (SLO), and the local convexity of the topological vector space  $V$ , we can find a convex neighborhood  $V_v$  of  $v$  in  $V$  such that  $f(U_x) = V_v \cap C_{x,f(x)}$ . Since  $f$  is open onto its image, the neighborhood  $V_v$  can be shrunk further to a convex neighborhood of  $v$ , also denoted by  $V_v$ , such that  $f(U_x) = V_v \cap f(X)$ . Taking this as the neighborhood of  $v$  and shrinking  $U_x$  if necessary, we get  $V_v \cap C_{x,f(x)} = f(U_x) = V_v \cap f(X)$ . Since the intersection of two convex sets is convex, it follows that  $V_v \cap C_{x,f(x)}$  is also convex. Thus the point

$v \in f(X)$  has a neighborhood  $V_v$  in  $V$  such that  $V_v \cap f(X)$  is convex; that is,  $f(X)$  is locally convex (see Definition 2.1).

Now assume, in addition, that  $f(X)$  is closed in a convex subset  $C$  of  $V$ . Connectedness of  $X$  and continuity of  $f$  imply that  $f(X)$  is connected. Therefore,  $f(X)$  is a closed, connected, and locally convex subset of  $C$  (by what was just proved), so Klee's theorem (see Theorem 2.3) ensures that  $f(X)$  is convex in  $C$ . Since  $C$  is convex in  $V$ , this implies that  $f(X)$  is convex in  $V$ .  $\square$

*Remark 2.14.* Note that in Theorem 2.13 it was not assumed that the cones that give the local convexity data are closed. This could be useful for convexity theorems with infinite dimensional range. It is also worth noting that connectivity of  $X$  was not really used. In other words, the theorem above holds for each connected component of  $X$ .

It is not obvious when a map that has local convexity data is open onto its image. In order to give sufficient conditions under which this happens we need a few more preliminary results. First we need the following concept.

**Definition 2.15.** Let  $X$  and  $Y$  be two topological spaces and  $f : X \rightarrow Y$  a continuous map. The subset  $A \subset X$  satisfies the **locally fiber connected condition (LFC)** if  $A$  does not intersect two different connected components of the fiber  $f^{-1}(f(x))$ , for any  $x \in A$ .

Let  $X$  be a connected, locally connected, Hausdorff topological space and  $V$  a locally convex topological vector space. The continuous map  $f : X \rightarrow V$  is said to be **locally fiber connected** if for each  $x \in X$ , any open neighborhood of  $x$  contains a neighborhood  $U_x$  of  $x$  such that  $U_x$  satisfies the **(LFC)** condition.

Recall that  $X_f$  denotes the quotient topological space of  $X$  whose points are the connected components of the fibers of the continuous map  $f : X \rightarrow V$ , and  $\tilde{f} : X_f \rightarrow V$  is the map such that  $\tilde{f} \circ \pi_f = f$ . Note that a subset  $A \subset X$  satisfies (LFC) if and only if  $\tilde{f}|_{\pi_f(A)}$  is injective. Similarly,  $f$  is locally fiber connected if and only if for any  $x \in X$ , any open neighborhood of  $x$  contains an open neighborhood  $U_x$  of  $x$  such that the restriction of  $f$  to  $\pi_f(U_x)$  is injective.

**Lemma 2.16.** *Assume that the continuous map  $f : X \rightarrow V$  has local convexity data and is also locally fiber connected.*

- (i) *The quotient projection  $\pi_f : X \rightarrow X_f$  is an open map.*
- (ii) *If  $f$  has connected fibers, then  $X_f$  is Hausdorff.*

*Proof.* (i) We begin by noting that it suffices to prove that for each  $x \in X$  and for each open connected neighborhood  $U_x$  that satisfies (VN), (SLO), and (LFC), its image  $\pi_f(U_x)$  is open in  $X_f$ . This is so because any open neighborhood of  $x$  contained in  $U_x$  also satisfies the same three properties.

Take  $x$  to be an arbitrary point in  $X$  and  $U_x$  a connected neighborhood of  $x$  that satisfies (VN), (SLO), and (LFC). We will prove that  $\pi_f^{-1}(\pi_f(U_x))$  is open in  $X$ . To show this, let  $y$  be arbitrary in  $\pi_f^{-1}(\pi_f(U_x))$ . Then the connected component  $E_y$  of  $f^{-1}(f(y))$  that contains  $y$  intersects  $U_x$ . Let  $y' \in E_y \cap U_x$ . Choose a neighborhood  $U_{y'} \subset U_x$  that also satisfies (VN), (SLO) and (LFC). Since  $E_y$  is a connected space with respect to the induced topology from  $X$ , it is well-chained with respect to this topology; hence we can find a finite chain of open sets in  $X$  satisfying (VN), (SLO) and (LFC) such that  $U_1 = U_{y'}$  as above,  $y \in U_n$  and  $U_i \cap U_{i+1} \cap E_y \neq \emptyset$ . The set

$W_{yy'} := \bigcap_{i=1}^{n-1} f(U_i \cap U_{i+1})$  is an open subset of  $C_{y,f(y)}$  because of (SLO) and due to the fact that the associated cones depend only on the connected components of the fibers. Additionally,  $W_{yy'}$  is nonempty since by construction it contains the point  $f(E_y)$ , because  $U_i \cap U_{i+1} \cap E_y \neq \emptyset$ , for any  $i \in \{1, \dots, n-1\}$ . We now show that  $O_y := U_n \cap f^{-1}(W_{yy'})$  is an open subset of  $\pi_f^{-1}(\pi_f(U_x))$  that contains  $y$ . Indeed,  $O_y$  is open in  $X$  because it is an open subset of  $U_n$ . By the construction of  $O_y$ ,  $y$  clearly belongs to  $O_y$ . It remains to be shown that  $O_y \subset \pi_f^{-1}(\pi_f(U_x))$ .

Let  $z \in O_y$  be arbitrary. The connected component  $E_z$  of  $f^{-1}(f(z))$  that contains  $z$  intersects  $U_n$ . By the construction of  $O_y$ , the fiber  $f^{-1}(f(z))$  intersects every open set  $U_i \cap U_{i+1}$  of the finite chain that links  $y$  and  $y'$ . The (LFC) property guarantees that the connected component of  $f^{-1}(f(z))$  that intersects  $U_n \cap U_{n-1}$  has to be  $E_z$ . Repeating the argument we obtain that  $E_z \cap U_{y'} \neq \emptyset$  and  $E_z \cap U_{y'} \subset U_x$ . Then  $E_z \subset \pi_f^{-1}(\pi_f(U_x))$  for every  $z \in O_y$ , which proves that  $O_y \subset \pi_f^{-1}(\pi_f(U_x))$  and, consequently,  $\pi_f^{-1}(\pi_f(U_x))$  is an open subset of  $X$ .

(ii) Since all the fibers of  $f$  are connected and  $f$  is continuous, it follows that the graph of the relation determined by  $f$  is closed. As  $\pi_f$  is open we obtain that  $X_f$  is a Hausdorff space. □

*Remark 2.17.* Notice that neither local convexity data nor the locally fiber connected condition alone would imply openness of  $\pi_f$ . Indeed, if we consider the example where  $X$  is the square in  $\mathbb{R}^2$  with vertices  $(2, 2), (-2, 2), (-2, -2), (2, -2)$  minus the interior of the square with vertices  $(0, 1), (-1, 0), (0, -1), (1, 0)$ , and  $f(x, y) = y$ , then  $\pi_f$  is not open. However,  $f$  has local convexity data but it does not satisfy the locally fiber connected condition. If we consider the example where  $X$  is the square in  $\mathbb{R}^2$  with vertices  $(2, 2), (-2, 2), (-2, -2), (2, -2)$  minus the interior of the rotated square with vertices  $(1, 1), (-1, 1), (-1, -1), (1, -1)$ , and  $f(x, y) = y$ , then again  $\pi_f$  is not open and  $f$  satisfies the locally fiber connected condition but does not have local convexity data, precisely because it does not satisfy the (SLO) condition.

An immediate consequence of Lemma 2.16 and Theorem 2.13 is the following corollary. It states that for a map that has local convexity data and connected fibers the condition to be open onto its image, and consequently to have a locally convex image, is implied by the condition to be closed onto its image or by the stronger condition to be a proper map.

**Corollary 2.18.** *Let  $X$  be a connected, locally connected, Hausdorff topological space,  $V$  a locally convex topological vector space, and  $f : X \rightarrow V$  a continuous map that has local convexity data. Assume that  $f$  is a closed map onto its image  $f(X)$  and that it has connected fibers. Then  $f$  is open onto its image  $f(X)$  and  $f(X)$  is locally convex. Moreover, if  $f(X)$  is closed, then it is convex.*

*Proof.* The hypothesis implies that the induced map  $\tilde{f} : X_f \rightarrow f(X)$ , uniquely determined by the equality  $\tilde{f} \circ \pi_f = f$ , is a homeomorphism. Indeed, closedness of  $\tilde{f}$  follows from the identity  $\tilde{f}(A) = f(\pi_f^{-1}(A))$  for any subset  $A$  of  $X_f$ . Since  $\tilde{f}$  is open onto  $f(X)$  it follows that  $f = \tilde{f} \circ \pi_f$  is also open onto its image. The rest is a consequence of Theorem 2.13. □

Note that by Lemma 2.5, a necessary condition for the map  $f$  that has connected fibers to be open onto its image is that the inverse image of any connected set in

$f(X)$  is connected in  $X$ . The next proposition states that if  $f$  has local convexity data with closed cones, this condition is also sufficient.

**Proposition 2.19.** *Let  $f : X \rightarrow V$  be a continuous map that has local convexity data with closed cones. If the fibers of  $f$  are connected and for every point  $v \in f(X)$  and for all small neighborhoods  $V_v$  of  $v$  the set  $f^{-1}(V_v)$  is connected, then  $f$  is open onto its image.*

*Proof.* Suppose that  $f$  is not open onto its image, has local convexity data with closed cones, and has connected fibers. So there exists a point  $x \in X$  and an open neighborhood  $U_x$  (included in a neighborhood of  $x$  from the definition of local convexity data) such that  $V_{f(x)} \cap C_{x,f(x)} = f(U_x) \subsetneq f(X) \cap V_{f(x)}$  for some open neighborhood  $V_{f(x)}$  of  $f(x)$  in  $V$ . Consequently,  $(V_{f(x)} \cap f(X)) \setminus f(U_x) \neq \emptyset$  is open in  $f(X)$  since  $f(U_x) = V_{f(x)} \cap C_{x,f(x)} \cap f(X)$  is closed in the topology of  $V_{f(x)} \cap f(X)$  due to the fact that  $C_{x,f(x)} \cap f(X)$  is closed in  $f(X)$  (by the closed cone hypothesis). We can also choose  $V_{f(x)}$  small enough so that the hypothesis holds for it; that is,  $f^{-1}(V_{f(x)} \cap f(X))$  is connected.

Note that connectedness of the fibers, and thus bijectivity of  $\tilde{f}$ , implies that  $\tilde{f}^{-1}(f(A)) = \pi_f(A)$  for any subset  $A$  of  $X$ .

The sets that enter in the equality

$$\tilde{f}^{-1}(V_{f(x)} \cap f(X)) = \tilde{f}^{-1}((V_{f(x)} \cap f(X)) \setminus f(U_x)) \cup \tilde{f}^{-1}(f(U_x))$$

or equivalently

$$\pi_f(f^{-1}(V_{f(x)} \cap f(X))) = \tilde{f}^{-1}((V_{f(x)} \cap f(X)) \setminus f(U_x)) \cup \pi_f(U_x)$$

are all open because  $\pi_f$  is open and we also have that  $\tilde{f}^{-1}((V_{f(x)} \cap f(X)) \setminus f(U_x)) \cap \tilde{f}^{-1}(f(U_x)) = \emptyset$ . But this contradicts the connectivity of  $\pi_f(f^{-1}(V_{f(x)} \cap f(X)))$ .  $\square$

**The Local-to-Global Principle.** The rest of this section is dedicated to the generalization of the so-called Local-to-Global Principle used in the convexity proof of Condevaux, Dazord and Molino [7] and of Hilgert, Neeb, and Plank [14]. On the one hand we will prove that one can drop the condition on the compactness of the fibers necessary in the classical proof and still have the same conclusions, and on the other hand we will extend this result to maps that have an infinite dimensional target. In order to avoid the compactness condition (we will call a topological space compact if it is Hausdorff and every open cover has a finite subcover) on the fibers we need to further investigate the topology of the problem. We start with a short account of some topological results needed in the sequel.

