ON CLOSED INVARIANT SETS IN LOCAL DYNAMICS

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Abstract. We investigate the dynamical behaviour of a holomorphic map on a $f$-invariant subset $C$ of $U$, where $f : U \to \mathbb{C}^k$. We study two cases: when $U$ is an open, connected and polynomially convex subset of $\mathbb{C}^k$ and $C \subset U$, closed in $U$, and when $\partial U$ has a p.s.h. barrier at each of its points and $C$ is not relatively compact in $U$. In the second part of the paper, we prove a Birkhoff’s type Theorem for holomorphic maps in several complex variables, i.e. given an injective holomorphic map $f$, defined in a neighborhood of $U$, with $U$ star-shaped and $f(U)$ a Runge domain, we prove the existence of a unique, forward invariant, maximal, compact and connected subset of $\overline{U}$ which touches $\partial U$.

1. Introduction

Let $f : U \to \mathbb{C}^k$ be a holomorphic map. Here $U$ is an open, connected and bounded (or hyperbolic) subset in $\mathbb{C}^k$. Since the semi-local holomorphic dynamics isn’t well understood yet, specially when $k > 2$, we describe the dynamical behaviour of $f$ on a $f$-invariant subset $C$ of $U$ in two different cases:

a) when $C \subset U$, closed in $U$, and $U$ is polynomially convex;

b) when $C$ isn’t relatively compact in $U$ and every point in $\partial U$ has a p.s.h. barrier.

When there is a recurrent component $V$ in the interior of the polynomially convex hull of $C$ in case a) or in the interior of $\overline{C}$ in case b), we prove that the dynamical behaviour on $V$ is of three types:

1. $V$ is the basin of attraction of an attractive periodic orbit;

2. $V$ is a Siegel domain;

3. if $h$ is a limit of a subsequence of $\{f^n\}_{n \in \mathbb{N}}$, then $0 < \text{rank}(h) < k$.

In particular when $C$ is a closed orbit or a countable union of closed orbits, we prove that $C$ cannot have a non-empty interior with a recurrent point. This has been proved by Fornaess-Stensones in [6] when $U$ has a Lipschitz boundary; here it is proved in a different situation, i.e. when $U$ is polynomially convex or with a p.s.h. barrier at each boundary point, then $U$ has not necessarily Lipschitz boundary.

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In the second part of the paper, see section 4, we give a version of Birkhoff’s Theorem which was originally stated for surface transformations \( f \) having a Lyapunov unstable fixed point \( p \) for \( f \) or for \( f^{-1} \). Under these hypotheses Birkhoff has shown, [3], the existence, in each neighborhood \( U \) of \( p \), of a compact set \( K_+ \) (or \( K_- \)) which is positive (or negative) invariant by \( f \) and touching the boundary of \( U \). In this general setting there is no forward and backward invariant compact set with this property.

In the same spirit, our theorem 4.1 asserts that if \( f : U \to \mathbb{C}^k \) is a holomorphic injective map of \( \mathbb{C}^k \) such that \( f(0) = 0 \), with \( U \) bounded and star-shaped and \( f(U) \) a Runge domain, then there exists a unique, maximal, compact, connected set \( K \) such that:

1. \( 0 \in K \subset \overline{U} \);
2. \( K \cap \partial U \neq \emptyset \);
3. \( f(K) \subset K \).

In general, this compact set \( K \) isn’t totally invariant: we will give an example, see example 5.1. So the several variables analogue of R. Perez-Marco’s hedgehogs, [15], does not hold: in the one variable case the compact is totally invariant and touches the boundary, [15].

2. Preliminaries

We recall some definitions and fix our notations.

Let \( K \) be a compact set of \( \mathbb{C}^k \), then the polynomially convex hull of \( K \) is defined as:

\[
\hat{K}_P = \{ z \in \mathbb{C}^k \mid |p(z)| \leq \sup_{\zeta \in K} |p(\zeta)| \ \forall \ p \ \text{polynomial}\}.
\]

A compact set \( K \) is polynomially convex if \( K = \hat{K}_P \).

