CONTINUITY OF SRB MEASURE AND ENTROPY FOR BENEDICKS-CARLESON QUADRATIC MAPS

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Abstract. We consider the quadratic family of maps given by $f_a(x) = 1 - ax^2$ on $I = [-1, 1]$, for a positive Lebesgue measure set of parameters close to $a = 2$- the Benedicks-Carleson parameters, on which there is exponential growth of the derivative of the critical point and an absolutely continuous SRB invariant measure. We show that the volume of the set of points of I that at a given time fail to present an exponential growth of the derivative decays exponentially as time passes. We also show that the set of points of I that are not slowly recurrent to the critical set decays sub-exponentially. As a consequence we obtain continuous variation of the SRB measures and associated metric entropies with the parameter on the referred set.

1. Introduction

Our object of study is the logistic family. Concerning the asymptotic behavior of orbits of points $x \in I = [-1, 1]$ we know that:

(1) The set of parameters H for which f_a has an attracting periodic orbit, is open and dense in $[0, 2]$.
(2) There is a positive Lebesgue measure set of parameters, close to the parameter value 2, for which f_a has no attracting periodic orbit and exhibits a chaotic behavior, in the sense of existence of an ergodic, f_a-invariant measure absolutely continuous with respect to the Lebesgue measure on $I = [-1, 1]$.

The first result was a conjecture with long history that was finally established by Graczyk, Swiatek [GS97] and Lyubich [Ly97, Ly00]. The last one was studied on Jakobson's pioneer work [Ja81] and latter by Benedicks and Carleson on their celebrated papers [BC85, BC91].

A remarkable fact is the crucial role played by the orbit of the unique critical point $\xi_0 = 0$ on the determination of the dynamical behavior of f_a. It is well known that if f_a has an attracting periodic orbit then $\xi_0 = 0$ belongs to its *basin of attraction*, which is the set of points $x \in I$ whose ω-limit set is the attracting periodic orbit. Also, the *basin of attraction* of the periodic orbit is an open and dense full Lebesgue measure subset of I. See [MS93], for instance.

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Benedicks and Carleson [BC85, BC91] show the existence of a positive Lebesgue measure set of parameters Ω_∞ for which there is exponential growth of the derivative of the orbit of the critical point ξ_0. This implies the non-existence of attracting periodic orbits and leads to a new proof of Jakobson's theorem.

In this work, we study the regularity on the variation of invariant measures and their metric entropy for small perturbations on the parameters. We are interested on investigating *statistical stability* of the system, that is, the persistence of its statistical properties for small modifications of the parameters. Alves and Viana [AV02] formalized this concept *statistical stability* in terms of continuous variation of *physical measures* as a function of the governing law of the dynamical system.

By *physical measure* or *Sinai-Ruelle-Bowen (SRB) measure* we mean a Borel probability measure μ on I for which there is a positive Lebesgue measure set of points $x \in I$ such that

$$\lim_{n\to\infty} \frac{1}{n} \sum_{j=0}^{n-1} \varphi\left(f_a^j(x)\right) = \int \varphi \, d\mu,$$

for any continuous function $\varphi : I \to \mathbb{R}$. The set of points $x \in I$ with this property is called the *basin* of μ. One should regard SRB measures as Borel probability measures that provide a fairly description of the statistical behavior of orbits, at least for a large set of points that constitute the *basin* of the SRB measure.

It is not hard to conclude that if $a \in H$, and $\{p, f_a(p), \ldots, f_a^{k-1}(p)\}$ is the attracting periodic orbit then

$$\eta_a = \frac{1}{k} \sum_{i=0}^{k-1} \delta_{f_a^i(p)},$$

where δ_x is the Dirac probability measure at $x \in I$, is a SRB measure whose *basin* coincides with the *basin of attraction* of the periodic orbit. Moreover, the quadratic family is *statistically stable* for $a \in H$, i.e., the SRB measure η_a varies continuously with $a \in H$, in a weak sense (convergence of measures in the weak* topology).

Benedicks and Young [BY92] proved that for each Benedicks-Carleson parameter $a \in \Omega_\infty$, there is an unique, ergodic, f_a-invariant, absolutely continuous measure (with respect to Lebesgue measure on I) μ_a. These measures qualify as SRB measures by Birkhoff's ergodic theorem and their *basin* is the whole interval I.

In the subsequent sections we will prove that the quadratic family is *statistically stable*, in strong sense, for $a \in \Omega_\infty$. To be more precise, we will show that the densities of the SRB measures vary continuously, in L^1-norm, with the parameters $a \in \Omega_\infty$. This result extends the one by Rychlik and Sorets [RS92] who showed the same for Misiurevicz parameters, which form a subset of zero Lebesgue measure.

Concerning the stability of the statistical behavior of the system in a broader perspective, we are also specially interested in the variation of entropy. Entropy is related to the unpredictability of the system. Topological entropy measures the complexity of a dynamical system in terms of the exponential growth rate of the number of orbits distinguishable over long time intervals, within a fixed small precision. Metric entropy with respect to an SRB measure, quantifies the average level of uncertainty every time we iterate, in terms of exponential growth rate of the number of statistically significant paths an orbit can follow.

It is known that topological entropy varies continuously with $a \in [0, 2]$ (see [MS93]). This is not the case in what respects to metric entropy of SRB measures. We note that the metric entropy associated to η_a, with $a \in H$, is zero. H is an open and dense set which means we can find a sequence of parameters $(a_n)_{n\in\mathbb{N}}$, such that $a_n \in H$ and thus with zero metric entropy with respect to the SRB measure η_{a_n}, accumulating on $a \in \Omega_\infty$ whose metric entropy associated to the absolutely continuous SRB measure, μ_a, is strictly positive.

However, we will show that the metric entropy of the absolutely continuous SRB measure μ_a varies continuously on the Benedicks and Carleson parameters, $a \in \Omega_\infty$. We would like to stress that the continuous variation of the metric entropy is not a direct consequence of the continuous variation of the SRB measures and the entropy formula, because $\log(f_a')$ is not continuous on the interval I.

1.1. **Motivation and main strategy.**

The work developed by Alves and Viana on [AV02] lead Alves [Al03] to obtain sufficient conditions for the strong statistical stability of certain classes of *non-uniformly expanding* maps with *slow recurrence to the critical set*. By *non-uniformly expanding*, we mean that for Lebesgue almost all points we have exponential growth of the derivative along their orbits. *Slow recurrence to the critical set* means, roughly speaking, that almost all points cannot have their orbits spending long periods of time in a very small vicinity of the critical set.

Alves, Oliveira and Tahzibi [AOT03] determined abstract conditions for continuous variation of metric entropy with respect to SRB measures. They also obtained conditions for *non-uniformly expanding* maps with *slow recurrence to the critical set* to satisfy their initial abstract conditions.

In both cases, the conditions obtained for continuous variation of SRB measures and their metric entropy are tied with the volume decay of the *tail set*, which is the set of points that resist to satisfy either the *non-uniformly expanding* or the *slow recurrence to the critical set* conditions, up to a given time.

Consequently, our main objective is to show that on the Benedicks-Carleson set of parameter values, where we have exponential growth of the derivative along the orbit of the critical point $\xi_0 = 0$, the maps f_a are *non-uniformly expanding*, have *slow recurrence to the critical set*, and the volume of the *tail set* decays sufficiently fast. In fact, we will show that the volume of the points whose derivative has not reached a satisfactory exponential rate, up to a given time $n \in \mathbb{N}$, decays exponentially fast with n. While the points that up to a fixed time $n \in \mathbb{N}$, could not be sufficiently kept away from a vicinity of the critical point, decays sub-exponentially with n.

Finally we apply the results on [Al03, AOT03] to obtain the continuous variation of the SRB measures and their metric entropy inside the set of Benedicks and Carleson parameters Ω_∞.

We also refer to the recent work [ACP04] from which we conclude, by the *non-uniformly expanding* character of these maps, that for almost every $x \in I$ and any y on a pre-orbit of x, one has an exponential growth of the derivative of y.

1.2. **Statement of results.** In the sequel we will only consider parameter values $a \in \Omega_\infty$ which are Benedicks-Carleson parameters, in the sense that for those $a \in \Omega_\infty$ we have exponential growth of the derivative of $f_a(\xi_0)$,

$$\left|\left(f_a^j\right)'(f_a(\xi_0))\right| \geq e^{cj},\ \forall j \in \mathbb{N}, \tag{EG}$$

where $c \in \left[\frac{2}{3}, \log 2\right)$ is fixed, and the basic assumption is valid

$$\left|f_a^j(\xi_0)\right| \geq e^{-\alpha j},\ \forall j \in \mathbb{N}, \tag{BA}$$

where α is a small constant. Note that Ω_∞ is a set of parameter values of positive Lebesgue measure, very close to $a = 2$. (See Theorem 1 of [BC91] or [Mo92] for a detailed version of its proof).

We say that f_a is *non-uniformly expanding* if there is a $d > 0$ such that for Lebesgue almost every point in $I = [-1, 1]$

$$\liminf_{n\to\infty} \frac{1}{n}\sum_{i=0}^{n-1} \log\left|f_a'\left(f_a^i(x)\right)\right| > d, \tag{1.1}$$

while having *slow recurrence to the critical set* means that for every $\epsilon > 0$, there exists $\gamma > 0$ such that for Lebesgue almost every $x \in I$

$$\limsup_{n\to\infty} \frac{1}{n}\sum_{j=0}^{n-1} -\log \operatorname{dist}_\gamma\left(f_a^j(x), 0\right) < \epsilon, \tag{1.2}$$

where

$$\operatorname{dist}_\gamma(x,y) = \begin{cases} |x-y| & \text{if } \ |x-y| \leq \gamma \\ 0 & \text{if } \ |x-y| > \gamma \end{cases}.$$

Observe that by (EG) it is obvious that ξ_0 satisfies (1.1) for all $a \in \Omega_\infty$. However, in what refers to condition (1.2) the matter is far more complicated and one has that ξ_0 satisfies it for Lebesgue almost all parameters $a \in \Omega_\infty$. We provide an heuristic argumentation for the validity of the last statement on remark 8.2.

It is well known that the validity of (1.1) Lebesgue almost everywhere derives from the existence of an ergodic absolutely continuous invariant measure. Nevertheless we are also interested on knowing how fast does the volume of the points that resist to satisfy (1.1) up to n, decays to 0 as n goes to ∞. With this in mind, we define the *expansion time function*, first introduced on [ALP02]

$$\mathcal{E}(x) = \min\left\{N \geq 1 :\ \frac{1}{n}\sum_{i=0}^{n-1}\log\left|f_a'\left(f_a^i(x)\right)\right| > d,\ \forall n \geq N\right\}, \tag{1.3}$$

which is defined and finite almost everywhere on I if (1.1) holds.

Similarly, we define the *recurrence time function*, also introduced on [ALP02]

$$\mathcal{R}(x)=\min\left\{N\geq 1:\ \frac{1}{n}\sum_{j=0}^{n-1}-\log \operatorname{dist}_\gamma\left(f_a^j(x),0\right)<\epsilon,\ \forall n\geq N\right\}, \tag{1.4}$$

which is defined and finite almost everywhere in I, as long (1.2) holds.