**Theorem 2.20** ([9]). *Let  $f : X \rightarrow Y$  be a continuous mapping.*

- (i)  *$f$  is closed if and only if for every  $B \subset Y$  and every open set  $A \subset X$  which contains  $f^{-1}(B)$ , there exists an open set  $C \subset Y$  containing  $B$  and such that  $f^{-1}(C) \subset A$ .*
- (ii)  *$f$  is closed if and only if for every point  $y \in Y$  and every open set  $U \subset X$  which contains  $f^{-1}(y)$ , there exists in  $Y$  a neighborhood  $V_y$  of the point  $y$  such that  $f^{-1}(V_y) \subset U$ .*

We now prove a crucial lemma needed for the generalization of the Local-to-Global Principle.

**Lemma 2.21.** *Let  $X$  be a normal first countable topological space and  $V$  a locally convex topological vector space. Let  $f : X \rightarrow V$  be a continuous map that has local convexity data and satisfies the locally fiber connected condition. Suppose  $f$  is a closed map. Then the following hold:*

- (i) *The projection  $\pi_f : X \rightarrow X_f$  is also a closed map.*
- (ii) *The quotient  $X_f$  is a Hausdorff topological space.*

*Proof.* (i) Let  $[x]$  be an arbitrary point in  $X_f$  and  $U \subset X$  an arbitrary open set that contains  $\pi_f^{-1}([x]) = E_x$ , the connected component of  $f^{-1}(f(x))$  that contains  $x$ . Denote by  $F := f^{-1}(f(x)) \setminus E_x$ , which is the union of all (closed) connected components of  $f^{-1}(f(x))$  minus  $E_x$ . We claim that  $F$  is a closed subset of  $X$ . Indeed, if  $z \in \overline{F}$ , then there exist a sequence  $\{z_n\}_{n \in \mathbb{N}}$  in  $F$  which converges to  $z$ . Continuity of  $f$  implies that  $z \in f^{-1}(f(x))$ . If  $z \in E_x$ , then any neighborhood of  $z$  intersects at least one other connected component of the fiber  $f^{-1}(f(x))$ , which contradicts the locally fiber connected condition. Since  $z \in f^{-1}(f(x))$  it follows that  $z \in F$  and hence  $F$  is closed. The same argument as above shows that (LFC) implies that  $E_x$  is also closed in  $X$ .

Due to the normality of  $X$ , there exist two open sets  $U_{E_x}$  and  $W$  such that  $E_x \subset U_{E_x}$ ,  $F \subset W$ , and  $U_{E_x} \cap W = \emptyset$ . After shrinking, if necessary, we can take  $U_{E_x} \subset U$ . By the closedness of  $f$  there exists an open neighborhood  $V_{f(x)}$  of  $f(x)$  in  $V$  such that  $E_x \subset f^{-1}(f(x)) \subset f^{-1}(V_{f(x)}) \subset U_{E_x} \cup W$ , by Theorem 2.20 (ii).

The set  $A := U_{E_x} \cap f^{-1}(V_{f(x)})$  is a nonempty open subset of  $X$  which is also saturated with respect to the equivalence relation that defines  $\pi_f$  or, otherwise stated,  $\pi_f^{-1}(\pi_f(A)) = A$ . Indeed, if a connected component of a fiber of  $f$  from  $f^{-1}(V_{f(x)})$  intersects  $U_{E_x}$ , respectively  $W$ , then it is entirely contained either in  $U_{E_x}$  or in  $W$  since  $U_{E_x} \cap W = \emptyset$ . We have hence proved that  $\pi_f(A)$  is an open neighborhood of  $[x]$  since  $\pi_f$  is an open map and  $\pi_f^{-1}(\pi_f(A)) \subset U$ . This shows, via Theorem 2.20 (ii), that  $\pi_f$  is a closed map.

(ii) Since  $\pi_f$  is open, it suffices to prove that the equivalence relation that defines  $X_f$  has a closed graph in order to show that  $X_f$  is Hausdorff.

For every  $x \in X$  there exists a neighborhood  $U_x$  that satisfies (VN), (SLO), and (LFC). Notice that the open set  $\pi_f^{-1}(\pi_f(U'_x))$  also satisfies the (LFC) condition. By the normality of  $X$  there also exists a neighborhood  $U'_x$  of  $x$  with  $\overline{U'_x} \subset U_x$ . We shall prove that  $\overline{\pi_f^{-1}(\pi_f(U'_x))} \subset \pi_f^{-1}(\pi_f(U_x))$  which shows that for every connected component  $E_x$  of a fiber there exists a saturated neighborhood of it which contains a smaller saturated neighborhood whose closure still satisfies (LFC). In order to prove the above inclusion observe that, since  $\pi_f$  is closed, we have  $\overline{\pi_f(U'_x)} = \pi_f(\overline{U'_x}) \subset \pi_f(U_x)$ . By the continuity of  $\pi_f$  we obtain the inclusion  $\overline{\pi_f^{-1}(\pi_f(U'_x))} \subset \pi_f^{-1}(\overline{\pi_f(U'_x)}) \subset \pi_f^{-1}(\pi_f(U_x))$ .

We now prove the closedness of the graph of the equivalence relation that defines  $X_f$ . Take  $\{x_n\}_{n \in \mathbb{N}}$  and  $\{y_n\}_{n \in \mathbb{N}}$  to be two convergent sequences in  $X$  such that  $x_n$  and  $y_n$  are in the same equivalence class for all  $n \in \mathbb{N}$ . Suppose that  $x_n \rightarrow x$  and  $y_n \rightarrow y$ . The continuity of  $f$  guarantees that  $f(x) = f(y)$ . Additionally, there exists  $n_0 \in \mathbb{N}$  such that for  $n > n_0$  all  $x_n \in \pi_f^{-1}(\pi_f(U'_x))$ . Consequently  $y_n \in \pi_f^{-1}(\pi_f(U'_x))$  since  $x_n$  and  $y_n$  are in the same equivalence class and  $\pi_f^{-1}(\pi_f(U'_x))$  is saturated. Since  $y \in \overline{\pi_f^{-1}(\pi_f(U'_x))}$  and  $\overline{\pi_f^{-1}(\pi_f(U'_x))}$  satisfies (LFC) we obtain that  $x$  and  $y$  sit necessarily on the same connected component of the fiber  $f^{-1}(f(x))$

and are hence equivalent. This shows that the graph of the equivalence relation is closed, as required.  $\square$

*Remark 2.22.* Let  $f : X \rightarrow V$  be a continuous map such that  $f$  has local convexity data and is locally fiber connected. Then for every point  $[x] \in X_f$  there is a neighborhood  $\tilde{U}_{[x]}$  of  $[x]$  such that  $\tilde{f} : \tilde{U}_{[x]} \rightarrow C_{x,f(x)}$  is a homeomorphism onto its open image. Eventually, after shrinking  $\tilde{U}_{[x]}$ , we can suppose that its image is convex.

Note that  $X_f$  is connected since  $X$  is connected. Additionally, this remark implies that  $X_f$  is locally path connected. Therefore,  $X_f$  is path connected.

From now on we take  $V$  to be a Banach space. Define a distance  $d$  on  $X_f$  in the following way: for  $[x], [y] \in X_f$  let  $d([x], [y])$  be the infimum of all the lengths  $l(\tilde{f} \circ \gamma)$ , where  $\gamma$  is a continuous curve in  $X_f$  that connects  $[x]$  and  $[y]$ . The length is calculated with respect to the distance  $d_V$  defined by the norm on  $V$ . From the definition it follows that  $d_V(\tilde{f}([x]), \tilde{f}([y])) \leq d([x], [y])$  and, by Remark 2.22, equality holds for  $[x]$  and  $[y]$  sufficiently close. Indeed, we shall prove that for any two points  $[x], [y] \in X_f$  that are both contained in an open subset  $U$  that satisfies (VN), (SLO), and (LFC), the equality  $d_V(\tilde{f}([x]), \tilde{f}([y])) = d([x], [y])$  is satisfied. Due to the (VN) condition, the set  $\tilde{f}(U)$  is convex in  $V$  and hence there exists a straight line  $c_0$  joining  $\tilde{f}([x])$  and  $\tilde{f}([y])$ . Since  $U$  satisfies (SLO) and (LFC), the map  $\tilde{f}|_U : U \rightarrow \tilde{f}(U)$  is a homeomorphism and hence the curve  $\gamma_0 := \tilde{f}^{-1} \circ c_0$  is continuous and joins  $[x]$  and  $[y]$ . Consequently,

$$d([x], [y]) = \inf_{\gamma \in \Gamma_{[x],[y]}} \{l(\tilde{f} \circ \gamma)\} = l(c_0) = d_V(\tilde{f}([x]), \tilde{f}([y])),$$

where  $\Gamma_{[x],[y]} := \{\gamma : [a, b] \rightarrow X_f \mid \gamma \text{ is continuous and } \gamma(a) = [x], \gamma(b) = [y]\}$ .

**Proposition 2.23.** *Assume the hypotheses of Lemma 2.21 and suppose that  $V$  is a Banach space. The distance on  $X_f$  introduced above defines a metric topology on  $X_f$  that coincides with the quotient topology of  $X_f$ .*

*Proof.* The proof mimics those in [7] or [14]. The symmetry of  $d$  and the triangle inequality for  $d$  are obvious. It remains to be proved that if  $d([x], [y]) = 0$ , then  $[x] = [y]$ . By contradiction, suppose that  $d([x], [y]) = 0$  with  $[x] \neq [y]$ . Then  $d_V(\tilde{f}([x]), \tilde{f}([y])) = 0$  and hence  $\tilde{f}([x]) = \tilde{f}([y])$ . Since  $X_f$  is Hausdorff we can find two disjoint open neighborhoods  $\tilde{U}_{[x]}$  and  $\tilde{U}_{[y]}$  of  $[x]$  and  $[y]$ , respectively, that behave as in Remark 2.22. Take  $r > 0$  such that the open disk  $D_r(f([x])) := \{v \in V \mid d_V(v, f([x])) < r\}$  satisfies  $D_r(f([x])) \cap C_{x,f(x)} \subset \tilde{f}(\tilde{U}_{[x]})$ . Then, for all the curves  $\gamma$  that connect  $[x]$  and  $[y]$  we have that  $l(\tilde{f} \circ \gamma) > 2r$ . So, in order to have  $l(\tilde{f} \circ \gamma) < 2r$ ,  $[y]$  must be contained in  $\tilde{U}_{[x]}$ , which is a contradiction since  $\tilde{U}_{[x]} \cap \tilde{U}_{[y]} = \emptyset$ .

The construction of  $d$  and Remark 2.22 show that  $\tilde{f} : X_f \rightarrow V$  is a local isometry on the image  $\tilde{f}(\tilde{U}_{[x]})$  of all the small enough neighborhoods  $\tilde{U}_{[x]}$  of any point  $[x] \in X_f$ . It follows that the metric topology on  $X_f$  coincides with the quotient topology of  $X_f$ .  $\square$

The proof of the following lemma can be found in [9].

**Lemma 2.24.** (*Vaiřštejn*) *If  $f : X \rightarrow Y$  is a closed mapping from a metrizable space  $X$  onto a metrizable space  $Y$ , then for every  $y \in Y$  the boundary  $\text{bd}(f^{-1}(y)) := \overline{f^{-1}(y)} \cap \overline{(X \setminus f^{-1}(y))}$  is compact.*

**Definition 2.25.** Let  $X$  be a Hausdorff topological space and  $f : X \rightarrow Y$  be a continuous map. We call  $f$  a **proper map** if  $f$  is closed and all fibers  $f^{-1}(y)$  are compact subsets of  $X$ .

**Theorem 2.26** ([9]). *If  $f : X \rightarrow Y$  is a proper map, then for every compact subset  $Z \subset Y$  the inverse image  $f^{-1}(Z)$  is compact.*

A converse of this theorem is available when  $Y$  is a  $k$ -space (i.e.,  $Y$  is a Hausdorff topological space that is the image of a locally compact space under a quotient mapping).