Definition 2.1. An open set \( U \) in \( \mathbb{C}^k \) is polynomially convex if, for every compact \( K \) in \( U \), \( K_P \subset \subset U \).

For example, the geometrically convex open sets of \( \mathbb{C}^k \) are polynomially convex in \( \mathbb{C}^k \). The property of being polynomially convex is not invariant by biholomorphisms, as Wermer showed, see Gunning’s book, [11], page 46.

If \( K \) is polynomially convex, each holomorphic function on a neighborhood of \( K \) is the uniform limit on \( K \) of polynomials; in the same way if \( \rho \) is p.s.h. and continuous on \( U \), polynomially convex open set, then it is the uniform limit on the compact sets of \( U \) of p.s.h. functions of \( \mathbb{C}^k \).

A consequence, when \( U \) is polynomially convex, is that convexity with respect to p.s.h. functions in \( U \) is the same as polynomial convexity.

If \( K \) is polynomially convex and compact in \( U \), there exists \( \rho_1 \) p.s.h. and continuous on \( \mathbb{C}^k \), \( K = \{ \rho_1 \leq 0 \} \) and \( \rho_1 \geq 1 \) on a neighborhood of \( \mathbb{C}^k \setminus U \).

Definition 2.2. A domain \( U \) is Runge if each holomorphic function on \( U \) can be approximated by polynomials, uniformly on compact subsets of \( U \).

In particular any polynomially convex open set is a Runge domain, [11]. It is possible to construct Runge domains such that the interior of \( \overline{U} \) is not equal
to $U$: for example $U = \{ w \in \mathbb{C}^k : |w| < \exp(-\varphi) \}$ with $\varphi$ subharmonic on the unit disc, $\varphi = 0$ on a dense set of $\Delta$ and $\varphi \geq 0$ and non identically zero, in particular it doesn’t have Lipschitz boundary.

3. Invariant Sets

3.1. $f$–Invariant Relatively Compact Subsets. Let $f : U \to \mathbb{C}^k$ be a holomorphic map with $U \subset \subset \mathbb{C}^k$ or $U$ Kobayashi hyperbolic. We assume that $U$ is an open, connected and polynomially convex set. We say that a close set $f$ doesn’t have Lipschitz boundary.

Proposition 3.1. Let $\mathcal{C} \subset \subset U$ be a closed $f$–invariant set, then $\hat{\mathcal{C}}_f$ is $f$–invariant.

Proof

By hypothesis, $\mathcal{C} \subset \subset U$. Choose $z_0 \in \hat{\mathcal{C}}_f$ and suppose $f(z_0) \notin \hat{\mathcal{C}}_f$. Then there is a p.s.h. smooth function $\rho_0$ in $\mathbb{C}^k$, such that $\rho_0 \leq 0$ on $\hat{\mathcal{C}}_f$ and $\rho_0(f(z_0)) > 1$.

The function $\rho_0 \circ f$ is p.s.h. on $U$, $\rho_0 \circ f \leq 0$ on $\mathcal{C}$ and $\rho_0 \circ f$ is also p.s.h. on the holomorphic hull of $\mathcal{C}$ with respect to $U$, which is the same as $\hat{\mathcal{C}}_f$. It follows, by Maximum Principle, that $\rho_0(f(z_0)) \leq 0$, which is a contradiction. \hfill \Box

Definition 3.2. A connected component $\Omega \subset U$, of the set of points where $\{ f^n \}_{n \in \mathbb{N}}$ is equicontinuous, is recurrent if there exists $p_0 \in \Omega$ such that $f^n(p_0)$ is relatively compact in $\Omega$ for some subsequence $n_i$, i.e. if $\Omega$ contains a recurrent point $p_0$.