We are now able to define the *tail set*, at time $n\in\mathbb{N}$,

$$\Gamma_n^{f_a}=\left\{x\in I:\ \mathcal{E}(x)>n \text{ or } \mathcal{R}(x)>n\right\}, \tag{1.5}$$

which can be seen as the set of points that at time n have not reached a satisfactory exponential growth of the derivative or could not be sufficiently kept away from $\xi_0=0$.

First we study the volume contribution to the *tail set*, $\Gamma_n^{f_a}$, of the points where f_a fails to present *non-uniformly expanding* behavior.We claim that in fact, (1.1) holds to be true and the volume of the set of points whose derivative has not achieved a satisfactory exponential growth at time n, decays exponentially as n goes to ∞.

Theorem A. *Assume that $a\in\Omega_\infty$. Then f_a is non-uniformly expanding, which is to say that* (1.1) *holds for Lebesgue almost all points $x\in I$. Moreover, there are positive real numbers C_1 and τ_1 such that for all $n\in\mathbb{N}$:*

$$\lambda\left\{x\in I:\ \mathcal{E}(x)>n\right\}\leq C_1e^{-\tau_1 n}.$$

Secondly, we study the volume contribution to $\Gamma_n^{f_a}$, of the points that fail to be *slowly recurrent* to ξ_0. We claim that (1.2) also holds to be true and the volume of the set of points that at time n, have been too close to the critical point, in mean, decays sub-exponentially with n.

Theorem B. *Assume that $a\in\Omega_\infty$. Then f_a has slow recurrence to the critical set, or in other words,* (1.2) *holds for Lebesgue almost all points $x\in I$. Moreover, there are positive real numbers C_2 and τ_2 such that for all $n\in\mathbb{N}$:*

$$\lambda\left\{x\in I:\ \mathcal{R}(x)>n\right\}\leq C_2e^{-\tau_2\sqrt{n}}.$$

Remark 1.1. The constants d in (1.1), ϵ,γ in (1.2) c,α from (EG) and (BA) can be chosen uniformly on Ω_∞. Moreover, the constants C_1,τ_1 given by theorem A and the constants C_2,τ_2 given by theorem B depend on the previous ones but are independent of the parameter $a\in\Omega_\infty$. Thus we may say that $\{f_a\}_{a\in\Omega_\infty}$ is a *uniform family* in the sense considered in [Al03]. For a further discussion on this subject see section 9.

Remark 1.2. Both theorems easily imply that the volume of the *tail set* decays to 0 at least sub-exponentially as n goes to ∞, ie, for all $n\in\mathbb{N}$, $\lambda\left(\Gamma_n^{f_a}\right)\leq \operatorname{const} e^{-\tau\sqrt{n}}$, for some $\tau>0$ and $\operatorname{const}>0$.

Remark 1.3. One may wonder if the sub-exponential decay rate on theorem B could be improved. As far as we know the answer is negative, at least with the same type of statistical argument used. In fact, the same kind of large deviation argument, also lead Viana to a sub-exponential decay of a resemblant tail set in [Vi97]. For better understanding of how the large deviation argument prevents a faster tail volume decay we refer to remark 8.1.

The sub-exponential volume decay of the *tail set* puts us in condition of applying theorem A from [Al03] to obtain, in a strong sense, continuous variation of the ergodic invariant measures under small perturbations on the set of parameters. By strong sense we mean convergence of the densities of the ergodic invariant measures in the L^1 norm.

Corollary C. *Let μ_a be the SRB measure invariant for f_a. Then $\Omega_\infty \ni a \mapsto \frac{d\mu_a}{d\lambda}$ is continuous.*

Theorems A and B also make it possible the application of corollary C figuring on [AOT03] to get continuous variation of metric entropy with the parameter.

Corollary D. *The entropy of the SRB measure invariant of f_a varies continuously with $a \in \Omega_\infty$.*

Theorem A alone, also allows us to apply corollary 1.2 from [ACP04] to obtain backward volume contraction.

Corollary E. *For Lebesgue almost every $x \in I$, there exists $C_x > 0$ and $b > 0$ such that $\left|(f_a^n)'(y)\right| > C_x e^{bn}$, for every $y \in f^{-n}(x)$.*

2. Setting of Notation and Vocabulary

In order to be precise about the meaning of “close to the critical set” and “distant from the critical set”, we introduce the following neighborhoods of $\xi_0 = 0$:

$$U_m = \left(-e^{-m}, e^{-m}\right), \qquad U_m^+ = \left(-e^{-m+1}, e^{-m+1}\right) \qquad , \text{ for } |m| \geq \Delta;$$

and consider also

$$\begin{aligned} I_m &= \left[e^{-(m+1)}, e^{-m}\right), \qquad I_m^+ = \left[e^{-(m+1)}, e^{-(m-1)}\right) \qquad , \text{ for } m \geq \Delta, \\ I_m &= \left(-e^{-m}, -e^{-(m+1)}\right], I_m^+ = \left(-e^{-(m-1)}, -e^{-(m+1)}\right], \text{ for } m \leq -\Delta, \end{aligned}$$

where Δ is a large positive integer.

We define $\delta = e^{-\Delta}$ that will indicate when closeness to the critical region is relevant. In fact, here and henceforth, we consider $\gamma = \delta$ in (1.2)

We will use λ to refer to Lebesgue measure on $\mathbb{R}$, although, sometimes we will write $|\omega|$ as an abbreviation of $\lambda(\omega)$, for $\omega \subset \mathbb{R}$.

We introduce the following notation for the orbit of the critical point, $\xi_n = f_a^n(0)$, for all $n \in \mathbb{N}_0$.

Consider a point $x \in I$ and $n \in \mathbb{N}$. We define

$$T_n(x) = \frac{1}{n} \sum_{j=0}^{n-1} -\log \operatorname{dist}_\delta \left(f_a^j(x), 0\right). \tag{2.1}$$

In order to explain the main ideas we also introduce a vocabulary suitable for making ourselves clear. We have a *return* of the orbit of a point to the neighborhood of $\xi_0 = 0$ if for some $j \in \mathbb{N}$, $f_a^j(x) \in U_\Delta = (-\delta, \delta)$. We say that the return had a *depth* of $\mu \in \mathbb{N}$ if $\mu = [-\log \operatorname{dist}_\delta (f_a^j(x), 0)]$, which is equivalent to say that $f_a^j(x) \in I_{\pm\mu}$.

We may have three types of returns: *essential*, *inessential* and *bound*. The essential returns are the ones that will play a prominent role in the reasoning. Let the sequence $t_1, t_2, \dots$ denote the instants corresponding to essential returns of the orbit of x. When $n \in \mathbb{N}$ is given, we can define s_n to be the number of essential returns of the orbit of x, occurring up to n. Let η_i denote the depth of the i-th essential return. Each t_i might be followed by bounded returns $u_{i,j}$, $j = 1, \dots, u$ and these can be followed by inessential returns $v_{i,j}$, $j = 1, \dots, v$. We will write $\eta_{i,j}$ to denote the depth of the inessential return correspondent to $v_{i,j}$. Note that each $v_{i,j}$ has a bound evolution where new bound returns may occur and although we refer to these returns later, it is not necessary to introduce here a notation for them. There is also no need to introduce a notation for the depths of the bound returns. Sometimes, for the sake of simplicity, it is convenient not to distinguish between essential and inessential returns, so we introduce the notation $z_1 < z_2 < \dots$ for the instants of occurrence of essential or inessential returns of the orbit of x.

We call the attention for the fact that t_i, for example, depends of the point $x \in I$ considered- $t_i(x)$ corresponds to the i-th instant of essential return of the orbit of x. So, t_i, s_n, η_i, $u_{i,j}$, $v_{i,j}$, $\eta_{i,j}$ and z_i, should be regarded as functions of the point $x \in I$.

We will build a sequence of partitions $\mathcal{P}_n$ of the set I, such that all $x \in \omega \in \mathcal{P}_n$ have the same return times and return depths up to n. In fact, if, for example, $t_i(x) \le n$ for some $x \in \omega \in \mathcal{P}_n$, then t_i and η_i are constant on ω. The same applies to the other above mentioned functions of x. The construction of the partition will also guarantee that f_a has bounded distortion on each component which will reveal to be of extreme importance.

3. Insight of the reasoning

In order to achieve our goals we will follow [BC85, BC91] and proceed for each point $x \in I$ as they proceeded for ξ_0, by splitting the orbit of x into *free periods*, *returns*, *bound periods*, which occur in this order.

The *free periods* correspond to the times on which the orbit stays away from the vicinity $U_\Delta = (-\delta, \delta)$ of ξ_0. During these periods the orbit of x experiences an exponential growth of its derivative $|(f_a^n)'(x)|$, provided we are close enough to the parameter value 2. In fact, the following lemma gives a first approach to the set Ω_∞ by stating that we may have an exponential growth rate $0 < c_0 < \log 2$ of the derivative of the orbit of x during free periods, for all $a \in [a_0, 2]$, where a_0 is chosen sufficiently close to 2.

Lemma 3.1. *For every $0 < c_0 < \log 2$ and Δ sufficiently large there exists $1 < a_0(c_0, \Delta) < 2$ such that for every $x \in I$ and $a \in [a_0, 2]$ one has:*

1. *If $x, f_a(x), \dots, f_a^{k-1}(x) \notin U_{\Delta+1}$ then $\left|(f_a^k)'(x)\right| \ge e^{-(\Delta+1)} e^{c_0 k}$;*
2. *If $x, f_a(x), \dots, f_a^{k-1}(x) \notin U_{\Delta+1}$ and $f_a^k(x) \in U_\Delta^+$, then $\left|(f_a^k)'(x)\right| \ge e^{c_0 k}$;*
3. *If $x, f_a(x), \dots, f_a^{k-1}(x) \notin U_{\Delta+1}$ and $f_a^k(x) \in U_1$, then $\left|(f_a^k)'(x)\right| \ge \frac{4}{5} e^{c_0 k}$.*

The proof relies on the fact that $f_2(x) = 1 - 2x^2$ is conjugate to $1 - 2|x|$. So it is only a question of choosing a sufficiently close to 2 for f_a to inherit the expansive behavior of f_2. See [BC85] or [Al92, Mo92] for detailed versions.

However, for almost every point $x \in I$, it is impossible to keep its orbit away from U_Δ. Since

$$|(f_a^n)'(x)| = \prod_{j=1}^{n} \left|2af_a^j(x)\right|,$$

the returns introduce some small factors on the derivative of the orbit of x. Also note that the only points of the orbit of x that contribute to the sum in (2.1) are those considered to be returns. After a free period we can only have either essential or inessential returns, and the first are the ones that will require more attention. To compensate the loss on the expansion of the derivative, we will show that a property very similar to (BA) holds for the orbit of $x \in I$ which can be seen as: we allow the orbit of x to get close to ξ_0 but we put some restraints on the velocity of possible accumulation on ξ_0. This will be the basis of the proof of theorem A. As for the proof of theorem B the strategy will be of different kind, it will be based on a statistical analysis of the depth of the returns, specially of the essential returns, which, fortunately, are very unlikely to reach large depths.