**The finite dimensional case.** For the next considerations we need that  $V$  is a finite dimensional vector space with a fixed chosen inner product that defines the distance  $d_V$ . The infinite dimensional case will be discussed later.

**Proposition 2.27.** *In the hypotheses of Lemma 2.21 with  $V$  a finite dimensional Euclidean vector space we have that  $\tilde{f} : X_f \rightarrow V$  is a proper map and  $B_r([x]) := \{[y] \in X_f \mid d([x], [y]) \leq r\}$  is compact.*

*Proof.* The locally fiber connectedness condition on  $f$  and the openness of  $\pi_f$  imply that  $\tilde{f}^{-1}(v)$  is a collection of isolated points in  $X_f$  and hence  $\tilde{f}^{-1}(v) = \text{bd}(\tilde{f}^{-1}(v))$ , for every  $v \in f(X)$ . As a consequence of the Vaiřštejn Lemma we obtain that the fibers of  $\tilde{f}$  are all compact. Also,  $\tilde{f}$  is closed since  $f$  is closed and hence  $\tilde{f}$  is a proper map.

The set  $B_r([x])$  is closed in  $X_f$  and, by the definition of the distance  $d$ , we have that  $\tilde{f}(B_r([x])) \subset B_r(\tilde{f}([x])) \subset V$ . Since the ball  $B_r(\tilde{f}([x])) \subset V$  is closed and bounded it is necessarily compact in the finite dimensional vector space  $V$ . Properness of  $\tilde{f}$  implies that  $\tilde{f}^{-1}(B_r(\tilde{f}([x])))$  is compact in  $X_f$ . Since  $B_r([x])$  is a closed subset of  $\tilde{f}^{-1}(B_r(\tilde{f}([x])))$ , it is necessarily compact in  $X_f$ .  $\square$

We can now prove one of the main results of this section, which is the generalization of the Local-to-Global Principle in [7] or [14] to the case of closed maps that are not necessarily proper.

**Theorem 2.28.** *Let  $f : X \rightarrow V$  be a closed map with values in a finite dimensional Euclidean vector space  $V$  and  $X$  a connected, locally connected, first countable, and normal topological space. Assume that  $f$  has local convexity data and is locally fiber connected. Then:*

- (i): *All the fibers of  $f$  are connected.*
- (ii):  *$f$  is open onto its image.*
- (iii): *The image  $f(X)$  is a closed convex set.*

*Proof.* We begin with the argument of [7, 14]. Let  $[x]_0, [x]_1 \in X_f$  be two arbitrary points and  $c := d([x]_0, [x]_1)$ . By the definition of  $d$ , we have that for every  $n \in \mathbb{N}$  there exists a curve  $\gamma_n$  defined on the interval  $[a, b]$ , connecting  $[x]_0$  and  $[x]_1$ , and satisfying  $l(\tilde{f} \circ \gamma_n) \leq c + \frac{1}{n}$ . Also, for every  $n \in \mathbb{N}$ , let  $v_n = (\tilde{f} \circ \gamma_n)(t_0)$  be the point on the curve  $\tilde{f} \circ \gamma_n$  such that  $l(\tilde{f} \circ \gamma_n|_{[a, t_0]}) = \frac{1}{2}l(\tilde{f} \circ \gamma_n)$ . Then there exists a finite set

of points  $\{[x]_1^n, \dots, [x]_{k_n}^n\}$  in  $X_f$  such that  $\tilde{f}^{-1}(v_n) \cap \text{range}(\gamma_n) = \{[x]_1^n, \dots, [x]_{k_n}^n\} \subset B_{c+1}([x]_0)$ , where  $B_{c+1}([x]_0) := \{[x] \in X_f \mid d([x]_0, [x]) \leq c + 1\}$  is compact by Proposition 2.27. Relabeling the elements of the set  $\bigcup_{n \in \mathbb{N}} \{[x]_1^n, \dots, [x]_{k_n}^n\}$  we obtain a sequence included in the compact set  $B_{c+1}([x]_0)$  and, consequently, it will have an accumulation point denoted by  $[x]_{\frac{1}{2}}$ .

The definition of  $d$  implies that  $d([x]_0, [x]_{\frac{1}{2}}) = d([x]_{\frac{1}{2}}, [x]_1) = \frac{c}{2}$ . Repeating this process for the pair of points  $([x]_0, [x]_{\frac{1}{2}})$  and  $([x]_{\frac{1}{2}}, [x]_1)$  we obtain the points  $[x]_{\frac{1}{4}}$  and  $[x]_{\frac{3}{4}}$  satisfying  $d([x]_0, [x]_{\frac{1}{4}}) = d([x]_{\frac{1}{4}}, [x]_{\frac{1}{2}}) = d([x]_{\frac{1}{2}}, [x]_{\frac{3}{4}}) = d([x]_{\frac{3}{4}}, [x]_1) = \frac{c}{4}$ . Inductively, we obtain points  $[x]_{n/2^m}, [x]_{n'/2^{m'}}$  for  $0 \leq n \leq 2^m, 0 \leq n' \leq 2^{m'}$ , such that

$$(2.1) \quad d([x]_{n/2^m}, [x]_{n'/2^{m'}}) = c \left| \frac{n}{2^m} - \frac{n'}{2^{m'}} \right|.$$

We can extend the map  $n/2^m \mapsto [x]_{n/2^m}$  to a continuous map  $\gamma : [0, 1] \rightarrow X_f$  such that

$$(2.2) \quad d(\gamma(t), \gamma(t')) = c|t - t'|.$$

To see this, note that every  $t \in [0, 1]$  can be approximated by a sequence of the type  $n_k/2^{m_k}$ . The corresponding points  $[x]_{n_k/2^{m_k}}$  are contained in the compact set  $B_{c+1}([x]_0)$ , and hence they have an accumulation point  $[x]_t$ . It is now easy to see, using (2.1), that  $[x]_t$  does not depend on the sequence  $n_k/2^{m_k}$  and that the curve  $\gamma$  constructed in this way is continuous.

Remark 2.22 and (2.2) imply that, locally,  $d_V((\tilde{f} \circ \gamma)(t), (\tilde{f} \circ \gamma)(t')) = c|t - t'|$  which shows that  $\tilde{f} \circ \gamma$  is locally a straight line. Due to (2.2),  $\tilde{f} \circ \gamma$  is necessarily a straight line that goes through  $\tilde{f}([x]_0)$  and  $\tilde{f}([x]_1)$ . This proves the convexity of  $f(X)$ . Since  $f$  is a closed map the set  $f(X)$  is closed in  $V$  which proves (iii).

In order to prove the connectedness of the fibers of  $f$  let  $[x]_0, [x]_1 \in X_f$  be two arbitrary points such that  $v := \tilde{f}([x]_0) = \tilde{f}([x]_1)$  and  $c := d([x]_0, [x]_1)$ . Any curve that connects these two points is mapped by  $\tilde{f}$  into a loop based at  $v$ . We shall prove that  $c = 0$ , which implies that  $[x]_0 = [x]_1$  and hence that the fibers of  $f$  are connected. Let  $\gamma$  be the curve constructed above. Then the range of  $\tilde{f} \circ \gamma$  is a segment that contains  $v$ . We will prove by contradiction that this segment consists of just one point which is  $v$  itself.

Suppose that this is not true. Since  $\tilde{f} \circ \gamma$  is a loop based at  $v$  and at the same time a straight line, there exists a turning point  $v_0 := (\tilde{f} \circ \gamma)(t_0)$  on the segment  $\tilde{f} \circ \gamma$  such that for  $t \leq t_0$  we approach  $v_0$  and for  $t' \geq t_0$  we move away from  $v_0$  staying on the same segment which is the range of  $\tilde{f} \circ \gamma$ . Otherwise stated,  $\text{range}(\tilde{f} \circ \gamma|_{[t, t_0]}) = \text{range}(\tilde{f} \circ \gamma|_{[t_0, t']})$  and hence in a neighborhood of  $\gamma(t_0)$  the map  $\tilde{f}$  is not injective. However, since  $f$  is locally fiber connected the map  $\tilde{f}$  is locally injective, which is a contradiction. This proves (i). Note that from  $c := d([x]_0, [x]_1)$  and  $d_V(\tilde{f}([x]_0), \tilde{f}([x]_1)) = d_V(v, v) = 0$  we cannot conclude that  $c = 0$  since the equality between the two metrics holds only locally.

The openness of  $f$  is implied by Corollary 2.18.  $\square$

*Remark 2.29.* This result remains true if we replace the vector space  $V$  by a convex subset  $C$  of  $V$ . More specifically, Theorem 2.28 is valid when we apply it to a map  $f : X \rightarrow C$ , with  $C$  a convex subset of  $V$ . In particular, this allows us to generalize

to the case of closed maps Theorem 4.2 of Lerman et al. [27] and Theorem 3.3 of Weinstein [36], initially stated for proper maps. This remark is also important later on when we generalize several other classical convexity theorems.

**The infinite dimensional case.** Now let  $V$  be an infinite dimensional Banach space and  $d_V$  the distance induced by the norm. Analyzing the proof of Proposition 2.27 it can be seen that the compactness of the closed balls in the norm topology was essential. Thus, there is no direct analog of this statement in infinite dimensions. What is needed is a second topology on  $V$  whose closed balls are compact. A natural hypothesis is that  $V$  is the topological dual space of another Banach space  $W$  for then Alaoglu’s Theorem guarantees that  $B_r(0) := \{v \in V \mid \|v\| \leq r\}$  is weak\* compact. We shall denote by  $(V, \|\cdot\|)$  the Banach space  $V$  endowed with the norm topology (and hence this is the Banach space dual  $W^*$ ) and by  $(V, w^*)$  the space  $V$  endowed with the weak\* topology of  $W^*$ . Since the weak\* topology is weaker than the norm topology we have

- if  $f : X \rightarrow (V, \|\cdot\|)$  is continuous, then  $f : X \rightarrow (V, w^*)$  is continuous;
- if  $f : X \rightarrow (V, w^*)$  is closed, then  $f : X \rightarrow (V, \|\cdot\|)$  is closed.

The analog of Proposition 2.27 is the following.

**Proposition 2.30.** *Assume the hypotheses of Lemma 2.21 with  $V = W^*$ , for  $W$  a Banach space. If  $f : X \rightarrow (V, \|\cdot\|)$  is continuous and  $f : X \rightarrow (V, w^*)$  is closed, then  $\tilde{f} : X_f \rightarrow V$  is a proper map relative to both topologies on  $V$  and  $B_r([x]) := \{[y] \in X_f \mid d([x], [y]) \leq r\}$  is compact in  $X_f$ .*

*Proof.* The locally fiber connectedness condition for  $f$  and the openness of  $\pi_f$  imply that  $\tilde{f}^{-1}(v)$  is a collection of isolated points in  $X_f$  and hence  $\tilde{f}^{-1}(v) = \text{bd}(\tilde{f}^{-1}(v))$ , for every  $v \in f(X)$ . Since  $\tilde{f} : X_f \rightarrow (V, w^*)$  is a closed map, then so is  $\tilde{f} : X_f \rightarrow (V, \|\cdot\|)$ . By Vainštein’s Lemma the fibers of  $\tilde{f}$  are all compact. Also  $\tilde{f} : X_f \rightarrow (V, w^*)$  is closed and hence  $\tilde{f} : X_f \rightarrow (V, w^*)$  is a proper map.

The set  $B_r([x])$  is closed in  $X_f$  and by the definition of the distance  $d$  we have that  $\tilde{f}(B_r([x])) \subset B_r(\tilde{f}([x])) \subset V$ . The ball  $B_r(\tilde{f}([x])) \subset V$  is weak\* compact and since  $\tilde{f} : X_f \rightarrow (V, w^*)$  is a proper map we have that  $\tilde{f}^{-1}(B_r(\tilde{f}([x])))$  is compact in  $X_f$ . As  $B_r([x])$  is a closed subset of  $\tilde{f}^{-1}(B_r(\tilde{f}([x])))$ , it is necessarily compact in  $X_f$ . □

Using Proposition 2.30, one can generalize Theorem 2.28 to the context of maps with an infinite dimensional range by virtually copying its proof.