Proposition 3.3. If $V = \text{Int}(\hat{\mathcal{C}}_f) \neq \emptyset$ then the sequence $\{ f^n \}_{n \in \mathbb{N}}$ defined on $V$ is a normal family and if $V$ has a recurrent component $U$ then there are three possibilities:

i) $f$ has an attractive periodic orbit,

ii) there is a Siegel domain, i.e. there is $U$, a component of $V$ and a subsequence $n_i$, s.t. $f^n_u \to \text{Id}$,

iii) if $h$ is a limit of a subsequence of $\{ f^n \}_{n \in \mathbb{N}}$, then $0 < \text{rank}(h) < k$.

Proof

We assume that for some $p_0$, $f^{n_i}(p_0) \to p \in U$, and $f^{n_i}$ converges uniformly on compact sets. We now write $f^{n_{i+1}-n_i} \circ f^{n_i} = f^{n_{i+1}}$. Extracting a subsequence we get a limit $h$ of $f^{n_{i+1}-n_i}$ such that $h(p) = p$. \hfill \Box

If $h$ is of rank 0, we show that $p$ is an attractive fixed point, \hfill \Box

If $h$ is of maximal rank, then we get a Siegel domain, \hfill \Box

The theorem of Carathéodory-Cartan-Kaup-Wu, see \hfill \Box

page 438 and \hfill \Box

page 66, describes the permitted eigenvalues. Otherwise for all possible $h$, \hfill \Box

0 < \text{rank}(h) < k.

In \hfill \Box

Fornaess and Sibony prove a more precise result when $f$ is an endomorphism of $\mathbb{P}^2$. Their stronger result is valid only in dimension two. \hfill \Box

3.2. $f$–Invariant Non-Relatively Compact Subsets.

Theorem 3.4. Let $f : U \to \mathbb{C}^k$ be a holomorphic open map defined on $U$, a bounded (or hyperbolic) open and connected subset of $\mathbb{C}^k$. Assume that every point in $\partial U$ has a p.s.h. barrier, i.e. if $q \in \partial U$, there exists a p.s.h. function $\rho_q$, $\rho_q < 0$ on
Consider all maps \( h \) of \( h \) has is of maximal rank then some iterate of \( f \) has \( p_0 \) as an attractive fixed point and \( f \) has \( p_0 \) as an attractive periodic point. If some \( h \) is of maximal rank \( k \), then \( W \) is a Siegel domain, otherwise all the limit maps have lower rank \( r \), \( 0 < r < k \). In [7] the authors analyze the case of holomorphic endomorphisms of \( \mathbb{P}^2 \) and thanks to the restriction to the dimension 2 and to the endomorphism case, the result there is much more precise: for example in case \( iii \), \( h(W) \) is always independent of \( h \) and attracts all orbits. \( \square \)

**Remark 3.5.** If \( f \) is not open it is enough to assume that \( (\rho_q = 0) \) does not contain the image of \( f \).

**Corollary 3.6.** Under the hypotheses of Theorem 3.4, if \( \overline{C} \) is an invariant closed set with a dense orbit in it or a countable union of closed invariant sets each one with a dense orbit, then the interior \( V \) of \( \overline{C} \) doesn’t contain recurrent points.

**Proof** Indeed in the possible dynamical behaviours described in Theorem 3.4, when \( \overline{C} \) is closed with a dense orbit cannot have interior; when we consider a countable union of closed sets with empty interior then, by Baire’s theorem, the union of them is still with empty interior. \( \square \)
4. Forward invariant sets

Theorem 4.1. Let $U$ be a bounded star-shaped domain with respect to $0$ in $\mathbb{C}^k$ and let $U'$ be an open neighborhood of $\overline{U}$. Let $f : U' \to \mathbb{C}^k$, be a holomorphic map, $f(0) = 0$, $f$ injective on $U$ (i.e. $f : U \to f(U)$ is a biholomorphic map) and $f(U)$ is a Runge domain. Assume $f(z) = Az + O(z^2)$, with $A$ a linear invertible map and with all the eigenvalues $\lambda_j$, for $1 \leq j \leq k$, of modulus $1$. Then there exists a unique maximal connected compact set $K$, with $0 \subset K \subset \overline{U}$ s.t. $(K \cap \partial U) \neq \emptyset$ and $f(K) \subset K$. Furthermore $f$ is linearizable iff $0 \in \text{Int}(K)$.