We are lead to the notion of *bound period* that follows a return during which the orbit of x is bounded to the orbit of ξ_0, or in other words: the orbit of x shadows the early iterates of ξ_0.

Let $\beta > 0$ be a small number such that $\beta > \alpha$, take, for example, $10^{-2} > \beta = 2\alpha$.

Definition 3.1. Suppose $x \in U_m^+$. Let $p(m,x)$ be the largest p such that the following binding condition holds:

$$\left|f_a^j(x) - \xi_j(a)\right| \le e^{-\beta j}, \quad \text{for all } i = 1, \dots, p-1 \tag{BC}$$

The time interval $1, \dots, p(m,x) - 1$ is called the *bound period* for x.

If $p(m)$ is the largest p such that (BC) holds for all $x \in I_m^+$, which is the same to define

$$p(m) = \min_{x \in I_m^+} p(m,x),$$

then the time interval $1, \dots, p(m) - 1$ is called the *bound period* for I_m^+.

One expects that the deeper is the return, the longer is its associated bound period. Next lemma confirms this, in particular.

Lemma 3.2. *If Δ is sufficiently large, then for each $|m| \ge \Delta$, $p(m)$ has the following properties:*

(1) *There is a constant $B_1 = B_1(\beta - \alpha)$ such that $\forall y \in f_a\left(U_{|m|-1}\right)$*

$$\frac{1}{B_1} \le \left|\frac{(f_a^j)'(y)}{(f_a^j)'(\xi_1)}\right| \le B_1, \quad \textit{for } j = 0, 1 \dots, p(m) - 1;$$

(2) *$p(m) < 3|m|$;*

(3) *$\left|(f_a^p)'(x)\right| \ge e^{(1-4\beta)|m|}$, for $x \in I_m^+$ and $p = p(m)$.*

The proof of this lemma depends heavily on the conditions (EG) and (BA). It can be found on [Al92, Mo92]. (Look up [BC85] for a similar version of the lemma but with sub-exponential estimates).

We call the attention for the fact that after the bound period not only we have recovered from the loss on the growth of the derivative caused by the return that originated the bound period, but we even have some exponential gain.

We are now in condition of making a sketch of the proofs of theorems A and B. The following two basic ideas are determinant for both the proofs.

(I) The depth of the inessential and bound returns is smaller than the depth of the essential return preceding them, as we will show on lemmas 5.1 and 5.2.

(II) The chances of occurring a very deep essential return are very small, in fact, they are less than $e^{-\tau\rho}$, where $\tau > 0$ is constant and ρ is the depth in question. See proposition 6.1 and corollary 6.2.

The first one derives from (BA) and (EG), while the main ingredient of the proof of the second is the bounded distortion on each element of the partition.

In order to prove theorem A, we define the following sets for a sufficiently large n.

$$E_1(n) = \left\{x \in I : \ \exists i \in \{1,\dots,n\},\ |f_a^i(x)| < e^{-\alpha n}\right\}. \tag{3.1}$$

Next, we will see that if $x \in I - E_1(n)$ then $\left|(f_a^n)'(x)\right| > e^{dn}$, for some $d = d(\alpha,\beta)$.

Let us fix a large n. Assume that z_i, $i = 1,\dots,\gamma$ are the instants of return of the orbit of x, either essential or inessential. Let p_i denote the length of the bound period associated to the return z_i. We set $z_0 = 0$, wether $x \in U_\Delta$ or not; $p_0 = 0$ if $x \notin U_\Delta$ and as usual if not. We define $q_i = z_{i+1}-(z_i+p_i)$, for $i = 0,1,\dots,\gamma-1$ and $q_\gamma = \begin{cases} 0 & \text{if} \quad n < z_\gamma + p_\gamma \\ n-(z_\gamma+p_\gamma & \text{if} \quad n \ge z_\gamma + p_\gamma \end{cases}$.
Finally, let

$$d = \min\left\{c, \frac{1-4\beta}{3}\right\} - 2\alpha = \frac{1-4\beta}{3} - 2\alpha. \tag{3.2}$$

If $n \ge z_\gamma + p_\gamma$ then

$$|(f_a^n)'(x)| = \prod_{i=0}^{\gamma} \left|(f_a^{q_i})'(f_a^{z_i+p_i}(x))\right| \left|(f_a^{p_i})'(f_a^{z_i}(x))\right|.$$

Using lemmas 3.1 and 3.2, we have

$$|(f_a^n)'(x)| = e^{-\Delta+1} e^{c\sum_{i=0}^{\gamma} q_i} e^{\frac{1-4\beta}{3}\sum_{i=0}^{\gamma} p_i} \ge e^{-\Delta+1} e^{dn} e^{2\alpha n} \ge e^{dn}, \tag{3.3}$$

for n large enough.

If $n < z_\gamma + p_\gamma$ then

$$|(f_a^n)'(x)| = |f_a'(f_a^{z_\gamma}(x))| \left|(f_a^{n-(z\gamma+1)})'(f_a^{z_\gamma+1}(x))\right| \prod_{i=0}^{\gamma-1} \left|(f_a^{q_i})'(f_a^{z_i+p_i}(x))\right| \left|(f_a^{p_i})'(f_a^{z_i}(x))\right|.$$

Now, by lemmas 3.1 and 3.2 together with the assumption that $x \in I - E_1(n)$, for n large enough we have

$$\begin{aligned}
|(f_a^n)'(x)| &\geq |f_a'(f_a^{z_\gamma}(x))| \tfrac{1}{B_1} \left|(f_a^{n-(z\gamma+1)})'(1)\right| e^{c\sum_{i=0}^{\gamma-1} q_i} e^{\frac{1-4\beta}{3}\sum_{i=0}^{\gamma-1} p_i} \\
&\geq e^{-\alpha n} \tfrac{1}{B_1} e^{c(n-(z_\gamma+1))} e^{c\sum_{i=0}^{\gamma-1} q_i} e^{\frac{1-4\beta}{3}\sum_{i=0}^{\gamma-1} p_i} \\
&\geq e^{-\alpha n - \log B_1} e^{(d+2\alpha)(n-1)} \\
&\geq e^{-2\alpha n} e^{dn} e^{2\alpha n} \\
&\geq e^{dn}.
\end{aligned} \tag{3.4}$$

Using(I) and (II) we will show that

$$\lambda\left(E_1(n)\right) \leq e^{-\tau_1 n}, \tag{3.5}$$

for a constant $\tau_1(\alpha,\beta) > 0$ and for all $n \geq N_1^*(\Delta,\tau_1)$. We consider $N_1(\Delta,\alpha,B_1,d,N_1^*)$ such that for all $n \geq N_1$ estimates (3.3), (3.4) and (3.5) hold. Hence for every $n \geq N_1$ we have that $|(f_a^n)'(x)| \geq e^{dn}$, except for a set $E_1(n)$ of points of $x \in I$ satisfying (3.5).

We take $E_1 = \bigcap_{k\geq N_1}\bigcup_{n\geq k} E_1(n)$. Since $\forall k \geq N_1$

$$\sum_{n\geq k} \lambda\left(E_1(n)\right) \leq \text{const}\, e^{-\tau_1 k},$$

we have by the Borel Cantelli lemma that $\lambda(E_1) = 0$. Thus on the full Lebesgue measure set $I - E_1$ we have that (1.1) holds. We note that $\{x \in I:\ \mathcal{E}(x) > k\} \subset \bigcup_{n\geq k} E_1(n)$, so for $k \geq N_1$

$$\lambda\left(\{x \in I:\ \mathcal{E}(x) > k\}\right) \leq \text{const}\, e^{-\tau_1 k}.$$

At this point we just have to compute an adequate $C_1 = C_1(N_1) > 0$ such that

$$\lambda\left(\{x \in I:\ \mathcal{E}(x) > n\}\right) \leq C_1 e^{-\tau_1 n}, \tag{3.6}$$

for all $n \in N$.

For the proof of theorem B, we define for $n \in \mathbb{N}$ the sets:

$$E_2(n) = \{x \in I:\ T_n(x) > \epsilon\}. \tag{3.7}$$

Again, using (BA) and (EG), we will show in lemma 5.3 that the elapsed time between two consecutive essential returns is smaller than $5\eta_i$, ie, $t_{i+1} - t_i \leq 5\eta_i$. This fact and basic idea (I) make it possible to bound T_n in the following way:

$$T_n(x) \leq \frac{1}{n}\sum_{i=1}^{s_n} 5\eta_i^2 = \frac{5}{n}B_n(x), \tag{3.8}$$

where s_n denotes the number of essential returns occurring up to n and η_i the depth of i-th essential return. Hence we have

$$\lambda(E_2(n)) \leq \lambda\left\{x : B_n(x) > \frac{\epsilon n}{5}\right\}.$$

Fact (II) and a large deviation argument allow us to obtain

$$\lambda\left\{x : B_n(x) > \frac{\epsilon n}{5}\right\} \leq \text{const}\, e^{-\tau_2\sqrt{n}}$$

where $\tau_2 = \tau_2(\beta, \epsilon) > 0$ is constant, which implies

$$\sum_{n\geq k} \lambda\left(E_2(n)\right) \leq \text{const}\, e^{-\tau_2\sqrt{k}}.$$

Consequently, applying Borel Cantelli's lemma, we get $\lambda(E_2) = 0$, where $E_2 = \bigcap_{k\geq 1}\bigcup_{n\geq k} E_2(n)$ and finally conclude that (1.2) holds on the full Lebesgue measure set $I - E_2$. Observe that $\{x \in I :\ \mathcal{R}(x) > k\} \subset \bigcup_{n\geq k} E_2(n)$, and thus, for all $n \in \mathbb{N}$,

$$\lambda\left(\{x \in I :\ \mathcal{R}(x) > n\}\right) \leq C_2 e^{-\tau_2\sqrt{n}},$$

where $C_2 = C_2(\tau_2) > 0$ is constant.

At this point we would like to bring the reader's attention for the fact that most proofs and lemmas that follow are standard, in the sense that they are very resemblant to the ones on [Al92, BC85, BC91, BY92, Mo92] (just to cite a few), that deal with the same subject. Nevertheless, we could not find the right version for our needs, either because in some cases they refer to sub-exponential estimates when we want exponential estimates or because the partition is built on the space of parameters instead of the set I, as we wish. Hence, we decided for the sake of completeness to include them in this work.

4. Construction of the partition and bounded distortion

We are going to build inductively a sequence of partitions $\mathcal{P}_0, \mathcal{P}_1, \ldots$ of I (modulus a zero Lebesgue measure set) into intervals. We begin by breaking each I_m, $|m| \geq \Delta$, into m^2 pieces of the same length in order to obtain bounded distortion on each member of the partition. For each $m \geq \Delta - 1$ and $k = 1, \ldots, m^2$, we introduce the following notation

$$I_{m,k} = \left[e^{-m} - k\frac{\lambda(I_m)}{m^2}, e^{-m} - (k-1)\frac{\lambda(I_m)}{m^2}\right)$$
$$I_{-m,k} = -I_{m,k}\,, \qquad I^+_{m,k} = I_{m_1,k_1} \cup I_{m,k} \cup I_{m_2,k_2},$$

where I_{m_1,k_1} and I_{m_2,k_2} are the adjacent intervals of $I_{m,k}$.