**Theorem 2.31.** *Let  $(V, \|\cdot\|)$  be a Banach space such that  $V = W^*$ , for  $W$  a Banach space. Let  $f : X \rightarrow (V, \|\cdot\|)$  be a continuous map and  $f : X \rightarrow (V, w^*)$  closed, where  $X$  is a connected, locally connected, first countable, and normal topological space. Assume that  $f$  has local convexity data and is locally fiber connected. Then:*

- (i): *All the fibers of  $f$  are connected.*
- (ii):  *$f : X \rightarrow (V, w^*)$  is open onto its image.*
- (iii): *The image  $f(X) \subset (V, w^*)$  is a closed convex set.*

*Remark 2.32.* Since the weak\* topology is weaker than the norm topology the previous theorem also implies that  $f : X \rightarrow (V, \|\cdot\|)$  is open onto its image and that  $f(X)$  is closed in  $(V, \|\cdot\|)$  (and obviously also convex since the notion of convexity is not related to the topology). Moreover, as the fibers of  $f$  are connected the map

$\tilde{f} : X_f \rightarrow f(X)$  is a homeomorphism when  $f(X)$  is considered as a topological subspace of either  $(V, \|\cdot\|)$  or  $(V, w^*)$ . This apparently strong conclusion is actually guaranteed to hold automatically for an important class of normed spaces  $(V, \|\cdot\|)$ . For instance, as  $V = W^*$ , if  $W$  is reflexive, then the weak and the weak\* topologies in  $V$  coincide. Moreover, Mazur's Theorem [29] guarantees that the weak and the norm closures of a convex set on a normed space coincide. The same interplay between the weak\* and norm topology can be found in the infinite dimensional convexity results of Bloch-Flaschka-Ratiu [4] and Neumann [31].

### 3. OPENNESS AND LOCAL CONVEXITY FOR MOMENTUM MAPS

In the previous section we presented sufficient conditions for the convexity of the image of a map that has both local convexity data and is locally fiber connected. More specifically, in Theorem 2.13 we saw that if the map is open onto its image, then the image is locally convex and therefore convex if it is also closed. In this section we will characterize the situations in which the momentum map associated to a compact and symplectic Lie group action on a symplectic manifold is an open map onto its image. We will also give several generalizations of convexity results found in the literature. Throughout this paper, all manifolds are assumed to be paracompact; that is, they are Hausdorff spaces and every open cover has a locally finite open refinement.

**Definition 3.1.** Let  $V$  be a finite dimensional vector space.

- (i): A subset  $K \subset V$  is called **polyhedral** if it is the intersection of a finite family of closed half-spaces of  $V$ . Consequently, a polyhedral subset of  $V$  is closed and convex.
- (ii): A subset  $K \subset V$  is called **locally polyhedral** if for every  $x \in K$  there exists a polytope  $P_x$  in  $V$  such that  $x \in \text{int}(P_x)$  and  $K \cap P_x$  is a polytope.

In order to proceed we need further preparation. First we specialize the Marle-Guillemin-Sternberg Normal Form Theorem to the case of torus actions in the formulation of [14]; see also [28, 13, 32] for general normal form theorems and their proofs.

**Theorem 3.2.** *Let  $(M, \omega)$  be a symplectic manifold and let  $T$  be a torus acting on  $M$  in a globally Hamiltonian fashion with invariant momentum map  $J_T : M \rightarrow \mathfrak{t}^*$ . Let  $m \in M$  and  $T_0 = (T_m)^0$  be the connected component of the stabilizer  $T_m$ . Let  $T_1 \subset T$  be a subtorus such that  $T = T_0 \times T_1$ . Then:*

- (i) *There exist a symplectic vector space  $(V, \omega_V)$ , a  $T$ -invariant open neighborhood  $U \subset M$  of the orbit  $T \cdot m$ , and a symplectic covering of a  $T$ -invariant open subset  $U'$  of  $T_1 \times \mathfrak{t}_1^* \times V$  onto  $U$  under which the  $T$ -action on  $M$  is modeled by*

$$\begin{aligned} (T_0 \times T_1) \times ((T_1 \times \mathfrak{t}_1^*) \times V) &\rightarrow ((T_1 \times \mathfrak{t}_1^*) \times V) \\ ((t_0, t_1), (t_1', \beta, v)) &\mapsto (t_1 t_1', \beta, \pi(t_0)v), \end{aligned}$$

where  $\pi : T_0 \rightarrow Sp(V)$  is a symplectic representation.

- (ii) *There exists a complex structure  $I$  on  $V$  such that  $\langle v, w \rangle := \omega_V(Iv, w)$  defines a positive definite scalar product on  $V$ . Then  $V = \bigoplus_{\alpha \in \mathcal{P}_V} V_\alpha$ , where*

$V_\alpha := \{v \in V \mid Y \cdot v = \alpha(Y)Iv, \text{ for all } Y \in \mathfrak{t}_0\}$  and  $\mathcal{P}_V := \{\alpha \in \mathfrak{t}_0^* \mid V_\alpha \neq \{0\}\}$ . The corresponding  $T$ -momentum map  $\Phi : T^*(T_1) \times V \rightarrow \mathfrak{t}_1^* \times \mathfrak{t}_0^* \simeq \mathfrak{t}^*$  is given by

$$\Phi \left( (t_1, \beta), \sum_{\alpha} v_\alpha \right) = \Phi(1, 0, 0) + \left( \beta, \frac{1}{2} \sum_{\alpha \in \mathcal{P}_V} \|v_\alpha\|^2 \alpha \right).$$

Notice that the original version of the Marle-Guillemin-Sternberg Normal Form Theorem provides the twisted product  $(T_0 \times T_1) \times_{T_0} (\mathfrak{t}_1^* \times V)$  as a  $T$ -invariant local model for  $M$ . This is equivariantly diffeomorphic to  $T_1 \times \mathfrak{t}_1^* \times V$  via the map

$$\begin{aligned} (T_0 \times T_1) \times_{T_0} (\mathfrak{t}_1^* \times V) &\longrightarrow T_1 \times \mathfrak{t}_1^* \times V \\ [(t_1, t_0), \eta, v] &\longmapsto (t_1, \eta, t_0 \cdot v). \end{aligned}$$

The next result shows that the momentum maps of globally Hamiltonian torus actions always have local convexity data with closed cones and are locally fiber connected. In fact, the associated cones are closed in  $\mathfrak{t}^*$ .

**Theorem 3.3.** *Let  $(M, \omega)$  be a symplectic manifold and let  $T$  be a torus acting on  $M$  in a globally Hamiltonian fashion with invariant momentum map  $J_T : M \rightarrow \mathfrak{t}^*$ . Then there exist an arbitrarily small neighborhood  $U$  of  $m$  and a convex polyhedral cone  $C_{J_T(m)} \subset \mathfrak{t}^*$  with vertex  $J_T(m)$  such that:*

- (i):  $J_T(U) \subset C_{J_T(m)}$  is an open neighborhood of  $J_T(m)$  in  $C_{J_T(m)}$ ;
- (ii):  $J_T : U \rightarrow C_{J_T(m)}$  is an open map;
- (iii): if  $\mathfrak{t}_0$  is the Lie algebra of the stabilizer  $T_m$  of  $m$ , then  $C_{J_T(m)} = J_T(m) + \mathfrak{t}_0^\perp + \text{cone}(\mathcal{P}_V)$ ;
- (iv):  $J_T^{-1}(J_T(m)) \cap U$  is connected for all  $m \in U$ .

Here is a sketch of the proof; for details, see [14]. Recall that  $\text{cone}(\mathcal{P}_V) := \{\sum_j a_j \alpha_j \mid a_j \geq 0\}$ . By Theorem 3.2, it suffices to work with the momentum map  $\Phi$ . For small neighborhoods  $B_{\mathfrak{t}_1^*}$  and  $B_V$  of the origin in  $\mathfrak{t}_1^*$  and  $V$ , respectively, the restriction of  $\Phi$  to  $U := T_1 \times B_{\mathfrak{t}_1^*} \times B_V$  takes values in the polyhedral closed convex cone  $C_{J_T(m)} = J_T(m) + \mathfrak{t}_1^* + \text{cone}(\mathcal{P}_V)$ , where  $\text{cone}(\mathcal{P}_V)$  denotes the cone generated by the finite set  $\mathcal{P}_V = \{\alpha_1, \dots, \alpha_n\}$  of  $T_0$ -weights for the action on  $V$ ;  $\text{cone}(\mathcal{P}_V)$  is clearly closed. In order to prove that  $J_T$  satisfies the conditions of the theorem, we decompose it into two maps  $\varphi_1 : (t_1, \beta, \sum_{\alpha} v_\alpha) \mapsto (\beta, (\|v_\alpha\|^2))$  and  $\varphi_2 : (\beta, a_1, \dots, a_n) \mapsto (\beta, \frac{1}{2} \sum_j a_j \alpha_j)$ . We have  $J_T = \varphi_2 \circ \varphi_1 + J_T(m)$ . One proves that  $\varphi_1, \varphi_2$  are open onto their images and have connected fibers, so  $J_T$  has the same properties.

We now state a generalization of the Atiyah-Guillemin-Sternberg Convexity Theorem for noncompact manifolds.

**Corollary 3.4.** *Let  $M$  be a paracompact connected symplectic manifold on which a torus  $T$  acts in a Hamiltonian fashion. Let  $J_T : M \rightarrow \mathfrak{t}^*$  be an associated momentum map which we suppose is closed. Then the image  $J_T(M)$  is a closed convex locally polyhedral subset in  $\mathfrak{t}^*$ . The fibers of  $J_T$  are connected and  $J_T$  is open onto its image.*

*Proof.* This is a consequence of Theorems 3.3 and 2.28. The image is locally polyhedral since  $J_T$  is open onto its image and the associated cones are polyhedral.  $\square$

Our approach to convexity also allows us to generalize a result due to Prato [33].

**Theorem 3.5.** *Let  $M$  be a connected symplectic manifold on which a torus  $T$  acts in a Hamiltonian fashion with associated invariant momentum map  $J_T : M \rightarrow \mathfrak{t}^*$ .*

- (i): *If there exists  $\xi \in \mathfrak{t}$  such that the map  $J_T^\xi \in C^\infty(M)$  defined by  $J_T^\xi := \langle J_T, \xi \rangle$  is proper, then the image  $J_T(M)$  is a closed convex locally polyhedral subset in  $\mathfrak{t}^*$ . Moreover, the fibers of  $J_T$  are connected and  $J_T$  is open onto its image.*
- (ii): *If there exists an integral element  $\xi \in \mathfrak{t}$  such that  $J_T^\xi$  is a proper function having a minimum as its unique critical value, then  $J_T(M)$  is the convex hull of a finite number of affine rays in  $\mathfrak{t}^*$  stemming from the images of  $T$ -fixed points.*

*Proof.* (i) We will carry out the proof using our generalization of the Local-to-Global Principle (Theorem 2.28). According to this result all that needs to be proved is that in the presence of our hypotheses  $J_T$  is a closed map. This will be shown by verifying that  $\overline{J_T(A)} \subset J_T(\overline{A})$ , for any subset  $A \subset M$ .