Proof

Define $f_{\mu_n}(z) = f(\mu_n \cdot z)$ with $\mu_n \in \mathbb{R}$, $0 < \mu_n < 1$ and $\mu_n \to 1$ for $n \to +\infty$. Then $f_{\mu_n} \to f$ uniformly on $\overline{U}$ and $|\text{Jac}(f_{\mu_n})(0)| = |\mu_n| \cdot |\text{Jac}(A)| < 1$ because $|\mu_n| < 1$ and $|\text{Jac}(A)| = 1$; indeed $f_{\mu_n}(z) = \mu_n \cdot A \cdot z + O((\mu_n \cdot z)^2)$.

For simplicity, we call $\mu := \mu_n$.

Let $f_{\mu} : \frac{1}{\mu} \cdot U \to f(U)$ indeed $f_{\mu}(\frac{1}{\mu} \cdot U) \equiv f(U)$. Hence $f_{\mu}$ is a biholomorphism from a star-shaped domain $\frac{1}{\mu} \cdot U$ to a Runge domain $f(U) = f_{\mu}(\frac{1}{\mu} \cdot U)$. Now applying a result of Andersen-Lempert, [2] Theorem 2.1, to the biholomorphism $f_{\mu} : \frac{1}{\mu} \cdot U \to f(U)$, we find a sequence of automorphisms $g_m$ of $\mathbb{C}^k$, such that $g_m \to f_{\mu}$ for $m \to +\infty$ uniformly on compact subsets of $\overline{U}$, i.e. the $g_m$’s converge to $f_{\mu}$, uniformly on compact sets and $g_m(0) = 0$ for all $m$.

Since $|\text{Jac}(f_{\mu})(0)| < 1$, then $|\text{Jac}(g_m)(0)| < 1$.

Hence $g_m \in \text{Aut}(\mathbb{C}^k)$ and $g_m : U \to g_m(U)$ with $0 \in U \cap g_m(U)$.

Let $B$ be a domain which is a homothetic of $U$, i.e. $B = \epsilon U$, sufficiently small s.t. $g_m^{-1}(B) \subset U$ i.e. $0 \in B \subset (U \cap g_m(U))$. Since the basin of attraction of $0$ for $g_m$ (i.e. $\bigcup_{n \in \mathbb{N}} g_m^n(B)$) is biholomorphic to $\mathbb{C}^k$, [10], and in particular is unbounded, there exists $n_0 \in \mathbb{N}$ s.t. $g_m^{-n_0}(B) \subset U$ but $\overline{g_m^{-n_0+1}(B)} \not\subset U$ ($n_0 \geq 1$).

We consider the one-parameter family $\{B_t\}_{t \geq 1}$ where $B_t = t \cdot B$. [15]. Then we consider the $t$’s for which:

$g_m^{-n_0}(B_t) \subset U$.

The set is not empty because for $t = 1$ the inclusion is true. By continuity, there exists $\overline{t}$ s.t.

$g_m^{-n_0}(B_{\overline{t}}) \subset U$

and

$g_m^{-n_0}(\overline{B_{\overline{t}}}) \cap (\partial U) \neq \emptyset$.

We call $F_m := g_m^{-n_0}(B_{\overline{t}})$.

Then $(F_m)_{m \in \mathbb{N}}$ is a sequence of compact sets in $\overline{U}$ s.t. $g_m(F_m) \subset F_m$ because $g_m^{-n_0+1}(\overline{B_{\overline{t}}}) \subset g_m^{-n_0}(\overline{B_{\overline{t}}})$; this follows from the description of the basin of attraction of $0$.