We will also define inductively the sets $R_n(\omega) = \left\{z_1, \ldots, z_{\gamma(n)}\right\}$ which is the set of the return times of $\omega \in \mathcal{P}_n$ up to n and a set $Q_n(\omega) = \left\{(m_1, k_1), \ldots, (m_{\gamma(n)}, k_{\gamma(n)})\right\}$, which records the indices of the intervals such that $f_a^{z_i}(\omega) \subset I_{m_i,k_i}$, $i = 1, \ldots, z_{\gamma(n)}$.

Among with the construction of the partition we will show, inductively that for all $n \in \mathbb{N}_0$

$$\forall \omega \in \mathcal{P}_n \quad f_a^{n+1}|_\omega \text{ is a diffeomorphism,} \tag{4.1}$$

which is vital for the construction itself.

For $n = 0$ we define

$$\mathcal{P}_0 = \{[-1, -\delta], [\delta, 1]\} \cup \left\{I_{m,k} : |m| \geq \Delta,\ 1 \leq k \leq m^2\right\}.$$

It is obvious that $\mathcal{P}_0$ satisfies (4.1). We set $R_0([-1,-\delta]) = R_0([\delta,1]) = \emptyset$ and $R_0(I_{m,k}) = \{0\}$.

Assume that $\mathcal{P}_{n-1}$ is defined, satisfies (4.1) and R_{n-1}, Q_{n-1} are also defined on each element of $\mathcal{P}_{n-1}$. We fix an interval $\omega \in \mathcal{P}_{n-1}$. We have three possible situations:

(1) If $R_{n-1}(\omega) \neq \emptyset$ and $n < z_{\gamma(n-1)} + p(m_{\gamma(n-1)})$ then we say that n is a *bound time* for ω, put $\omega \in \mathcal{P}_n$ and set $R_n(\omega) = R_{n-1}(\omega)$, $Q_n(\omega) = Q_{n-1}(\omega)$.

(2) If $R_{n-1}(\omega) = \emptyset$ or $n \geq z_{\gamma(n-1)} + p(m_{\gamma(n-1)})$, and $f_a^n(\omega) \cap U_\Delta \subset I_{\Delta,1} \cup I_{-\Delta,1}$, then we say that n is a *free time* for ω, put $\omega \in \mathcal{P}_n$ and set $R_n(\omega) = R_{n-1}(\omega)$, $Q_n(\omega) = Q_{n-1}(\omega)$.

(3) If the above two conditions do not hold we say that ω has *a return situation* at time n. We have to consider two cases:

   (a) $f_a^n(\omega)$ does not cover completely an interval $I_{m,k}$, with $|m| \geq \Delta$ and $k = 1, \ldots, m^2$. Because f_a^n is continuous and ω is an interval, $f_a^n(\omega)$ is also an interval and thus is contained in some $I_{m,k}^+$, for a certain $|m| \geq \Delta$ and $k = 1, \ldots, m^2$, which is called the *host interval* of the return. We say that n is an *inessential return time* for ω and set $R_n(\omega) = R_{n-1}(\omega) \cup \{n\}$, $Q_n(\omega) = Q_{n-1}(\omega) \cup \{(m,k)\}$.

   (b) $f_a^n(\omega)$ contains at least an interval $I_{m,k}$, with $|m| \geq \Delta$ and $k = 1, \ldots, m^2$, in which case we say that ω has an *essential return situation* at time n. Then we consider the sets

$$\omega'_{m,k} = f_a^{-n}(I_{m,k}) \cap \omega \quad \text{ for } |m| \geq \Delta$$
$$\omega'_{\Delta-1,(\Delta-1)^2} = f_a^{-n}([\delta,1]) \cap \omega$$
$$\omega'_{1-\Delta,(\Delta-1)^2} = f_a^{-n}([-1,-\delta]) \cap \omega$$

   and if we denote by $\mathcal{A}$ the set of indices (m,k) such that $\omega'_{m,k} \neq \emptyset$ we have

$$\omega - f_a^{-n}(0) = \bigcup_{(m,k)\in\mathcal{A}} \omega'_{m,k}. \tag{4.2}$$

   By the induction hypothesis $f_a^n|_\omega$ is a diffeomorphism and then each $\omega'_{m,k}$ is an interval. Moreover $f_a^n(\omega'_{m,k})$ covers the whole $I_{m,k}$ except eventually for the two end intervals. When $f_a^n(\omega'_{m,k})$ does not cover entirely $I_{m,k}$, we join it with its adjacent interval in (4.2) and get a new decomposition of $\omega - f_a^{-n}(0)$ into intervals $\omega_{m,k}$ such that

$$I_{m,k} \subset f_a^n(\omega_{m,k}) \subset I_{m,k}^+,$$

   when $|m| \geq \Delta$.

   We define $\mathcal{P}_n$, by putting $\omega_{m,k} \in \mathcal{P}_n$ for all indices (m,k) such that $\omega_{m,k} \neq \emptyset$, with $|m| \geq \Delta$, which results on a refinement of $\mathcal{P}_{n-1}$ at ω. We set $R_n(\omega_{m,k}) = R_{n-1}(\omega) \cup \{n\}$ and n is called an *essential return time* for $\omega_{m,k}$. The intervals $I_{m,k}^+$ is called once more the *host interval* of $\omega_{m,k}$ and $Q_n(\omega_{m,k}) = Q_n(\omega) \cup \{(m,k)\}$.

On the eventuality of the set $\omega_{\Delta-1,(\Delta-1)^2}$ being not empty we say that n is a *free time* for $\omega_{\Delta-1,(\Delta-1)^2}$ and $R_n(\omega_{\Delta-1,(\Delta-1)^2}) = R_{n-1}(\omega)$, $Q_n(\omega_{\Delta-1,(\Delta-1)^2}) = Q_{n-1}(\omega)$. We proceed likewise for $\omega_{1-\Delta,(\Delta-1)^2}$.

To end the construction we need to verify that (4.1) holds for $\mathcal{P}_n$. Since for any interval $J \subset I$

$$\left.\begin{array}{l} f_a^n|_J \text{ is a diffeomorphism} \\ 0 \notin f_a^n(J) \end{array}\right\} \Rightarrow f_a^{n+1}|_J \text{ is a diffeomorphism},$$

all we are left to prove is that $0 \notin f_a^n(\omega)$ for all $\omega \in \mathcal{P}_n$. So take $\omega \in \mathcal{P}_n$. If n is a free time for ω then we have nothing to prove. If n is a return for ω, either essential or inessential, we have by construction that $f_a^n(\omega) \subset I_{m,k}^+$ for some $|m| \geq \Delta$, $k = 1, \ldots, m^2$ and thus $0 \notin f_a^n(\omega)$. If n is a bound time for ω then by definition of bound period and (BA) we have for all $x \in \omega$

$$\begin{aligned} |f_a^n(x)| &\geq \left|f_a^{n-z_{\gamma(n-1)}}(0)\right| - \left|f_a^n(x) - f_a^{n-z_{\gamma(n-1)}}(0)\right| \\ &\geq e^{-\alpha(n-z_{\gamma(n-1)})} - e^{-\beta(n-z_{\gamma(n-1)})} \\ &\geq e^{-\alpha(n-z_{\gamma(n-1)})}\left(1 - e^{-(\beta-\alpha)(n-z_{\gamma(n-1)})}\right) \\ &> 0 \quad \text{since } \beta - \alpha > 0. \end{aligned}$$

Now we will obtain estimates of the length of $|f_a^n(\omega)|$.

Lemma 4.1. *Suppose that z is a return time for $\omega \in \mathcal{P}_{n-1}$, with host interval $I_{m,k}^+$. Let $p = p(m)$ denote the length of its bound period. Then*

(1) *Assuming that $z^* \leq n-1$ is the next return time for ω (either essential or inessential) and defining $q = z^* - (z+p)$ we have, for a sufficiently large Δ, $\left|f_a^{z^*}(\omega)\right| \geq e^{cq} e^{(1-4\beta)|m|} \left|f_a^z(\omega)\right| \geq 2\left|f_a^z(\omega)\right|$.*

(2) *If z is the last return time of ω up to $n-1$ and n is either a free time for ω or a return situation for ω, then putting $q = n - (z+p)$ we have, for a sufficiently large Δ,*
   (a) $|f_a^n(\omega)| \geq e^{cq-(\Delta+1)} e^{(1-4\beta)|m|} \left|f_a^z(\omega)\right|$
   (b) $|f_a^n(\omega)| \geq e^{cq-(\Delta+1)} e^{-5\beta|m|}$ *if z is an essential return.*

(3) *If z is the last return time of ω up to $n-1$, n is a return situation for ω and $f_a^n(\omega) \subset U_1$, then putting $q = n-(z+p)$ we have, for a sufficiently large Δ,*
   (a) $\left|f_a^{z^*}(\omega)\right| \geq e^{cq} e^{(1-5\beta)|m|} \left|f_a^z(\omega)\right| \geq 2\left|f_a^z(\omega)\right|$;
   (b) $|f_a^n(\omega)| \geq e^{cq} e^{-5\beta|m|}$ *if z is an essential return.*

Proof. By the mean value theorem, for some $\zeta \in \omega$,

$$|f_a^n(\omega)| \geq \left|\left(f_a^{n-z}\right)'(f_a^z(\zeta))\right| \left|f_a^z(\omega)\right|.$$

Using lemma 3.1 part 2 and lemma 3.2 part 3 we get

$$\begin{aligned}|f_a^n(\omega)| &\geq \left|(f_a^q)'\left(f_a^{z+p}(\zeta)\right)\right| \left|(f_a^p)'\left(f_a^z(\zeta)\right)\right| |f_a^z(\omega)| \\ &\geq \tfrac{4}{5}e^{cq}e^{(1-4\beta)|m|}\,|f_a^z(\omega)| \\ &\geq \tfrac{4}{5}e^{\beta|m|}e^{cq}e^{(1-5\beta)|m|}\,|f_a^z(\omega)| \\ &\geq 2e^{cq}e^{(1-5\beta)|m|}\,|f_a^z(\omega)|,\end{aligned}$$

if Δ is sufficiently large in order to have $\frac{4}{5}e^{\beta|m|} \geq 2$.

Note that part 3a is proved. To demonstrate part 1 one only needs to use lemma 3.1 part 2 instead of 3. For obtaining 3b observe that because z is an essential return time $I_{m,k} \subset f_a^z(\omega)$ which implies $\lambda(f_a^z(\omega)) \geq \frac{e^{-|m|}}{2m^2}$ and so

$$\begin{aligned}|f_a^n(\omega)| &\geq \tfrac{4}{5}e^{\beta|m|}e^{cq}e^{(1-5\beta)|m|}\,|f_a^z(\omega)| \\ &\geq e^{cq}e^{(1-5\beta)|m|}e^{-|m|}\tfrac{2e^{\beta|m|}}{5m^2} \\ &\geq e^{cq}e^{-5\beta|m|},\end{aligned}$$

if Δ is large enough.