We start by noticing that the map  $J_T^\xi \in C^\infty(M)$  can be written as  $J_T^\xi = b \circ \pi \circ J_T$ , where  $\pi : \mathfrak{t}^* \rightarrow \text{span}\{\xi\}^*$  is the dual of the inclusion  $\text{span}\{\xi\} \hookrightarrow \mathfrak{t}$  and  $b : \text{span}\{\xi\}^* \rightarrow \mathbb{R}$  is the linear isomorphism obtained as the map that assigns to each element in  $\text{span}\{\xi\}^*$  its coordinate in the dual basis of  $\{\xi\}$  as a basis of  $\text{span}\{\xi\}$ . Let  $\mu \in \overline{J_T(A)}$  be arbitrary and  $\{\mu_n\}_{n \in \mathbb{N}} \subset J_T(A)$  a sequence such that  $\mu_n \rightarrow \mu$ . Let  $\{x_n\}_{n \in \mathbb{N}} \subset A$  be a sequence such that  $J_T(x_n) = \mu_n$ . By continuity we have that  $J_T^\xi(x_n) = b \circ \pi \circ J_T(x_n) \rightarrow b \circ \pi(\mu)$ . Since by hypothesis  $J_T^\xi$  is a proper map there exists a convergent subsequence  $x_{n_k} \rightarrow x \in \overline{A}$  and hence  $J_T(x_{n_k}) \rightarrow J_T(x) = \mu$ , which shows that  $\mu \in J_T(\overline{A})$ , as required. Part (ii) is the original result of Prato [33].  $\square$

We now recall some standard notions from the theory of proper Lie group actions. Let  $M$  be a manifold and  $G$  a Lie group acting properly on it. The orbit  $G \cdot m$  is called **regular** if the dimension of nearby orbits coincides with the dimension of  $G \cdot m$ . Let  $M^{reg}$  denote the union of all regular orbits. For every connected component  $M^0$  of  $M$  the subset  $M^{reg} \cap M^0$  is connected, open, and dense in  $M^0$ . Note that if  $U$  is a  $G$ -invariant connected open submanifold, then the set of regular points for the induced  $G$ -action on  $U$  equals  $U \cap M^{reg}$ . This shows that  $U \cap M^{reg}$  is open, dense, and connected in  $U$ .

Next, we give necessary topological conditions on the image of  $J_T$  that ensure that  $J_T$  is open onto its image. Later we will show that these conditions are also sufficient. We recall that a **region** in a topological space is, by definition, a connected open set.

**Proposition 3.6.** *Let  $J_T : M \rightarrow \mathfrak{t}^*$  be the momentum map of a torus action on the connected symplectic manifold  $(M, \omega)$ . Suppose that  $J_T$  is open onto its image. Then the complement  $\mathbf{C}J_T(M^{reg}) := J_T(M) \setminus J_T(M^{reg})$  does not disconnect any region in  $J_T(M)$ .*

*Proof.* Suppose there exists a region  $V \subset J_T(M)$  (relative to the induced topology from  $\mathfrak{t}^*$ ) such that  $V \setminus \mathbf{C}J_T(M^{reg})$  is disconnected and hence  $V \setminus \mathbf{C}J_T(M^{reg}) = A \cup B$ , where  $A$  and  $B$  are open in  $V$  and  $A \cap B = \emptyset$ . Moreover, since  $J_T(M^{reg})$  is dense in  $J_T(M)$ , we have that  $J_T(M^{reg}) \cap V = V \setminus \mathbf{C}J_T(M^{reg}) = A \cup B$  is dense in  $J_T(M) \cap V = V$ . Hence  $\overline{(A \cup B)} \cap V = V = (\overline{A} \cap V) \cup (\overline{B} \cap V)$ .

We claim that there exists an element  $v \in \mathbf{C}J_T(M^{reg}) \cap V$  such that any neighborhood  $V_v \subset V$  of  $v$  in  $V$  is disconnected by  $\mathbf{C}J_T(M^{reg}) \cap V$ . Suppose that this claim is false. Then for every  $v \in \mathbf{C}J_T(M^{reg}) \cap V$  there would exist a neighborhood  $V_v \subset V$  of  $v$  such that  $V_v \setminus \mathbf{C}J_T(M^{reg})$  is connected. Therefore, we must have that either  $V_v \setminus \mathbf{C}J_T(M^{reg}) \subset A$  or  $V_v \setminus \mathbf{C}J_T(M^{reg}) \subset B$ . Thus, either  $v \in \overline{A} \cap V$  or  $v \in \overline{B} \cap V$ . Since  $v \in \mathbf{C}J_T(M^{reg}) \cap V$  is arbitrary, this shows that  $(\overline{A} \cap V) \cap (\overline{B} \cap V) = \emptyset$ . This contradicts the connectivity of  $V$  and hence there exist a  $v \in \mathbf{C}J_T(M^{reg}) \cap V$  such that any neighborhood  $V_v \subset V$  is disconnected by  $\mathbf{C}J_T(M^{reg})$ .

Take an arbitrary element  $x \in J_T^{-1}(v)$  and  $U_x$  a small neighborhood of  $x$  such that  $J_T(U_x) \subset V$  is an open neighborhood of  $v$  in  $J_T(M)$ ; this holds because  $J_T$  is open onto its image by hypothesis. Then, by assumption,  $J_T(U_x) \cap J_T(M^{reg})$  is disconnected. Taking the  $T$ -saturation of  $U_x$  we get a  $T$ -invariant neighborhood whose image is in  $V$  since  $J_T$  is  $T$ -invariant. Thus, we can assume that  $U_x$  is  $T$ -invariant and then the set of regular points for the induced  $T$ -action on  $U_x$  equals the set  $U_x \cap M^{reg}$ , which in turn is open, dense, and connected in  $U_x$ .

Let  $E := \{z \in U_x \mid J_T(z) \in \mathbf{C}J_T(M^{reg})\}$ . Since we can write  $U_x = E \cup D$  with  $D := U_x \setminus E$ , by the construction of  $E$  we have  $J_T(E) = J_T(U_x) \cap \mathbf{C}J_T(M^{reg})$  and  $J_T(D) = J_T(U_x) \cap J_T(M^{reg})$ . Now, since  $E \subset U_x \setminus M^{reg}$ , the inclusion  $U_x \cap M^{reg} \subset D$  also holds. Because  $U_x \cap M^{reg}$  is dense and connected in  $U_x$ , so is  $D$  in  $U_x$ . But this is a contradiction with the fact that  $J_T(D) = J_T(U_x) \cap J_T(M^{reg})$  is disconnected. This proves the result.  $\square$

Now we will prove the converse of Proposition 3.6 in the case in which the momentum map has connected fibers. For this we need a preparatory lemma.

**Lemma 3.7.** *Let  $(M, \omega)$  be a connected symplectic manifold and  $J_T : M \rightarrow \mathfrak{t}^*$  be the invariant momentum map associated to a canonical  $T$ -action on  $M$ . Then  $J_T|_{M^{reg}} : M^{reg} \rightarrow J_T(M)$  is an open map. In particular  $J_T(M^{reg})$  is an open dense subset of  $J_T(M)$ .*

*Proof.* We shall prove that for each point in  $M^{reg}$  there is an open neighborhood such that the restriction of  $J_T$  to this neighborhood is an open map onto its image. Let  $x_0 \in M^{reg}$  be an arbitrary point. By the openness and the  $T$ -invariance of  $M^{reg}$  we can find an open connected  $T$ -invariant neighborhood  $U_{x_0}$  of  $x_0$  included in  $M^{reg}$ . Therefore, for any  $x \in U_{x_0}$ , we have  $\dim T \cdot x = \dim T \cdot x_0 = \dim T/T_0 = \dim T_1$ , where  $T_0 := (T_{x_0})^0$  and  $T = T_0 \times T_1$ . Eventually shrinking  $U_{x_0}$ , using Theorem 3.2, we can work with the normal form. Recall that the original action is symplectically and  $T$ -equivariantly transformed to the action

$$\begin{aligned} (T_0 \times T_1) \times ((T_1 \times \mathfrak{t}_1^*) \times V) &\rightarrow ((T_1 \times \mathfrak{t}_1^*) \times V) \\ ((t_0, t_1), (t_1', \beta, v)) &\mapsto (t_1 t_1', \beta, \pi(t_0)v), \end{aligned}$$

where  $\pi : T_0 \rightarrow Sp(V)$  is a linear symplectic representation. Since the isotropy subgroup of this action at the point  $(t_1', \beta, v)$  equals  $\{t_0 \in T_0 \mid \pi(t_0)v = v\} \times \{e\} \subset T_0 \times T_1$ , the condition that it be equal to  $T_0 \times \{e\}$  implies that the representation  $\pi$  is trivial. Therefore all its weights are zero. By Theorem 3.3 we conclude that  $C_{J_T(x_0)} = J_T(x_0) + \mathfrak{t}_1^* + \text{cone}(\mathcal{P}_V) = J_T(x_0) + \mathfrak{t}_1^*$  and that  $J_T : U_{x_0} \rightarrow C_{J_T(x_0)} = J_T(x_0) + \mathfrak{t}_1^*$  is an open map.

Note that  $J_T(M^{reg}) \subset J_T(x_0) + \mathfrak{t}_1^*$  for some (and hence any)  $x_0 \in M^{reg}$  and  $T_1$  is the torus whose Lie algebra is  $\mathfrak{t}_0^\perp$ , where  $\mathfrak{t}_0$  is the isotropy algebra of a regular point

in  $M$  and the perpendicular is taken relative to an a priori chosen  $T$ -invariant inner product on  $\mathfrak{t}$ . Indeed, using the well-chained property of  $M^{reg}$  any two points in  $M^{reg}$  can be linked by a finite chain formed by the open neighborhoods constructed above. The image of each such neighborhood lies in a translate of  $\mathfrak{t}_1^*$  and since the neighborhoods intersect pairwise, all these affine spaces coincide. Thus,  $J_T(M^{reg})$  lies in just one translate of  $\mathfrak{t}_1^*$ . By the density of  $M^{reg}$  in  $M$  and the closedness of the affine space in  $\mathfrak{t}^*$  it follows that  $J_T(M)$  lies in the same affine space.

Hence, we have shown that for any  $x_0 \in M^{reg}$  there exists an open neighborhood  $U_{x_0} \subset M^{reg}$  such that  $J_T(U_{x_0})$  is open in a given translate of  $\mathfrak{t}_1^*$ . Therefore,  $J_T(U_{x_0})$  is open in  $J_T(M)$ .  $\square$

**Proposition 3.8.** *Let  $J_T : M \rightarrow \mathfrak{t}^*$  be the momentum map of a torus action. Assume that  $J_T$  has connected fibers and that  $\mathbf{C}J_T(M^{reg}) := J_T(M) \setminus J_T(M^{reg})$  does not disconnect any region in  $J_T(M)$ . Then  $J_T$  is open onto its image.*

*Proof.* If  $M$  has more than one connected component, then the  $J_T$ -images of any two components do not intersect, for otherwise this would contradict the connectedness of the fibers. Since connected components of  $M$  are necessarily  $T$ -invariant, we can suppose without loss of generality that  $M$  is connected. We will establish the openness of  $J_T$  onto its image through Proposition 2.19. In order to apply this result it only remains to be shown that for any  $v \in J_T(M)$  and any neighborhood  $V_v$ , the pre-image  $J_T^{-1}(V_v)$  is connected in  $M$ .

By Lemma 3.7 we know that  $J_T|_{M^{reg}} : M^{reg} \rightarrow J_T(M)$  is an open map. Denote, as in Lemma 3.7, by  $\mathfrak{t}_1^*$  the dual of the subtorus whose translate contains  $J_T(M)$ .

Since  $M$  is path connected,  $J_T(M)$  is also path connected and thus it is also locally connected. Let  $J_T(x) \in J_T(M)$  be arbitrary. Choose a small neighborhood  $V_{J_T(x)}$  of  $J_T(x)$  in  $\mathfrak{t}_1^*$  such that  $V := V_{J_T(x)} \cap J_T(M)$  is a region in  $J_T(M)$ . Then  $V_0 := V_{J_T(x)} \cap J_T(M^{reg})$  is connected due to the hypothesis that the region  $V := V_{J_T(x)} \cap J_T(M)$  cannot be disconnected by removing  $\mathbf{C}J_T(M^{reg})$ . Now we are in the hypotheses of Lemma 2.5. Indeed,  $J_T|_{M^{reg}} : M^{reg} \rightarrow J_T(M)$  is an open map and we just showed that  $V_0 \subset J_T(M^{reg})$  is connected. Any fiber of  $J_T$  is connected by hypothesis. Since such a fiber is  $T$ -invariant, the set of its regular points for the induced  $T$ -action is open dense and connected in it. If  $v \in J_T(M^{reg})$ , then  $J_T^{-1}(v) \cap M^{reg}$  is connected. Now applying Lemma 2.5 we conclude that  $J_T^{-1}(V_0) \cap M^{reg}$  is connected. Since  $J_T^{-1}(V_0) \cap M^{reg}$  is dense in  $J_T^{-1}(V_0)$  it follows that  $U_0 := J_T^{-1}(V_0)$  is connected.