Each $F_m$ is a connected set because it is the closure of the pre-image by a biholomorphic of a connected set.

By compactness of the space $\mathcal{K}_c(\overline{U}) = \{\text{connected compact subsets of } \overline{U}\}$, there exists a subsequence $(m_k)_{k \in \mathbb{N}}$ t.c. $F_{m_k} \to K_{\mu} \in \mathcal{K}_c(\overline{U})$. Finally we prove that $f_{\mu}(K_{\mu}) \subset K_{\mu}$.

We use that:
exists a maximal connected compact set invariant for $f$.

\textbf{Remark} shows, see Example 5.1 below.

and backward invariant compact subsets are different, as the case of Hénon maps.

\textbf{4.2 Remark} that $h$ is still $f$-invariant. Hence $K_\mu$ is $f_\mu$-invariant.

Therefore for each $\mu$ we have found a forward invariant connected compact set for $f_\mu$ and $K_\mu$ intersects $\partial U$. Now, with an argument similar to the one already used for $\{g_m\}_{m \in \mathbb{N}}$ and $\{F_m\}_{k \in \mathbb{N}}$, we prove that, up to considering a subsequence, $K_{\mu_n} \to K$ in the Hausdorff metric. Since $f_{\mu_n} \to f$ uniformly on compact sets, we have that $f(K) \subset K$ and $K$ touches $\partial U$. In order to have the unique, maximal, connected, invariant compact set, it is enough to take the closure of the union of all such compact sets $K$. Obviously, the closure of a union of $f-$invariant sets is still $f-$invariant and it is also connected because each compact set contains $0$.

Since $K_{\mu_n}$ intersects $\partial U$ for all $\mu_n$, also its limit $K$ in the Hausdorff topology does.

Suppose $0 \in \text{Int}(K)$, we show that $f$ is linearizable. The family $(f^n)_{n \in \mathbb{N}}$ is locally equicontinuous on $\text{Int}(K)$ and $f(0) = 0$. Following a standard trick, we define

$$h(z) := \lim_{n_j \to +\infty} \frac{1}{n_j} \sum_{j=0}^{n_j-1} A^{-j} f^j(z).$$

The limit exists in a neighborhood of zero. Indeed there is a $c > 1$ such that $f^n(\overline{B}(0,r)) \subset \overline{B}(0,cr) \subset K$ for all $n$. Then we can consider a limit map $h$ for an appropriate subsequence $n_j$. We have $h(0) = 0$, $\text{Jac}(h)(0) = Id$ and we easily check that $h(f) = Ah$. \hfill $\Box$

\textbf{Remark 4.2.} If we take a sequence $\mu_n > 1$, $\mu_n \to 1$, we can prove that there exists a maximal connected compact set invariant for $f^{-1}$. In general the forward and backward invariant compact subsets are different, as the case of Hénon maps shows, see Example 5.1 below.

\textbf{Remark 4.3.} We want to point out that $K$ is not necessarily a proper subset of $\overline{U}$, indeed if $f$ is an automorphism of the ball $\mathbb{B}^k \subset \mathbb{C}^k$ fixing $0$, then $K = \overline{\mathbb{B}^k}$.

\textbf{Remark 4.4.} Suppose that $f, g$ are two commuting maps satisfying all the hypotheses of Theorem 4.1 then they share the same maximal, compact, connected, invariant set $K \ni 0$.

Indeed let $K_f$ and $K_g$ be the maximal, compact, connected invariant sets containing $0$, for $f$ and $g$ respectively, which exist by Theorem 4.1. Then consider $f \circ g(K_f) = g \circ f(K_f) \subset g(K_f)$, hence $g(K_f) \subset K_f$ which implies that $K_f \subset K_g$. Analogously, considering $g \circ f(K_g) = f \circ g(K_g)$, we can prove that $K_g \subset K_f$.