To obtain part 2 it is just a matter of repeating the proof using lemma 3.1 part 1 instead of 3. Note that when n is a return situation for ω and not a return time for ω we cannot guarantee that $f_a^{t_{i+1}}(\omega) \subset U_1$, and thus the point given by the mean value theorem to obtain the above inequality is not certain to belong to U_1, which justifies the usage of part 1 of lemma 3.1, also in this case. □

Lemma 4.2 (Bounded Distortion)**.** *For some $n \in \mathbb{N}$ let $\omega \in \mathcal{P}_{n-1}$ be such that $f_a^n(\omega) \subset U_1$. Then there is a constant $C(\beta - \alpha)$ such that for every $x, y \in \omega$*

$$\frac{\left|(f_a^n)'(x)\right|}{\left|(f_a^n)'(y)\right|} \leq C$$

Proof. Let $R_{n-1}(\omega) = \{z_1, \ldots, z_\gamma\}$ and $Q_{n-1}(\omega) = \{(m_1, k_1), \ldots, (m_\gamma, k_\gamma)\}$, be, respectively, the sets of return times and host indices of ω, defined on the construction of the partition. Note that for $i = 1, \ldots, \gamma$, $f_a^{z_i}(\omega) \subset I^+_{m_i,k_i}$. Let $\sigma_i = f_a^{z_i}(\omega)$, $p_i = p(m_i)$, $x_i = f_a^i(x)$ and $y_i = f_a^i(y)$.

Observe that

$$\left|\frac{(f_a^n)'(x)}{(f_a^n)'(y)}\right| = \prod_{j=0}^{n-1}\left|\frac{f_a'(x_j)}{f_a'(y_j)}\right| = \prod_{j=0}^{n-1}\left|\frac{x_j}{y_j}\right| \leq \prod_{j=0}^{n-1}\left(1 + \left|\frac{x_j - y_j}{y_j}\right|\right)$$

Hence the result is proved if we manage to bound uniformly

$$S = \sum_{j=0}^{n-1}\left|\frac{x_j - y_j}{y_j}\right|.$$

For the moment assume that $n \leq z_\gamma + p_\gamma - 1$.

We first estimate the contribution of the free period between z_{q-1} and z_q for the sum S

$$F_q = \sum_{j=z_{q-1}+p_{k-1}}^{z_q-1} \left|\frac{x_j - y_j}{y_j}\right| \le \sum_{j=z_{q-1}+p_{k-1}}^{z_q-1} \left|\frac{x_j - y_j}{\delta}\right|$$

For $j = z_{q-1} + p_{k-1}, \cdots, z_q - 1$ we have

$$\begin{aligned} \lambda(\sigma_q) &\ge |f_a^{z_q-j}(x_j) - f_a^{z_q-j}(y_j)| \\ &= \left|(f_a^{z_q-j})'(\zeta)\right| \cdot |x_j - y_j|, \text{for some } \zeta \text{ between } x_j \text{ and } y_j \\ &\ge e^{c(z_q-j)}|x_j - y_j|, \text{ by Lemma 3.1} \end{aligned}$$

and so

$$\begin{aligned} F_q &\le \sum_{j=z_{q-1}+p_{k-1}}^{z_q-1} e^{-c(z_q-j)} \cdot \frac{\lambda(\sigma_q)}{\delta} \\ &\le \sum_{j=1}^{\infty} e^{-cj} \cdot \frac{\lambda(I_{m_q})}{\delta} \cdot \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})} \\ &\le a_1 \cdot \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})} \text{ for some constant } a_1 = a_1(c). \end{aligned}$$

The contribution of the return z_q is

$$\left|\frac{x_{z_q} - y_{z_q}}{y_{z_q}}\right| \le \frac{\lambda(\sigma_q)}{e^{-|m_q|-2}} \le a_2 \cdot \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})} \text{ where } a_2 \text{ is a constant.}$$

Finally, let us compute the contribution of bound periods

$$B_q = \sum_{j=1}^{p_q-1} \left|\frac{x_{z_q+j} - y_{z_q+j}}{y_{z_q+j}}\right|$$

We have that

$$\begin{aligned} |x_{z_q+j} - y_{z_q+j}| &= |(f_a^j)'(\zeta)| \cdot |x_{z_q} - y_{z_q}|, \text{for some } \zeta \text{ between } x_{z_q} \text{ and } y_{z_q} \\ &= \left|(f_a^{j-1})'\left(f_a(\zeta)\right)\right| \cdot |f_a'(\zeta)| \cdot |x_{z_q} - y_{z_q}| \\ &= \left|(f_a^{j-1})'\left(f_a(\zeta)\right)\right| \cdot 2a|\zeta| \cdot |x_{z_q} - y_{z_q}| \\ &\le B_1|(f_a^{j-1})'(\xi_1)| \cdot 2ae^{-|m_q|+1} \cdot \lambda(\sigma_q). \end{aligned}$$

On the other hand, we have

$$|y_{z_q+j} - \xi_j| = |(f_a^{j-1})'(\theta)| \cdot |y_{z_q+1} - \xi_1|$$

for some $\theta \in [y_{z_q+1}, \xi_1]$. Noting that $[y_{z_q+1}, \xi_1] \subset f_a\left(U^+_{|m_q|}\right)$, we apply Lemma 3.2 and get

$$\begin{aligned}
|y_{z_q+j} - \xi_j| &\geq \frac{1}{B_1}|(f_a^{j-1})'(\xi_1)| \cdot |y_{z_q+1} - \xi_1| \\
&= \frac{1}{B_1}|(f_a^{j-1})'(\xi_1)| \cdot 2ay_{z_q}^2 \\
&\geq \frac{1}{B_1}|(f_a^{j-1})'(\xi_1)| \cdot 2ae^{-2|m_q|-4}.
\end{aligned}$$

Combining what we know about $|x_{z_q+j} - y_{z_q+j}|$ and $|y_{z_q+j} - \xi_j|$ we obtain

$$\begin{aligned}
\frac{|x_{z_q+j} - y_{z_q+j}|}{|y_{z_q+j}|} &= \frac{|x_{z_q+j} - y_{z_q+j}|}{|y_{z_q+j} - \xi_j|} \cdot \frac{|y_{z_q+j} - \xi_j|}{|y_{z_q+j}|} \\
&\leq B_1^2 \frac{e^5}{e^{-|m_q|}} \cdot \lambda(\sigma_q) \cdot \frac{|y_{z_q+j} - \xi_j|}{|y_{z_q+j}|} \\
&\leq B_1^2 \cdot e^5 \cdot \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})} \cdot \frac{e^{-\beta j}}{e^{-\alpha j} - e^{-\beta j}}
\end{aligned}$$

since

$$|y_{z_q+j}| \geq |\xi_j| - |y_{z_q+j} - \xi_j| \geq e^{-\alpha j} - e^{-\beta j}.$$

Clearly,

$$\sum_{j=1}^{\infty} \frac{e^{-\beta j}}{e^{-\alpha j} - e^{-\beta j}} < \infty$$

and so

$$B_q \leq a_3 \cdot \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})}$$

for some constant $a_3 = a_3(\alpha - \beta)$.

From the estimates obtained above, we get

$$S \leq a_4 \cdot \sum_{q=0}^{\gamma} \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})}, \text{ where } a_4 = a_1 + a_2 + a_3.$$

Defining $q(m) = \max\{q : m_q = m\}$ and using the fact that $\lambda(\sigma_{q+1}) \geq 2\lambda(\sigma_q)$ (lemma 4.1 part 1), we can easily see that

$$\sum_{\{q:m_q=m\}} \lambda(\sigma_q) \leq 2\lambda(\sigma_{q(m)}),$$

and so

$$\sum_{q=0}^{\gamma} \frac{\lambda(\sigma_q)}{\lambda(I_{m_q})} \leq \sum_{m\geq\Delta} \frac{1}{\lambda(I_m)} \sum_{\{q:m_q=m\}} \lambda(\sigma_q) \leq \sum_{m\geq\Delta} \frac{2\lambda(\sigma_{q(m)})}{\lambda(I_m)}.$$

Since

$$\frac{\lambda(\sigma_{q(m)})}{\lambda(I_m)} \leq \frac{10}{m^2},$$

it follows that

$$\sum_{m\geq\Delta}\frac{2\lambda(\sigma_{q(m)})}{\lambda(I_m)}\leq 20\sum_{m\geq\Delta}\frac{1}{m^2},$$

which proves that S is uniformly bounded .

Now, if $n\geq z_\gamma+p_\gamma$ we are left with a last piece of free period to study:

$$F_{\gamma+1}=\sum_{j=z_\gamma+p_\gamma}^{n}\left|\frac{x_j-y_j}{y_j}\right|$$

We consider two cases. On the first one we suppose that $|f_a^n(\omega)|\leq e^{-2\Delta}$. Proceeding as before we have for $j=z_\gamma+p_\gamma,\ldots,n-1$,

$$\begin{aligned}\lambda(\sigma_n)&\geq|f_a^{n-j}(x_j)-f_a^{n-j}(y_j)|\\&=\left|(f^{n-j})'(\zeta)\right|\cdot|x_j-y_j|,\text{for some }\zeta\text{ between }x_j\text{ and }y_j\\&\geq e^{-(\Delta+1)}e^{c(n-j)}|x_j-y_j|,\ \text{ by Lemma 3.1 part 1.}\end{aligned}$$

So,

$$\begin{aligned}F_{\gamma+1}&\leq\sum_{j=z_\gamma+p_\gamma}^{n}\frac{e^{\Delta+1}e^{-c(n-j)}\lambda(\sigma_n)}{\delta}\\&\leq\sum_{j=z_\gamma+p_\gamma}^{n}e^{2\Delta+1}e^{-c(n-j)}e^{-2\Delta}\\&\leq e\sum_{j=1}^{\infty}e^{-cj}\leq a_5,\end{aligned}$$

where a_5 is constant.

On the second case we assume that $|f_a^n(\omega)|>e^{-2\Delta}$. Let q_1 be the first integer such that $q_1\geq z_\gamma+p_\gamma$, $|f_a^{q_1}(\omega)|>e^{-2\Delta}$, and for $i=z_\gamma+p_\gamma,\ldots,q_1-1$,$|f_a^i(\omega)|\leq e^{-2\Delta}$. From the previous argumentation we have that

$$\left|\frac{(f_a^{q_1})'(x)}{(f_a^{q_1})'(y)}\right|\leq C.$$

At this point we consider the interval $[q_1,q_2-1]$ (eventually empty) whose times i verify $y_i\notin U_1$. Then, using lemma 3.1 part 3 (here we use for the first time the hypothesis $f_a^n(\omega)\subset U_1$),

$$\begin{aligned}\sum_{i=q_1}^{q_2-1}\frac{|x_i-y_i|}{|y_i|}&\leq e\sum_{i=q_1}^{q_2-1}|x_i-y_i|\leq 3\sum_{i=q_1}^{q_2-1}\tfrac{5}{4}e^{-c(n-1)}|f_a^n(\omega)|\\&\leq\tfrac{15}{2}\sum_{i=1}^{\infty}e^{-ci}\leq a_6,\end{aligned}$$

where a_6 is a constant.