Next we will show that  $U_0$  is dense in  $U := J_T^{-1}(V)$ . Indeed, if this is not true, then there exist an element  $x_0 \in U \setminus U_0$  and a neighborhood  $U_{x_0}$  that does not intersect  $U_0$ . For the open set  $U' := U \cap U_{x_0} \cap M^{reg} \neq \emptyset$  we have that  $J_T(U') \subset V_0$  is open in  $V_0$ . So there exists an element  $v_0 \in J_T(U')$  such that  $J_T^{-1}(v_0) \cap U_{x_0} \neq \emptyset$  and  $J_T^{-1}(v_0) \cap U_0 \neq \emptyset$ . But  $J_T^{-1}(v_0) \subset U_0$ , which contradicts the assumption that  $U_{x_0} \cap U_0 = \emptyset$ .

By the connectedness of  $U_0$  and the fact that it is dense in  $U$  we obtain that  $U$  is connected and hence the result follows by Proposition 2.19.  $\square$

We summarize Propositions 3.6 and 3.8 in the following theorem. Since we assume that  $J_T$  has connected fibers, we work on a possibly disconnected symplectic manifold and we apply these propositions to each connected component separately.

**Theorem 3.9.** *Let  $J_T : M \rightarrow \mathfrak{t}^*$  be the momentum map of a torus action which has connected fibers. Then  $J_T$  is open onto its image if and only if  $\mathbf{C}J_T(M^{reg})$  does not disconnect any region in  $J_T(M)$ . Moreover, the image of the momentum map is locally convex and locally polyhedral.*

*Remark 3.10.* The proof of Theorem 3.9 does not use in an essential way the finite dimensionality of the manifold and the torus. A careful look at the proof shows that the same result holds for continuous maps  $f : X \rightarrow V$  that have local convexity data with closed cones, where  $X$  is a connected Hausdorff topological space and  $V$  is a locally convex topological vector space. Additionally, assume that

- $X$  is path connected;
- there exists an open dense connected subset  $X' \subset X$  such that  $f|_{X'}$  is open in  $f(X)$ ;
- for any  $v \in V$ , the fiber  $f^{-1}(v)$  is connected and  $f^{-1}(v) \cap X'$  is connected.

Then  $f$  is open onto its image if and only if  $\mathbf{C}f(X') := f(X) \setminus f(X')$  does not disconnect any region in  $f(X)$ . Moreover, the image of  $f$  is locally convex. If  $f(X)$  is, in addition, closed, then it is convex.

We illustrate the above results with two examples, one in which the momentum map is open onto its image and another one in which it is not. This information is obtained by inspection of the image.

**Example 3.11** (Prato [33]). Let  $M := \mathbb{C}^2 \setminus (D^1 \times D^1)$ , where  $D^1$  is the closed unit disc in  $\mathbb{C}$ . If we consider  $M$  as a symplectic submanifold of  $\mathbb{C}^2$  with its standard symplectic structure, then we have on  $M$  a natural globally Hamiltonian action of  $T^2$  given by  $(e^{i\theta_1}, e^{i\theta_2}) \cdot (z_1, z_2) := (e^{i\theta_1}z_1, e^{i\theta_2}z_2)$ . The momentum map for this action is  $(z_1, z_2) \mapsto (|z_1|^2, |z_2|^2)/2$ . This momentum map has connected fibers. Denote by  $\mathbb{R}_+ := \{x \in \mathbb{R} \mid x \geq 0\}$ . The image of the momentum map is  $\mathbb{R}_+^2 \setminus \{(x, y) \mid x \leq 1/2 \text{ and } y \leq 1/2\}$  and  $\mathbf{C}(J_{T^2}(M^{reg}))$  is the union of  $\{(x, 0) \mid x > 1/2\}$  and  $\{(0, y) \mid y > 1/2\}$  which does not disconnect any region in the image  $J_{T^2}(M)$ . Consequently, according to Theorem 3.9, this momentum map is open onto its image and has a locally convex image, in agreement with Theorem 2.13.  $\blacklozenge$

**Example 3.12** (Karshon and Lerman [18]). Let  $M_1 := T^2 \times U$ , where  $T^2$  is the two dimensional torus and  $U$  is the subset of  $\mathbb{R}^2$  obtained by removing the origin and the positive  $x$ -axis.  $M_1$  is a symplectic manifold when viewed as an open submanifold of the cotangent bundle of  $T^2$ . The restriction to  $M_1$  of the lifted action of  $T^2$  on its cotangent bundle has as momentum map the projection onto  $U$ . Hence, the image of this momentum map is  $\mathbb{R}^2$  minus the origin and the positive  $x$ -axis.

Let  $M_2$  be the symplectic manifold  $\mathbb{C}^2$  minus the points whose first coordinate is nonzero. The momentum map for the  $T^2$ -action on  $M_2$  is given by  $(z, w) \mapsto (|z|^2, |w|^2)/2$  and the image is the set  $\{(x, y) \in \mathbb{R}^2 \mid x > 0, y \geq 0\}$ .

Gluing these two spaces  $M_1$  and  $M_2$  along the pre-images of the positive quadrant we obtain another globally Hamiltonian  $T^2$ -space with a momentum map with connected fibers whose image is  $\mathbb{R}^2$  minus the origin. It is easy to see that  $\mathbf{C}(J_{T^2}(M^{reg}))$  is the open positive  $x$ -axis which disconnects regions in  $\mathbb{R}^2$ . Theorem 3.9 implies that this momentum map is not open onto its image.  $\blacklozenge$

To prove a converse to Proposition 3.6 in the case when the fibers are not connected we need a few more topological facts. A metric space is called a **generalized continuum** if it is locally compact and connected. In a topological space a

**quasi-component** of a point is the intersection of all closed-and-open sets that contain that point. A topological space is called **totally disconnected** if the quasi-component of any point consists of the point itself. A continuous map  $f : X \rightarrow Y$  is called **light** if all fibers  $f^{-1}(y)$  are totally disconnected. We say that a subset of a topological space is **nondense** if and only if it contains no open subsets. Whyburn [37] (page 94) proved the following result called “the extension of openness”.

**Theorem 3.13** (Whyburn). *Let  $X$  and  $Y$  be locally connected generalized continua and let  $f : X \rightarrow Y$  be an onto light mapping which is open on  $X \setminus f^{-1}(F)$ , where  $F$  is a closed nondense set in  $Y$  which separates no region in  $Y$  and is such that  $f^{-1}(F)$  is nondense. Then  $f$  is open on  $X$ .*

If the fibers of  $J_T$  are not connected we still need a control on the connected components of the fibers of  $J_T$  in order to have a similar result to that in Proposition 3.8 (which is a converse of Proposition 3.6).

**Definition 3.14.** Let  $J_T : M \rightarrow \mathfrak{t}^*$  be the momentum map of a torus action on a connected symplectic manifold  $(M, \omega)$ . We say that  $J_T$  satisfies the **connected component fiber condition**

**(CCF):** if  $J_T(x) = J_T(y)$  and  $E_x \cap M^{reg} \neq \emptyset$ , then  $E_y \cap M^{reg} \neq \emptyset$ , where  $E_x$  and  $E_y$  are the connected components of the fiber  $J_T^{-1}(J_T(x))$  that contain  $x$  and  $y$  respectively.

Recall that  $M_{J_T}$  is the quotient topological space whose points are the equivalence classes given by the connected components of the fibers of  $J_T$ . Denote by  $\pi_{J_T} : M \rightarrow M_{J_T}$  the canonical projection.

**Proposition 3.15.** *Suppose that  $M_{J_T}$  is a Hausdorff space,  $J_T(M)$  is locally compact,  $\mathbf{C}J_T(M^{reg})$  does not disconnect any region in  $J_T(M)$ , and  $J_T$  also satisfies condition (CCF). Then  $J_T$  is open onto its image.*

*Proof.* To prove the result we will show that the conditions of Whyburn’s Theorem are satisfied where we take  $f$  to be  $\tilde{J}_T : M_{J_T} \rightarrow J_T(M) \subset \mathfrak{t}^*$ , that is, the quotient map uniquely defined by  $J_T = \pi_{J_T} \circ \tilde{J}_T$  and  $F := \mathbf{C}J_T(M^{reg})$ , which is closed and nondense in  $J_T(M)$  by Lemma 3.7.

By hypothesis  $M_{J_T}$  is a Hausdorff space. Using the fact that  $M$  is locally compact and  $\pi_{J_T}$  is open (see Lemma 2.16 (i)) we obtain that  $M_{J_T}$  is locally compact. Since  $M$  is connected, its quotient  $M_{J_T}$  is connected. Proposition 2.23 guarantees that  $M_{J_T}$  is a metric space since it is Hausdorff. Therefore,  $M_{J_T}$  is a generalized continuum. The same is true for  $J_T(M)$ . Both are locally connected since  $M$  is path connected.

Now we prove that  $\tilde{J}_T : M_{J_T} \rightarrow J_T(M)$  is a light map. For this, take  $v \in J_T(M)$ . We want to show that  $\tilde{J}_T^{-1}(v)$  is totally disconnected. Let  $[x] \in \tilde{J}_T^{-1}(v)$  be arbitrary and choose  $x \in M$  to be a representative of this class. Since  $J_T$  has local convexity data and is locally fiber connected (see Theorem 3.3), we can find a small neighborhood  $U_x$  of  $x$  in  $M$  such that  $\pi_{J_T}(U_x)$  is open in  $M_{J_T}$  and is such that  $\tilde{J}_T^{-1}(v) \cap \pi_{J_T}(U_x) = [x]$ . Thus,  $\tilde{J}_T : M_{J_T} \rightarrow J_T(M)$  is a light map.

Now we prove that  $\tilde{J}_T^{-1}(F)$  is nondense in  $M_{J_T}$ . By contradiction, suppose that this is not true. Then there exists an open set  $U \subset \tilde{J}_T^{-1}(F)$ . Because  $\pi_{J_T}(M^{reg})$  is dense in  $M_{J_T}$  we have that  $U \cap \pi_{J_T}(M^{reg}) \neq \emptyset$ . Thus there exists an element

$[x] \in \tilde{J}_T^{-1}(F) \cap \pi_{J_T}(M^{reg})$  and hence there is an  $x \in M^{reg}$  such that  $J_T(x) = \tilde{J}_T([x]) \in F$ . This contradicts the definition of  $F$ .

The last thing to be verified is that  $\tilde{J}_T$  restricted to  $M_{J_T} \setminus \tilde{J}_T^{-1}(F)$  is an open map. To see this note that the inclusion

$$\tilde{J}_T^{-1}(F) = \tilde{J}_T^{-1}(\mathbf{C}J_T(M^{reg})) = \mathbf{C}\tilde{J}_T^{-1}(J_T(M^{reg})) \subset \mathbf{C}\pi_{J_T}(M^{reg})$$

shows that  $M_{J_T} \setminus \tilde{J}_T^{-1}(F) \supset \pi_{J_T}(M^{reg})$ . Now we shall prove the reverse inclusion. Let  $[x] \in M_{J_T} \setminus \tilde{J}_T^{-1}(F)$ . If the connected component  $E_x$  of the fiber  $J_T^{-1}(J_T(x))$  intersects  $M^{reg}$ , then  $[x] \in \pi_{J_T}(M^{reg})$ . If not, then we have  $J_T(x) = \tilde{J}_T([x]) \notin F$ , that is,  $J_T(x) \in \mathbf{C}F = J_T(M^{reg})$ . Therefore, there is some  $y \in M^{reg}$  such that  $J_T(x) = J_T(y)$ . By condition (CCF),  $E_x \cap M^{reg} \neq \emptyset$  and hence  $[x] \in \pi_{J_T}(M^{reg})$ , which proves the equality  $M_{J_T} \setminus \tilde{J}_T^{-1}(F) = \pi_{J_T}(M^{reg})$ . Thus, since  $\tilde{J}_T$  is open in  $\pi_{J_T}(M^{reg})$  the last requirement of Whyburn's Theorem is verified.  $\square$

To summarize, in the situation for nonconnected fibers we obtain the following result.