\section{Examples}

In this section we are going to prove that our theorem 4.1 is optimal, we mean that there exist a map $f : \mathbb{B} \to \mathbb{C}^k$ which satisfy all the hypotheses of the Theorem...
such that it has a forward invariant compact and connected set containing 0 which touches the boundary of $\mathcal{B}$ but it doesn’t admit a totally invariant compact and connected set containing 0 which touches the boundary of $\mathcal{B}$.

**Example 5.1.** Let $f$ be the following Hénon map:

$$f(z, w) = (z^2 + w, z).$$

Then $f(0, 0) = (0, 0)$ and

$$Jac(f) = \begin{pmatrix} 2z & 1 \\ 0 & 0 \end{pmatrix}$$

So, at $0$, $\lambda_1 = 1$, $\lambda_2 = -1$, i.e. $|\lambda_j| = 1$ for $j = 1, 2$. Clearly $f \in Aut(\mathbb{C}^2)$. From the well known study of the dynamics of $f$, there exist the following closed invariant subsets of $\mathbb{C}^2$:

$$K_f^+ = \{ z \in \mathbb{C}^2 \mid f^n(z) \text{ is bounded} \}$$

$$K_f^- = \{ z \in \mathbb{C}^2 \mid f^{-n}(z) \text{ is bounded} \}$$

and the following compact set of $\mathbb{C}^2$ containing 0:

$$K = K_f^+ \cap K_f^-.$$  

Consider a ball $\mathbb{B}(0, R) \subset \mathbb{C}^2$ with $R >> 1$ such that $\mathbb{B}(0, R) \supset K$. If we consider the restriction $f : \mathbb{B}(0, R) \rightarrow \mathbb{C}^2$, by Theorem 4.1 there exists a connected compact subset $X$ of $\mathbb{B}(0, R)$ which touches the $\partial \mathbb{B}(0, R)$, which is $f$–invariant and which contains 0. For any such $X$, we have $X \subset K_f^+$, [17], because if $z \in X$, $f^n(z)$ is bounded since $X$ is $f$–invariant and compact. Hence $X \subset (K_f^+ \cap \overline{\mathbb{B}(0, R)})$. It is well known from the study of the dynamics of Hénon maps that:

$$dist(f^n(X), K) \rightarrow 0$$

uniformly on compact sets. Hence there exists $n_0 \in \mathbb{N}$ such that $dist(f^{n_0}(X), K) < \frac{1}{2} \cdot dist(K, \partial \mathbb{B}(0, R))$. So $X$ cannot be at the same time forward and backward invariant i.e. $f(X) \subset X$, but $f(X) \neq X$.

If $f^{n_0}(X)$ is distant from $K$ less than $dist(\partial \mathbb{B}(0, R), K)$, then it means that $f^{n_0}(X) \subset X$ and they are different. Hence, if we consider $g := f^{n_0}$, then $g(X) \subset \subset X$.

**Example 5.2.** In some cases it is possible that the forward and the backward invariant compact sets coincide. For example, if in the previous example we consider a ball $\overline{\mathbb{B}(0, r)}$ which contains $K = K_f^+ \cap K_f^-$ and such that $K \cap \partial \mathbb{B}(0, r) \neq \emptyset$, then the restriction of the Hénon map $f$ to $\mathbb{B}(0, r)$ admits a forward and backward invariant compact set $K$ which touches the boundary of $\mathbb{B}(0, r)$.

**Remark 5.3.** Let $K$ be one of the $f$–invariant, connected and compact set of Theorem 4.1 and let $X = \bigcap_{n \in \mathbb{N}} f^n(K)$. The set $X$ is connected because it is a decreasing intersection of connected sets, $X \supseteq 0$, $X$ is compact and $f(X) = X$. For example if $f$ is an Hénon map, $X = K_f^+ \cap K_f^-$. 
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