If $q_2 = n$ the lemma is proved. Otherwise writing:

$$\left|\frac{(f_a^n)'(x)}{(f_a^n)'(y)}\right| = \left|\frac{(f_a^{n-q_2})'(x_{q_2})}{(f_a^{n-q_2})'(y_{q_2})}\right| \left|\frac{(f_a^{q_2})'(x)}{(f_a^{q_2})'(y)}\right|,$$

we observe that in order to obtain the result we need only to bound the first factor. We do this considering again two cases:

1. $x_{q_2} \geq \frac{1}{2}$. Then since $|y_{q_2}| \leq e^{-1}$ (by definition of q_2), we have $|x_{q_2} - y_{q_2}| \geq \frac{1}{10}$. Therefore by lemma 3.1 part 3

$$\tfrac{4}{5}e^{c(n-q_2)}\tfrac{1}{10} \leq |f_a^n(\omega)| \leq 1,$$

which implies that $n - q_2 \leq \frac{3}{2}\log\left(\frac{25}{2}\right)$ (remember that by hypothesis $c \geq \frac{2}{3}$).

Attending to the facts: $|(f_a^{n-q_2})'(x_{q_2})| \leq 4^{n-q_2}$ and $|(f_a^{n-q_2})'(y_{q_2})| \geq \frac{4}{5}e^{c(n-q_2)}$, we have

$$\left|\frac{(f_a^{n-q_2})'(x_{q_2})}{(f_a^{n-q_2})'(y_{q_2})}\right| \leq a_7,$$

for some constant a_7.

2. $x_{q_2} < \frac{1}{2}$. We can write (see Lemma 2.2 of [Al92] or Lemma 3.3 of [Mo92] for details)

$$\left|\frac{(f_a^{n-q_2})'(x_{q_2})}{(f_a^{n-q_2})'(y_{q_2})}\right| = L\left|\frac{(g_a^{n-q_2})'(h^{-1}(x_{q_2}))}{(f_a^{n-q_2})'(h^{-1}(y_{q_2}))}\right|,$$

where

$$L = \sqrt{\frac{1-(f_a^{n-q_2}(x_{q_2}))^2}{1-x_{q_2}^2}}\sqrt{\frac{1-y_{q_2}^2}{1-(f_a^{n-q_2}(y_{q_2}))^2}} \leq \sqrt{\frac{1}{1-\frac{1}{4}}}\sqrt{\frac{1}{1-e^{-2}}} \leq \frac{3}{4},$$

$h : [-1,1] \to [-1,1]$ is the homeomorphism that conjugates $f_2(x)$ to the tent map $1-2|x|$ and $g_a = h^{-1} \circ f_a \circ h$.

For the second factor, we have (see Lemma 3.1 of [Mo92] for details)

$$\left|\frac{(g_a^{n-q_2})'(h^{-1}(x_{q_2}))}{(f_a^{n-q_2})'(h^{-1}(y_{q_2}))}\right| \leq \left(\frac{2+\frac{3\pi}{\delta^3}(2-a)}{2-\frac{3\pi}{\delta^3}(2-a)}\right)^{n-q_2}.$$

Note that $|f_a^{q_1}(\omega)| > e^{-2\Delta}$ and $\frac{4}{5}e^{c(n-q_1)}|f_a^{q_1}(\omega)| \leq |f_a^n(\omega)| \leq 1$, from which we conclude that $n - q_2 \leq n - q_1 \leq 4\Delta$. So if a is sufficiently close to 2 in order to have

$$\left(\frac{2+\frac{3\pi}{\delta^3}(2-a)}{2-\frac{3\pi}{\delta^3}(2-a)}\right)^{4\Delta} \leq 2, \tag{4.3}$$

then

$$\left|\frac{(f_a^{n-q_2})'(x_{q_2})}{(f_a^{n-q_2})'(y_{q_2})}\right| \leq \frac{8}{3}.$$

□

5. Return depths and time between consecutive returns

On this section we justify the preponderance of the depths of essential returns over the depths of bound and inessential returns, stated on basic idea (I). We also get an upper bound for the elapsed time between two consecutive essential returns.

As we have already mentioned, there are three types of returns: essential, bounded and inessential, which we denote by t, u and v respectively. Remember, that up to n, the essential return that occurs at time t_i has depth η_i, for $i = 1, \ldots, s_n$; each t_i might be followed by bounded returns $u_{i,j}$, $j = 1, \ldots, u$ and these can be followed by inessential returns $v_{i,j}$, $j = 1, \ldots, v$.

The following lemma states that the depth of an inessential return is not greater than the depth of the essential return that precedes it.

Lemma 5.1. *Suppose that t_i is an essential return for $\omega \in \mathcal{P}_{t_i}$, with $I_{\eta_i,k_i} \subset f_a^{t_i}(\omega) \subset I^+_{\eta_i,k_i}$. Then the depth of each inessential return occurring on $v_{i,j}$, $j = 1, \ldots, v$ is not grater than η_i.*

Proof. By lemma 4.1 part 1 we have

$$\lambda\left\{f_a^{v_{i,j}}(\omega)\right\} \geq 2^j \lambda\left\{f_a^{t_i}(\omega)\right\} \geq 2^j \lambda\left(I_{\eta_i,k_i}\right)$$

Thus,

$$\lambda\left\{f_a^{v_{i,j}}(\omega)\right\} \geq \lambda\left\{I_{\eta_i,k_i}\right\} = \frac{e^{-\eta_i}\left(1-e^{-1}\right)}{\eta_i^2}.$$

But, since $v_{i,j}$ is an inessential return time we must have $f_a^{v_{i,j}}(\omega) \subset I_{m,k}$ for some $m \geq \Delta$, then out of necessity: $m \leq \eta_i$, because $f_a^{v_{i,j}}(\omega)$ is too large to fit on some $I_{m,k}$ with $m > \eta_i$. □

On the next lemma, we prove a similar result for bounded returns.

Lemma 5.2. *Let t be a return time (either essential or inessential) for $\omega \in \mathcal{P}_t$, with $f_a^t(\omega) \subset I^+_{\eta,k}$. Let $p = p(\eta)$ be the bound period length associated to this return. Then, for all $x \in \omega$, if the orbit of x returns to U_Δ between t and $t+p$, then the depth of this bound return will not be grater than η, if Δ is sufficiently large.*

Proof. Consider a point $x \in \omega$. We will show that if Δ is large enough then $|f_a^{t+j}(x)| \geq e^{-\eta}$, $\forall j \in \{1, \ldots, p-1\}$.

$$\left|f_a^j(1)\right| - \left|f_a^{t+j}(x)\right| \leq \left|f_a^{t+j}(x) - f_a^j(1)\right| \leq e^{-\beta j}$$

which implies that

$$\begin{aligned}
\left|f_a^{t+j}(x)\right| &\geq \left|f_a^j(1)\right| - e^{-\beta j} \overset{\text{(BA)}}{\geq} e^{-\alpha j} - e^{-\beta j} \geq e^{-\alpha j}\left(1-e^{(\alpha-\beta)j}\right) \\
&\geq e^{-\alpha j}\left(1-e^{(\alpha-\beta)}\right), \text{ since } \alpha-\beta<0 \\
&\geq e^{-\alpha p}\left(1-e^{(\alpha-\beta)}\right), \text{ since } j<p \\
&\geq e^{-3\alpha\eta}\left(1-e^{(\alpha-\beta)}\right), \text{ since } p\leq 3\eta \text{ by lemma 3.2} \\
&\geq e^{-4\alpha\eta}, \text{ if we choose a large } \Delta \text{ so that } 1-e^{\alpha-\beta}\geq e^{-\alpha\eta} \\
&\geq e^{-\eta}, \text{ since } \alpha<\frac{1}{4}
\end{aligned}$$

□

The next lemma gives an upper bound for the time we have to wait between two essential return situations.

Lemma 5.3. *Suppose t_i is an essential return for $\omega \in \mathcal{P}_{t_i}$, with $I_{\eta_i,k_i} \subset f_a^{t_i}(\omega) \subset I^+_{\eta_i,k_i}$. Then the next essential return situation t_{i+1} satisfies:*

$$t_{i+1} - t_i < 5\left|\eta_i\right|.$$

Proof. Let $v_{i,1} < \ldots < v_{i,v}$ denote the inessential returns between t_i and t_{i+1}, with host intervals $I_{\eta_{i,1},k_{i,1}}, \ldots, I_{\eta_{i,v},k_{i,v}}$, respectively. We also consider $v_{i,0} = t_i$; $v_{i,v+1} = t_{i+1}$; for $j = 0, \ldots, v+1$, $\sigma_j = f_a^{v_{i,j}}(\omega)$; and for $j = 0, \ldots, v$, $q_j = v_{i,j+1} - (v_{i,j} + p_j)$, where p_j is the length of the bound period associated to the return $v_{i,j}$.

We consider two different cases: $v = 0$ and $v > 0$.

(1) $v = 0$

In this situation $t_{i+1} - t_i = p_0 + q_0$. Applying lemma 4.1 part 2b we get that

$$|\sigma_1| \geq e^{-5\beta|\eta_i|} e^{c_0 q_0 - (\Delta+1)}.$$

Attending to the fact that $|\sigma_1| \leq 2$ we have

$$\begin{aligned}
&c_0 q_0 \leq 1 + 5\beta|\eta_i| + \Delta + 1 \\
&q_0 \leq 8\beta|\eta_i| + \frac{3}{2}\Delta + 3, \text{ since } c_0 \geq \frac{2}{3} \\
&q_0 \leq 9\beta|\eta_i| + \frac{3}{2}\Delta, \text{for } \Delta \text{ large enough so that } \beta|\eta_i| > 3.
\end{aligned}$$

Therefore,

$$\begin{aligned} t_{i+1} - t_i &= p_0 + q_0 \\ &\le 3|\eta_i| + 9\beta|\eta_i| + \frac{3}{2}\Delta \\ &\le 4|\eta_i| + \Delta, \text{since } 9\beta < \frac{1}{2} \\ &\le 5|\eta_i|. \end{aligned}$$

(2) $v > 0$

In this case, $t_{i+1} - t_i = \sum_{j=0}^{v}(p_j + q_j)$. We separate this sum into three parts and control each separately:

$$t_{i+1} - t_i = p_0 + \left(\sum_{j=1}^{v-1} p_j + \sum_{j=0}^{v-1} q_j \right) + (p_v + q_v)$$