**Theorem 3.16.** *Let  $J_T : M \rightarrow \mathfrak{t}^*$  be the momentum map of a torus action on a connected symplectic manifold  $(M, \omega)$ . Suppose that  $M_{J_T}$  is a Hausdorff space.*

*Then  $J_T$  is open onto its image if and only if  $J_T(M)$  is locally compact,  $\mathbf{C}J_T(M^{reg})$  does not disconnect any region in  $J_T(M)$ , and  $J_T$  satisfies condition (CCF). Moreover, under these hypotheses, the image of the momentum map is locally convex and locally polyhedral.*

*Proof.* The only thing that remains to be shown is that if  $J_T : M \rightarrow J_T(M)$  is open onto its image, then condition (CCF) holds. Suppose that the condition (CCF) does not hold. So there exists a fiber with at least two connected components  $E_x$  and  $E_y$  such that  $E_x \cap M^{reg} \neq \emptyset$  and  $E_y \cap M^{reg} = \emptyset$ .

Consequently, we can suppose that  $x \in M^{reg}$  and  $y$  is contained in a lower stratum of the  $T$ -action. Then we have the strict inclusion  $C_{J_T(y)} = v + \mathfrak{t}_0^1 + \text{cone}(\mathcal{P}_V) \subset C_{J_T(x)} = v + \mathfrak{t}_1^*$ , where  $v = J_T(x) = J_T(y)$  (see Theorem 3.3 and the proof of Lemma 3.7). By condition (VN), there exist open neighborhoods  $U_x$  and  $U_y$  of  $x$  and  $y$ , respectively, such that  $J_T(U_x)$  is an open ball in  $\mathfrak{t}_1^*$  centered at  $v$  and  $J_T(U_y)$  is the intersection of an open ball in  $\mathfrak{t}_1^*$  centered at  $v$  with a closed proper cone in  $\mathfrak{t}_1^*$  with vertex  $v$ . This contradicts the openness onto its image of  $J_T$ .  $\square$

In the case of a compact, connected, and non-Abelian group, the momentum map  $J_G : M \rightarrow \mathfrak{g}^*$  is, in general, not open onto its image even if it is a proper map. Nevertheless, we will show that similar results to those obtained in the Abelian case hold for the quotient map  $j_G : M \rightarrow \mathfrak{g}^*/G \simeq \mathfrak{t}_+^*$ , where  $j_G = \pi_G \circ J_G$  and  $\pi_G : \mathfrak{g}^* \rightarrow \mathfrak{t}_+^*$  is the projection map which is always proper if  $G$  is compact.

The quotient map  $j_G$  has local convexity data due to the following result of Sjamaar [35, Theorem 6.5].

**Theorem 3.17** (Sjamaar). *Let  $M$  be a connected Hamiltonian  $G$ -manifold. Then for every  $x \in M$  there exist a unique, closed, polyhedral convex cone  $C_x$  in  $\mathfrak{t}_+^*$  with vertex at  $j_G(x)$  such that for every sufficiently small  $G$ -invariant neighborhood  $U$  of  $x$  the set  $j_G(U)$  is an open neighborhood of  $j_G(x)$  in  $C_x$ .*

Using Lerman's [26] symplectic cut technique, Knop [23, Theorem 5.1] proved that  $j_G$  is locally fiber connected. As a consequence of these results we have the following theorem.

**Theorem 3.18** (Knop-Sjamaar). *The map  $j_G$  is locally fiber connected and has local convexity data.*

Using the above theorem and Theorem 2.28 we obtain the following generalization of Kirwan's convexity result [20]. In the next statement we will use the map  $\tilde{j}_G : M/G \rightarrow \mathfrak{t}_+^*$  defined by the identity  $j_G = \tilde{j}_G \circ \pi$ , where  $\pi : M \rightarrow M/G$  is the projection. We will say that the  $G$ -equivariant momentum map  $J_G : M \rightarrow \mathfrak{g}^*$  is  $G$ -open onto its image whenever  $\tilde{j}_G$  is open onto its image.

**Theorem 3.19.** *Let  $M$  be a connected Hamiltonian  $G$ -manifold with  $G$  a compact connected Lie group. If the momentum map  $J_G$  is closed, then  $J_G(M) \cap \mathfrak{t}_+^*$  is a closed convex locally polyhedral set. Moreover,  $J_G$  is  $G$ -open onto its image and all its fibers are connected.*

*Proof.* As a direct application of Theorem 2.28 we obtain that  $j_G$  is open onto its image and consequently that  $J_G$  is  $G$ -open onto its image. Additionally, the set  $j_G(M) = J_G(M) \cap \mathfrak{t}_+^*$  is a closed convex locally polyhedral set and  $j_G$  has connected fibers.

It remains to be proved that  $J_G$  has connected fibers. To see this, note that since  $j_G$  has connected fibers, the pre-images  $J_G^{-1}(\mathcal{O}_\mu)$  are connected as topological subspaces of  $M$  for every coadjoint orbit  $\mathcal{O}_\mu \subset J_G(M)$ . Note now that  $J_G^{-1}(\mathcal{O}_\mu)$  can also be endowed with the initial topology induced by the map

$$J_G^{\mathcal{O}_\mu} : J_G^{-1}(\mathcal{O}_\mu) \longrightarrow \mathcal{O}_\mu \\ z \longmapsto J_G(z),$$

where the orbit  $\mathcal{O}_\mu$  comes with its orbit smooth structure induced by the homogeneous manifold  $G/G_\mu$ . Since  $G$  is compact, the orbit  $\mathcal{O}_\mu$  is an embedded submanifold of  $\mathfrak{g}^*$  and hence the initial topology for  $J_G(\mathcal{O}_\mu)$  is weaker than the subspace topology. Indeed, the sets of the form  $(J_G^{\mathcal{O}_\mu})^{-1}(U \cap \mathcal{O}_\mu) = J_G^{-1}(U) \cap J_G^{-1}(\mathcal{O}_\mu)$ , with  $U$  open in  $\mathfrak{g}^*$ , form a subbasis of the initial topology of  $J_G^{\mathcal{O}_\mu}$  and since they are open in  $M$  by the continuity of  $J_G$ , the claim follows. Therefore,  $J_G^{-1}(\mathcal{O}_\mu)$  is also connected for the initial topology. Proposition 8.4.1 in [32] states that if  $J_G^{-1}(\mathcal{O}_\mu)$  is endowed with its initial topology, then the map

$$f : G \times_{G_\mu} J_G^{-1}(\mu) \longrightarrow J_G^{-1}(\mathcal{O}_\mu) \\ [g, z] \longmapsto g \cdot z$$

is a homeomorphism, where  $G \times_{G_\mu} J_G^{-1}(\mu)$  denotes the orbit space of the free and continuous action  $h \cdot (g, z) := (gh, h^{-1} \cdot z)$ ,  $h \in G_\mu$ ,  $g \in G$ ,  $z \in J_G^{-1}(\mu)$ , of the compact connected group (see Theorem 3.3.1 in [8])  $G_\mu$  on the product  $G \times J_G^{-1}(\mu)$ . The set  $J_G^{-1}(\mu)$  is considered with its subspace topology. Let  $\pi_\mu : G \times J_G^{-1}(\mu) \rightarrow G \times_{G_\mu} J_G^{-1}(\mu)$  be the continuous and open projection. Since the fibers of  $\pi_\mu$  are connected (they are homeomorphic to  $G_\mu$ ) and  $\pi_\mu$  is open it follows that the pre-image of any connected set is connected by Lemma 2.5. Therefore  $G \times J_G^{-1}(\mu)$  is connected and hence so is  $J_G^{-1}(\mu)$  since  $G$  is connected.  $\square$

*Remark 3.20.* We emphasize that  $J_G$  is  $G$ -open but not open in general. See [30] for a counterexample.

Analyzing the proofs of the results leading to Theorem 3.9 and using the natural definition of the (CCF) condition for the map  $j_G$  we have the following two results (see Remark 3.10) which are the non-Abelian analogs of Theorems 3.9 and 3.16.

**Theorem 3.21.** *Let  $G$  be a compact connected Lie group and  $M$  be a connected Hamiltonian  $G$ -manifold with equivariant momentum map  $J_G : M \rightarrow \mathfrak{g}^*$ . Suppose that  $J_G$  has connected fibers. Then  $J_G$  is  $G$ -open onto its image if and only if  $\mathbf{C}((\pi_G \circ J_G)(M^{reg}))$  does not disconnect any region in  $J_G(M) \cap \mathfrak{t}_+^*$ . Moreover, in this context, the image  $J_G(M) \cap \mathfrak{t}_+^*$  is a locally convex and locally polyhedral set.*

**Theorem 3.22.** *Let  $G$  be a compact connected group and  $M$  be a connected Hamiltonian  $G$ -manifold with the momentum map  $J_G : M \rightarrow \mathfrak{g}^*$ . Suppose that  $(M/G)_{j_G}$  is a Hausdorff space. Then  $J_G$  is  $G$ -open onto its image if and only if  $J_G(M)$  is locally compact,  $\mathbf{C}(\pi_G \circ J_G(M^{reg}))$  does not disconnect any region in  $J_G(M) \cap \mathfrak{t}_+^*$ , and  $j_G$  satisfies the (CCF) condition. Moreover, in this context, the image  $J_G(M) \cap \mathfrak{t}_+^*$  is a locally convex and locally polyhedral set.*

#### 4. CONVEXITY FOR POISSON ACTIONS OF COMPACT LIE GROUPS

In this section we shall prove a generalization of the Flaschka-Ratiu convexity theorem (Theorem 4.39 in [10]) which has as one of its main consequences the convexity theorem for Poisson actions of compact connected Poisson Lie groups on compact connected symplectic manifolds. We hasten to add that the hypotheses of this theorem do *not* imply that the compact Lie group action is necessarily a Poisson action of a Poisson Lie group and that this theorem can be applied in other situations. The generalization below will require only that a certain map is closed (not even properness is assumed) instead of assuming compactness of the symplectic manifold.

Let  $K$  be a compact connected semisimple Lie group. Since any compact Lie group  $K$  is the commuting product  $(Z_K)_0 K_{ss}$  of the connected component of the identity  $(Z_K)_0$  of the center  $Z_K$  and of a closed semisimple subgroup  $K_{ss}$  (see Theorem 4.29 in [22]) we will provide in what follows, without any loss of generality, the proofs for the compact semisimple case, even though the results will be stated for general compact Lie groups. Since  $K$  admits a complexification, we can think of it as the compact real form of a connected complex semisimple Lie group  $G$ . Denote by  $G^{\mathbb{R}}$  the real Lie group underlying  $G$  and let  $G^{\mathbb{R}} = KAN$  be its Iwasawa decomposition. Denote by  $\mathfrak{g}^{\mathbb{R}}, \mathfrak{k}, \mathfrak{a}$ , and  $\mathfrak{n}$  the real Lie algebras of  $G^{\mathbb{R}}, K, A$ , and  $N$ , respectively. Then  $\mathfrak{g}^{\mathbb{R}} = \mathfrak{k} \oplus \mathfrak{a} \oplus \mathfrak{n}$  is the Iwasawa decomposition of  $\mathfrak{g}^{\mathbb{R}}$ . If  $\mathfrak{t} = i\mathfrak{a}$ , then  $T = \exp \mathfrak{t}$  is a maximal torus of  $K$ . Define  $B := AN$  whose Lie algebra is  $\mathfrak{b} := \mathfrak{a} \oplus \mathfrak{n}$ .

Let  $\kappa$  be the Killing form of  $\mathfrak{g}$ . Its imaginary part  $\text{Im } \kappa$  is a nondegenerate invariant symmetric bilinear form on  $\mathfrak{g}^{\mathbb{R}}$ . Since  $\text{Im } \kappa(\mathfrak{k}, \mathfrak{k}) = \text{Im}(\mathfrak{b}, \mathfrak{b}) = 0$ , the vector spaces  $\mathfrak{k}$  and  $\mathfrak{b}$  are dual to each other relative to  $\langle \cdot, \cdot \rangle := \text{Im } \kappa$ . The Cartan decomposition  $G^{\mathbb{R}} = PK$  defines the Cartan involution  $\tau : G^{\mathbb{R}} \rightarrow G^{\mathbb{R}}$ . Define  $g^* := \tau(g^{-1})$  for any  $g \in G$ . The derivative of these maps at the identity will be denoted by the same symbols. The map  $\tau : \mathfrak{g}^{\mathbb{R}} \rightarrow \mathfrak{g}^{\mathbb{R}}$  has eigenvalues  $\pm 1$ . The  $+1$  eigenspace is  $\mathfrak{k}$  and the  $-1$  is denoted by  $\mathfrak{p}$ . Note that  $\langle \cdot, \cdot \rangle$  identifies  $\mathfrak{k}^*$  with  $\mathfrak{p}$ . The exponential map is a diffeomorphism from  $\mathfrak{p}$  to  $P$ .

Let  $\mathfrak{a}_+$  be the positive Weyl chamber in  $\mathfrak{a} \cong \mathfrak{t}^*$  corresponding to the subgroup  $B$ , let  $\mathfrak{a}_0$  be the interior of  $\mathfrak{a}_+$ , and set  $A_+ = \exp \mathfrak{a}_+$  and  $A_0 = \exp \mathfrak{a}_0$ . Let  $W^1, W^2, \dots$  be all the closed walls of varying dimensions of the positive Weyl chamber  $\mathfrak{a}_+$ ; there are only finitely many such walls. If  $P^i$  is the subspace of  $\mathfrak{a}$  spanned by  $W^i$ , then  $W^i$  is closed in  $P^i$  and  $W_0^i$  denotes the interior of  $W^i$  in  $P^i$ . We will also use the notation  $W^0 = \mathfrak{a}_+$  and  $W_0^0 = \mathfrak{a}_0$ ; note that  $P^0 = \mathfrak{a}$ .

**Theorem 4.1.** *Suppose that a compact connected Lie group  $K$  acts on a paracompact connected symplectic manifold  $(M, \omega)$  and that a maximal torus  $T$  of  $K$  acts in a Hamiltonian fashion with equivariant momentum map  $J_T : M \rightarrow \mathfrak{k}^*$ . Suppose there exists a closed map  $\mathcal{P} : M \rightarrow \mathfrak{p}$  with the following properties:*

- (i):  $\mathcal{P}$  is equivariant (with respect to the adjoint action of  $K$  on  $\mathfrak{p}$ );
- (ii): for every  $x \in M$ ,  $T_x \mathcal{P}(T_x M) = \mathfrak{k}_x^{\text{ann}} := \{\mu \in \mathfrak{p} \mid \langle \mu, \xi \rangle = 0 \text{ for all } \xi \in \mathfrak{k}\}$ ;

- (iii): for every  $x \in M$ , the kernel of  $T_x \mathcal{P}$  is

$$(\mathfrak{k} \cdot x)^\omega := \{v \in T_x M \mid \omega(x)(v, \xi_M(x)) = 0 \text{ for all } \xi \in \mathfrak{k}\};$$

- (iv): the restriction of  $\mathcal{P}$  to  $\mathcal{P}^{-1}(\mathfrak{a}_+)$  is proportional to  $J_T$ .

Then  $\mathcal{P}(M) \cap \mathfrak{a}_+$  is a closed convex set. If  $M$  is compact, the set  $\mathcal{P}(M) \cap \mathfrak{a}_+$  is a compact convex polytope.

*Proof.* To prove the statement we shall use the technique of symplectic cross sections for the map  $\mathcal{P}$  (see [11, 7, 14]). Two situations may arise: if the intersection  $\mathcal{P}(M) \cap \mathfrak{a}_0$  is nonempty, then the symplectic cross section can be taken to be  $Y := \mathcal{P}^{-1}(\mathfrak{a}_0)$ . Otherwise,  $\mathcal{P}(M) \cap \mathfrak{a}_0 = \emptyset$  and  $Y := \mathcal{P}^{-1}(W_0^i)$  is a symplectic cross section, where  $W^i$  is the unique closed wall such that  $\mathcal{P}(M) \cap \mathfrak{a}_+ \subset W^i$  and  $\mathcal{P}(M) \cap W_0^i \neq \emptyset$ .

The hypotheses in the theorem ensure via Proposition 4.27 in [10] that the set  $Y$  defined above is a symplectic cross section and that, additionally, the closure of  $\mathcal{P}(Y)$  in  $\mathfrak{a}_+$  is  $\mathcal{P}(M) \cap \mathfrak{a}_+$ . Consequently, it suffices to show that  $\mathcal{P}(Y)$  is convex in order to prove the convexity of  $\mathcal{P}(M) \cap \mathfrak{a}_+$ .

The proportionality of  $\mathcal{P}|_Y$  to  $J_T$  guarantees that  $\mathcal{P}|_Y$  is locally fiber connected and has local convexity data. Notice that  $\mathcal{P}|_Y : Y \rightarrow W_0^i$  is a closed map. Then, using Remark 2.29, it follows that  $\mathcal{P}(Y)$  is convex, closed, and locally polyhedral in  $W_0^i$ .

If  $M$  is compact, then Proposition 4.38 in [10] states that  $\overline{\mathcal{P}(M)}$  is polyhedral and that it has only a finite number of faces. Thus  $\mathcal{P}(M) \cap \mathfrak{a}_+$  is a compact convex polytope.  $\square$

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#### REFERENCES

- [1] R. ABRAHAM, J. E. MARSDEN, AND T. S. RATIU, *Manifolds, Tensor Analysis, and Applications*, second enlarged edition, Applied Mathematical Sciences **75**, Springer Verlag, 1989. MR960687 (89f:58001)
- [2] A. ALEKSEEV, *On Poisson actions of compact Lie groups on symplectic manifolds*, Journ. Diff. Geom., 45(1997), pp. 241–256. MR1449971 (99b:58086)

- [3] M. F. ATIYAH, *Convexity and commuting Hamiltonians*, Bull. London Math. Soc., 14(1982), pp. 1–15. MR642416 (83e:53037)
- [4] A. M. BLOCH, H. FLASCHKA, AND T. S. RATIU, *Schur-Horn-Kostant convexity theorem for the diffeomorphism group of the annulus*, Invent. Math. 113 (1993), no. 3, pp. 511–529. MR1231835 (94i:58063)
- [5] G. E. BREDON, *Introduction to Compact Transformation Groups*, Academic Press, New York and London, 1972. MR0413144 (54:1265)
- [6] C. O. CHRISTENSON AND W. L. VOXMAN, *Aspects of Topology*, Marcel Dekker, 1977. MR0487938 (58:7521)
- [7] M. P. CONDEVAUX, P. DAZORD AND P. MOLINO, *Géométrie du moment*, Travaux du Séminaire Sud-Rhodanien de Géométrie, I, Publ. Dép. Math. Nouvelle Sér. B, 88-1, Univ. Claude-Bernard, Lyon, 1988, 131–160. MR1040871
- [8] J. J. DUISTERMAAT AND J. A. KOLK, *Lie Groups*. Universitext, Springer-Verlag, 1999. MR2265844 (2007j:22016)
- [9] R. ENGELKING, *General Topology*. Second edition. Sigma Series in Pure Mathematics, 6. Heldermann Verlag, Berlin, 1989. MR1039321 (91c:54001)
- [10] H. FLASCHKA AND T. S. RATIU, *A convexity theorem for Poisson actions of compact Lie groups*, Ann. Sci. Ecole Norm. Sup., 4ème série, 29(6) (1995), pp. 787–809. MR1422991 (98a:58068)
- [11] V. GUILLEMIN AND S. STERNBERG, *Convexity properties of the moment mapping*, Invent. Math., 67(1982), pp. 491–513. MR664117 (83m:58037)
- [12] V. GUILLEMIN AND S. STERNBERG, *Convexity properties of the moment mapping II*, Invent. Math., 77(1984), pp. 533–546. MR759258 (86b:58042a)
- [13] V. GUILLEMIN AND S. STERNBERG, *A normal form for the moment map*, Differential Geometric Methods in Mathematical Physics, S. Sternberg ed., Mathematical Physics Studies, 6. Reidel Publishing Co., 1984, pp. 161–175. MR767835 (86d:58033)
- [14] J. HILGERT, K.-H. NEEB, AND W. PLANK, *Symplectic convexity theorems and coadjoint orbits*, Compositio Math. 94(1994), pp. 129–180. MR1302314 (96d:53053)
- [15] J. G. HOCKING AND G. S. YOUNG, *Topology*, Addison-Wesley Publishing Company, Inc., 1961. MR0125557 (23:A2857)
- [16] A. HORN, *Eigenvalues of sums of Hermitian matrices*, Pacific J. Math., 12(1962), pp. 225–241. MR0140521 (25:3941)
- [17] W. Y. HSIANG, *Lectures on Lie Groups*. Series on University Mathematics, World Scientific, Vol. 2, 2000. MR1788014 (2002d:22001)
- [18] Y. KARSHON AND E. LERMAN, *The centralizer of invariant functions and division properties of the moment map*, Illinois J. Math. 41(3) (1997), pp. 462–487. MR1458185 (98e:58077)
- [19] G. KIRCHHOFF, *Vorlesungen ueber Mathematische Physik*, Vol I, Kapitel 20, Teubner, Leipzig, 1883.
- [20] F. KIRWAN, *Convexity properties of the moment mapping III*, Invent. Math., 77(1984), pp. 547–552. MR759257 (86b:58042b)
- [21] V. L. KLEE, JR., *Convex sets in linear spaces*, Duke Math. J., 18(1951), pp. 443–466. MR0044014 (13:354f)
- [22] A. W. KNAPP, *Lie Groups Beyond an Introduction*. Progress in Mathematics, volume 140. Birkhäuser, 1996. MR1399083 (98b:22002)
- [23] F. KNOP, *Convexity of Hamiltonian manifolds*, J. Lie Theory, 12(2002), pp. 571–582. MR1923787 (2003j:53131)
- [24] A. KNUTSON AND T. TAO, *Honeycombs and sums of Hermitian matrices*, Notices of the AMS, 48(2) (2001), pp. 175–186. MR1811121 (2002g:15020)
- [25] B. KOSTANT, *On convexity, the Weyl group and the Iwasawa decomposition*, Ann. Sci. Ecole Norm. Sup., 4ème série, 6(1973), pp. 413–455. MR0364552 (51:806)
- [26] E. LERMAN, *Symplectic cuts*, Mathematical Research Letters, 2(1995), pp. 247–258. MR1338784 (96f:58062)
- [27] E. LERMAN, E. MEINRENKEN, S. TOLMAN, AND C. WOODWARD, *Nonabelian convexity by symplectic cuts*, Topology 37(1998), pp. 245–259. MR1489203 (99a:58069)
- [28] C.-M. MARLE, *Modèle d'action hamiltonienne d'un groupe de Lie sur une variété symplectique*, Rend. Sem. Mat. Univ. Politecn. Torino, 43(2)(1995), pp. 227–251. MR859857 (88a:58075)

- [29] S. MAZUR, *Über konvexe Mengen in linearen normierten Räumen*, *Studia Math.*, 4(1933), 70–84.
- [30] J. MONTALDI AND T. TOKIEDA, *Openness of momentum maps and persistence of extremal relative equilibria*, *Topology*, 42(2003), pp. 833–844. MR1958531 (2004b:37109)
- [31] A. NEUMANN, *An infinite-dimensional version of the Schur-Horn convexity theorem*, *J. Funct. Anal.* 161 (1999), no. 2, pp. 418–451. MR1674643 (2000a:22030)
- [32] J.-P. ORTEGA AND T. S. RATIU, *Momentum Maps and Hamiltonian Reduction*, *Progress in Mathematics* **222**, Birkhäuser Boston, 2004. MR2021152 (2005a:53144)
- [33] E. PRATO, *Convexity properties of the moment map for certain non-compact manifolds*, *Comm. Anal. Geom.*, 2(2) (1994), pp. 267–278. MR1312689 (95k:58065)
- [34] I. SCHUR, *Über eine Klasse von Mittelbildungen mit Anwendungen auf die Determinantentheorie*, *Sitzungsber. der Berliner Math. Gesellschaft*, 22(1923), pp. 9–20.
- [35] R. SJAMAAR, *Convexity properties of the moment map re-examined*, *Adv. Math.*, 138(1) (1998), 46–91. MR1645052 (2000a:53148)
- [36] A. WEINSTEIN, *Poisson geometry of discrete series orbits, and momentum convexity for noncompact group actions*, *Letters in Mathematical Physics*, 56(1) (2001), 17–30. MR1848163 (2002m:53130)
- [37] G. T. WHYBURN, *Topological Analysis*, Princeton University Press, 1964. MR0165476 (29:2758)

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