(i) For p_0 we have by lemma 3.2 that $p_0 \le 3|\eta_i|$.
(ii) By lemma 4.1 we get

$$|\sigma_1| \ge e^{c_0 q_0} e^{-5\beta|\eta_i|} \text{ and } \frac{|\sigma_{j+1}|}{|\sigma_j|} \ge e^{c_0 q_j} e^{(1-5\beta)|\eta_{i,j}|},$$

for $j = 1, \dots, v-1$. Now, we observe that $p_j \le 3|\eta_{i,j}| \le 4(1-5\beta)|\eta_{i,j}|$ and $q_j \le 4c_0 q_j$, for all $j = 0, \dots, v$. This means that controlling the second parcel resumes to bound

$$\sum_{j=1}^{v-1}(1-5\beta)|\eta_{i,j}| + \sum_{j=0}^{v-1} c_0 q_j. \tag{5.1}$$

We achieve our goal by noting that (5.1) corresponds to the growth rate of the size of the σ_j's, which cannot be very large since every σ_j, $j = 1, \dots, v$ is contained in some $I_{m,k} \subset U_\Delta$. Writing

$$|\sigma_v| = |\sigma_1| \prod_{j=1}^{v-1} \frac{|\sigma_{j+1}|}{|\sigma_j|},$$

and taking into account that $\sigma_v \in I_{\eta_{i,v}, k_{i,v}}$, with $|\eta_{i,v}| \ge \Delta$ and thus $|\sigma_v| \le e^{-(\Delta+1)}$, it follows that

$$\exp\left\{ -5\beta|\eta_i| + \sum_{j=0}^{v-1} c_0 q_j + \sum_{j=1}^{v-1}(1-5\beta)|\eta_{i,j}| \right\} \le \exp\{-(\Delta+1)\}$$

and consequently

$$\sum_{j=1}^{v-1}(1-5\beta)|\eta_{i,j}| + \sum_{j=0}^{v-1} c_0 q_j \le 5\beta|\eta_i| - (\Delta+1)$$

(iii) For the last term $p_v + q_v$ we proceed in a very similar manner to what we did in the case $v = 0$. By lemma 4.1we have

$$\frac{|\sigma_{v+1}|}{|\sigma_v|} \geq e^{c_0 q_v - (\Delta+1)} e^{(1-5\beta)|\eta_{i,v}|}.$$

From part 1 of the referred lemma 4.1 we have $|\sigma_v| \geq 2^{v-1}|\sigma_1| \geq |\sigma_1|$, from which we get

$$2 \geq |\sigma_{v+1}| \geq |\sigma_1| \frac{|\sigma_{v+1}|}{|\sigma_v|}$$

and consequently

$$\exp\left\{-5\beta|\eta_i| + c_0 q_v - (\Delta+1) + (1-5\beta)|\eta_{i,v}|\right\} \leq e^{\log 2}$$

implying

$$c_0 q_v + (1-5\beta)|\eta_{i,v}| \leq \Delta + 2 + 5\beta|\eta_i|.$$

Joining the three parts we get

$$\begin{aligned}
t_{i+1} - t_i &= p_0 + \left(\sum_{j=1}^{v-1} p_j + \sum_{j=0}^{v-1} q_j\right) + (p_v + q_v) \\
&\leq p_0 + 4\left\{\sum_{j=1}^{v-1}(1-5\beta)|\eta_{i,j}| + \sum_{j=0}^{v-1} c_0 q_j + c_0 q_v + (1-5\beta)|\eta_{i,v}|\right\} \\
&\leq 3|\eta_i| + 4\left\{5\beta|\eta_i| - (\Delta+1) + (\Delta+1) + 1 + 5\beta|\eta_i|\right\} \\
&\leq 3|\eta_i| + 40\beta|\eta_i| + 4 \\
&\leq 4|\eta_i|.
\end{aligned}$$

□

6. Probability of an essential return reaching a certain depth

Now, that we know that only the essential returns matter, we prove that the chances of occurring very deep essential returns, are very small. In fact, the probability of an essential return hitting the depth of ρ will be shown to be less than $e^{-\tau\rho}$, with $\tau > 0$.

We must make our statements more precise and we begin by defining a probability space. We define the probability measure λ^* on I by renormalizing the Lebesgue measure so that $\lambda^*(I) = 1$. We may now speak of expectations $E(\cdot)$, events and their probability of occurrence.

For each $x \in I$, let $s_n(x)$ denote the number of essential returns of the orbit of x between 1 and n, let $1 \leq t_1 \leq \ldots \leq t_{s_n} \leq n$ be the instants of occurrence of the essential returns and let $\eta_1, \ldots, \eta_{s_n}$ be the corresponding depths. Given an integer $s \leq n$ and s integers $\rho_1, \ldots, \rho_s$, each larger than Δ, we define the event:

$$A^s_{\rho_1,\ldots,\rho_s}(n) = \left\{x \in I \;:\; s_n(x) = s \;\text{ and }\; \left|f_a^{t_i}(x)\right| \in I_{\rho_i}\,,\ \forall i \in \{1,\ldots,s\}\right\}.$$

Proposition 6.1. *If Δ is large enough, then*

$$\lambda^*\left(A^s_{\rho_1,\dots,\rho_s}(n)\right) \le e^{-\frac{1-5\beta}{2}\sum_{i=1}^s \rho_i}$$

Proof. Fix $n \in \mathbb{N}$ and take $\omega_0 \in \mathcal{P}_0$. We denote by $\omega_i = \omega_{(\eta_1,k_1)\dots(\eta_i,k_i)}$ the subset of ω_0 belonging to $\mathcal{P}_{t_i}$ that satisfies

$$f_a^{t_j}(\omega_i) \subset I^+_{\eta_j,k_j}\,,\ \forall j \in \{1,\dots,i-1\} \text{ and } I_{\eta_i,k_i} \subset f_a^{t_i}(\omega_i) \subset I^+_{\eta_i,k_i}$$

Our next step is to estimate $\dfrac{|\omega_s|}{|\omega_0|}$.

$$\begin{aligned}
\frac{|\omega_s|}{|\omega_0|} &= \prod_{i=1}^s \frac{|\omega_i|}{|\omega_{i-1}|} \le \prod_{i=1}^s \frac{|\omega_i|}{|\widehat{\omega}_{i-1}|}, \quad \text{where } \widehat{\omega}_{i-1} = \omega_{i-1} \cap f_a^{-t_i}(U_1) \\
&\le \prod_{i=1}^s C \frac{|f_a^{t_i}(\omega_i)|}{\left|f_a^{t_i}(\widehat{\omega}_{i-1})\right|}, \text{ by the mean value theorem and lemma 4.2} \\
&\le \prod_{i=1}^s C \frac{\frac{5}{\eta_i^2} e^{-|\eta_i|}}{e^{-5\beta|\eta_{i-1}|}}, \text{ by lemma 4.1 part 3b and definition of } \omega_i \\
&\le \left(\prod_{i=1}^s \frac{5C}{\eta_i^2}\right) e^{5\beta|\eta_0|} e^{-(1-5\beta)\sum_{i=1}^s |\eta_i|}
\end{aligned}$$

Observe that if $\widehat{\omega}_{i-1} \ne \omega_{i-1}$ then, because we are assuming that $\omega_i \ne \emptyset$, $\lambda\left(f_a^{t_i}(\widehat{\omega}_{i-1})\right) \ge e^{-1} - e^{-\Delta} \ge e^{-5\beta|\eta_{i-1}|}$, for large Δ. When $\omega_0 = I_{m,k}$ for some $|m| \ge \Delta$ and $1 \le k \le m^2$, we consider $\eta_0 = m$. On the other hand, if $\omega_0 = [-1,-\delta)$ or $\omega_0 = (\delta, 1]$, then $t_1 = 1$ and $|f_a^{t_1}(\omega_0)| = a(1-\delta^2) \ge 1$, for large Δ, so we can take $\eta_0 = 0$ on these cases.

Now, the number of components in $\mathcal{P}_{t_s}$ of the form $\omega_{(\eta_1,k_1)\dots(\eta_s,k_s)}$ for which $|\eta_1| = \rho_1, \dots, |\eta_s| = \rho_s$ is at most $2^s \rho_1^2 \cdots \rho_s^2$.

Having these in mind, we are able to write:

$$\begin{aligned}
\lambda^*\left(A^s_{\rho_1,\dots,\rho_s}(n)\right) &\le \left(\prod_{i=1}^s 2\rho_i^2\right)\left(\prod_{i=1}^s \frac{5C}{\rho_i^2}\right) e^{-(1-5\beta)\sum_{i=1}^s \rho_i} \sum_{\omega_o \in \mathcal{P}_0} e^{5\beta|\eta_0|}|\omega_0| \\
&\le (10C)^s e^{-(1-5\beta)\sum_{i=1}^s \rho_i} \left(2(1-\delta) + \sum_{|\eta_0|\ge\Delta} e^{5\beta\eta_0} e^{-|\eta_0|}\right) \\
&\le 3(10C)^s e^{-(1-5\beta)\sum_{i=1}^s \rho_i}, \quad \text{for } \Delta \text{ large enough} \\
&\le e^{-\frac{1-5\beta}{2}\sum_{i=1}^s \rho_i},
\end{aligned}$$

where the last inequality results from the fact that $s\Delta \le \sum_{i=1}^s \rho_i$ and the freedom to choose a sufficiently large Δ. $\square$

Fix $n \in \mathbb{N}$, an integer $s \leq n$ and another integer $j \leq s$. Given an integer $\rho \geq \Delta$, consider also the event

$$A_\rho^{j,s}(n) = \left\{ x \in I \ : \ s_n(x) = s \ \text{ and } \ \left| f_a^{t_j}(x) \right| \in I_\rho \right\}$$

Corollary 6.2. *If Δ is large enough, then*

$$\lambda^* \left(A_\rho^{j,s}(n) \right) \leq e^{-\frac{1-5\beta}{2}\rho}$$

Proof. Since $A_\rho^{j,s}(n) \subset \bigcup_{\substack{\rho_i \geq \Delta \\ i \neq j}} A^s_{\rho_1,\ldots,\rho_{j-1},\rho,\rho_{j+1},\ldots,\rho_s}(n)$, then by proposition 6.1 we have

$$\lambda^* \left(A_\rho^{j,s}(n) \right) \leq e^{-\frac{1-5\beta}{2}\rho} \left(\sum_{\eta=\Delta}^{\infty} e^{-\frac{1-5\beta}{2}\eta} \right)^{s-1} \leq e^{-\frac{1-5\beta}{2}\rho},$$

as long as Δ is sufficiently large so that $\sum_{\eta=\Delta}^{\infty} e^{-\frac{1-5\beta}{2}\eta} \leq 1$. □

Remark 6.1. Observe that the bound for the probability of the event $A_\rho^{j,s}(n)$ does not depend on the $j \leq s$ chosen.

7. Conclusion of the proof of theorem A

According to section 3 to finish the proof we only need to show that

$$\lambda \left(E_1(n) \right) \leq e^{-\tau_1 n}, \quad \forall n \geq N_1^*$$

for some constant $\tau_1(\alpha, \beta) > 0$ and an integer $N_1^* = N_1^*(\Delta, \tau_1)$.

In order to accomplish this we define the following events:

$$A_\rho^s(n) = \left\{ x \in I : \ s_n(x) = s \text{ and } \exists j \in \{1, \ldots, s\} : \ |f_a^{t_j}(x)| \in I_\rho \right\},$$

for fixed $n \in \mathbb{N}$, $s \leq n$ and $\rho \geq \Delta$;

$$A_\rho(n) = \left\{ x \in I : \exists t \leq n : t \text{ is essential return time and } |f_a^t(x)| \in I_\rho \right\},$$

for fixed n and $\rho \geq \Delta$.

Now, because $A_\rho^s(n) \subset \bigcup_{j=1}^s A_\rho^{j,s}(n)$, by corollary 6.2, we have

$$\lambda^* \left(A_\rho^s(n) \right) \leq \sum_{j=1}^{s} \lambda^* \left(A_\rho^{j,s}(n) \right) \leq s e^{-\frac{1-5\beta}{2}\rho}. \tag{7.1}$$

Observing that $A_\rho(n) \subset \bigcup_{s=1}^n A_\rho^s(n)$, then by (7.1) we get

$$\lambda^* \left(A_\rho(n) \right) \leq \sum_{s=1}^{n} \lambda^* \left(A_\rho^s(n) \right) \leq \sum_{s=1}^{n} s e^{-\frac{1-5\beta}{2}\rho} \leq \tfrac{n(n+1)}{2} e^{-\frac{1-5\beta}{2}\rho}. \tag{7.2}$$

Since we know, by lemmas 5.1 and 5.2, that the depths of inessential and bound returns are not greater than the depth of the essential return preceding them we have, for all $n \geq N_1'$, where N_1' is such that $\alpha N_1' \geq \Delta$,

$$E_1(n) = \left\{ x \in I : \ \exists i \in \{1, \ldots, n\}, \ |f_a^i(x)| < e^{-\alpha n} \right\} \subset \bigcup_{\rho=\alpha n}^{\infty} A_\rho(n),$$

and consequently, for $\tau_1 = \frac{1-5\beta}{4}\alpha$

$$\begin{aligned}\lambda^*(E_1(n)) &\leq \tfrac{n(n+1)}{2} \sum_{\rho=\alpha n}^{\infty} e^{-\frac{1-5\beta}{2}\rho} \\ &\leq \text{const} \cdot \tfrac{n(n+1)}{2} e^{-2\tau_1 n} \\ &\leq e^{-\tau_1 n},\end{aligned}$$

for $n \geq N_1^*$, where N_1^* is such that $N_1^* \geq N_1'$ and for all $n \geq N_1^*$ we have

$$\text{const}\, \frac{n(n+1)}{2} e^{-\tau_1 n} \leq 1. \tag{7.3}$$

8. Conclusion of the proof of theorem B

As referred on section 3, we are left with the burden of having to show that for all $n \in \mathbb{N}$,

$$\lambda^*\{E_2(n)\} \leq \lambda^* \left\{ x : B_n(x) > \frac{\epsilon n}{5} \right\} \leq e^{-\tau_2 \sqrt{n}},$$

in order to complete the proof.

We achieve this goal, by means of a large deviation argument. Essentially we show that the moment generating function of $\sqrt{B_n}$ is bounded above by 1; then we use the Tchebychev inequality to obtain the desired result.

Lemma 8.1. *For* $0 < t < \frac{1-5\beta}{6}$ *we have that* $E\left(e^{t\sqrt{B_n}}\right) \leq 1$.

Proof.

$$\begin{aligned} E\left(e^{t\sqrt{B_n}}\right) = E\left(e^{t\sqrt{\sum_{i=1}^s \eta_i^2}}\right) &= \sum_{s,(\rho_1,\ldots,\rho_s)} e^{t\sqrt{\sum_{i=1}^s \rho_i^2}} \lambda^*\left(A^s_{\rho_1,\ldots,\rho_s}(n)\right) \\ &\leq \sum_{s,(\rho_1,\ldots,\rho_s)} e^{t\sqrt{\sum_{i=1}^s \rho_i^2}} e^{-3t\sum_{i=1}^s \rho_i}, \text{ by proposition 6.1} \\ &\leq \sum_{s,(\rho_1,\ldots,\rho_s)} e^{t\sum_{i=1}^s \rho_i} e^{-3t\sum_{i=1}^s \rho_i} \\ &\leq \sum_{s,R} \zeta(s,R) e^{-2tR}, \end{aligned}$$

where $\zeta(s,R)$ is the number of integer solutions of the equation $x_1 + \ldots + x_s = R$ satisfying $x_i \geq \Delta$ for all i.

We have

$$\zeta(s,R) \leq \#\{\text{solutions of } x_1 + \ldots + x_s = R, x_i \in \mathbb{N}_0\} = \binom{R+s-1}{s-1}.$$

By the Stirling formula, we have

$$\sqrt{2\pi m} m^m e^{-m} \leq m! \leq \sqrt{2\pi m} m^m e^{-m} \left(1 + \frac{1}{4m}\right),$$

which implies that

$$\binom{R+s-1}{s-1} \leq \text{const}\frac{(R+s-1)^{R+s-1}}{R^R(s-1)^{s-1}}.$$

So, if we choose Δ large enough we have

$$\zeta(s,R) \leq \left(\text{const}^{\frac{s}{R}}\left(1+\tfrac{s-1}{R}\right)\left(1+\tfrac{R}{s-1}\right)^{\frac{s-1}{R}}\right)^R \leq e^{tR}.$$

The last inequality derives from the fact that $s\Delta \leq R$, and so each factor on the middle expression can be made arbitrarily close to 1 by taking Δ sufficiently large.

Recovering where we stopped,

$$\begin{aligned} E\left(e^{t\sqrt{B_n}}\right) &\leq \sum_{s,R} e^{tR}e^{-2tR} \\ &\leq \sum_R \frac{R}{\Delta}e^{-tR}, \quad \text{because } s\Delta \leq R \\ &\leq 1, \quad \text{for } \Delta \text{ sufficiently large.} \end{aligned}$$

□

Now, observe that, for all $n \in N$

$$\lambda^*\{E_2(n)\} \leq \lambda^*\left\{x : B_n > \frac{\epsilon n}{5}\right\} = \lambda^*\left\{x : \sqrt{B_n(x)} > \sqrt{\frac{\epsilon n}{5}}\right\}.$$

so we only need to find an upper bound for the last probability:

$$\begin{aligned} \lambda^*\left(\sqrt{B_n} > \sqrt{\frac{\epsilon n}{5}}\right) &\leq e^{-t\sqrt{\frac{\epsilon n}{5}}}E\left(e^{t\sqrt{B_n}}\right), \text{ by Tchebychev's inequality} \\ &\leq e^{-t\sqrt{\frac{\epsilon n}{5}}}, \text{ by lemma 8.1.} \end{aligned}$$

Thus, $\lambda^*\{E_2(n)\} \leq e^{-\frac{t\sqrt{\epsilon}}{2}\sqrt{n}} = e^{-\tau_2\sqrt{n}}$, where $\tau_2 = \tau_2(\beta,\epsilon) = \frac{t\sqrt{\epsilon}}{2}$.

Remark 8.1. The problem of obtaining only sub-exponential volume decay of $E_2(n)$ is due to the fact that we can only bound the moment generating function of $\sqrt{B_n}$ and not the moment generating function of B_n. This is connected to our inability of providing a better bound for the time spent by the orbit of a point $x \in I$ inside U_Δ, between two consecutive essential returns. Any attempt on improving the result of lemma 5.3, resulted again on a bound of order η ($\gamma\eta$ for a positive small constant γ), where $\eta > 0$ stands for the depth of the first essential return considered. We note that, for example, the length of the bound period following the first essential return is also of order η, so it seems hopeless to obtain a significantly tighter bound for T_n than $\frac{5}{n}\sum_{i=1}^s \eta_i^2$ that we used on the proof.

Remark 8.2. Since the growth properties of the space and parameter derivatives along orbits are equivalent (see lemma 4 of [BC85] or lemma 3.4 of [Mo92]), it is possible to build a similar partition on the parameters as Benedicks and Carleson ([BC85, BC91]) did when they built Ω_∞. Then, using the same kind of arguments of sections 6 and 8 it is not difficult to bound, on a full Lebesgue measure subset of Ω_∞, the value of $\frac{5}{n}B_n(\xi_0) = \frac{5}{n}\sum_{i=1}^s \eta_i^2$, where η_i stands for the depth of the i-th essential return of the orbit of ξ_0. In fact, when Benedicks and Carleson ([BC85]) computed the distribution of the returns they managed to control $\frac{1}{s}\sum_{i=1}^{s}\eta_i$, for Lebesgue almost all parameter $a \in \Omega_\infty$. If one remembers that they accomplished this with sub-exponential estimates $e^{-\tau\sqrt{\eta}}$ for the probability of occurrence of an essential return hitting the depth η, it is not hard to convince ourselves that it is also possible to control $\frac{5}{n}B_n(\xi_0)$ having the exponential estimate $e^{-\tau\eta}$ for the depth probability and thus obtain the validity of condition (1.2) for the critical point ξ_0, on a full Lebesgue measure subset of Ω_∞.

9. Uniformness on the choice of the constants

As referred on remark 1.1 all constants involved must not depend on the parameter $a \in \Omega_\infty$. Because there are many constants in question and because they depend on each other in an intricate manner we dedicate this section to clarify their interdependencies.

We begin by considering the constants appearing on (EG) and (BA) that determine the space Ω_∞ of parameters. So we fix $c \in [\frac{2}{3}, \log 2]$ and $0 < \alpha < 10^{-3}$.

Then we consider $\beta > 0$ of definition 3.1 concerning the bound period, to be a small constant such that $\alpha < \beta < 10^{-2}$. A good choice for β would be considering that $\beta = 2\alpha$.

Afterward we fix a sufficiently large Δ such that we have validity on all estimates throughout the text. Most of the times the choice of a large Δ depends on the values of α and β. Note that at anytime does the choice of a large Δ depends on the parameter value considered.

After fixing Δ we choose $\frac{2}{3} \le c_0 \le \log 2$ (take, for example, $c_0 = c$), and compute a_0 given by lemma 3.1 and such that (4.3) holds. Note that this might bring some contraction on the set of parameters since we will only have to consider parameter values on $\Omega_\infty \cap [a_0, 2]$ which still is a positive Lebesgue measure set. If necessary we redefine Ω_∞ to be $\Omega_\infty \cap [a_0, 2]$.

Finally, we fix any small $\epsilon > 0$ referring to (1.2) and explicit the dependence of the rest of the appearing constants on the table below

Constant	Dependencies	Main References
d	α, β	(1.1) and (3.2)
γ	Δ	section 2
τ_1	α, β	theorem A and section 7
N_1^*	Δ, τ_1	(7.3)
N_1	Δ, α, B_1, d, N_1^*	section 3
C_1	N_1, τ_1	theorem A and (3.6)
τ_2	β, ϵ	theorem B and section 8
C_2	τ_2	theorem B and section 3
B_1	α, β	lemma 3.2
C	α, β	lemma 4.2

Table 1. Constants interdependency

In conclusion, all the constants involved depend ultimately on α, β, Δ and ϵ, which were chosen uniformly on Ω_∞, thus we may say $(f_a)_{a\in\Omega_\infty}$ is a uniform family in the sense referred on [Al03].

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