EVERY COMPACT MANIFOLD CARRIES A COMPLETELY HYPERBOLIC DIFFEOMORPHISM

DMITRY DOLGOPYAT AND YAKOV PESIN
The Pennsylvania State University

Abstract. We show that a smooth compact Riemannian manifold of dimension $\geq 2$ admits a Bernoulli diffeomorphism with nonzero Lyapunov exponents.

Introduction

In this paper we prove the following theorem that provides an affirmative solution of the problem posed in [BFK].

Main Theorem. Given a compact smooth Riemannian manifold $\mathcal{K} \neq S^1$ there exists a $C^\infty$ diffeomorphism $f$ of $\mathcal{K}$ such that

1. $f$ preserves the Riemannian volume $m$ on $\mathcal{K}$;
2. $f$ has nonzero Lyapunov exponents at $m$-almost every point $x \in \mathcal{K}$;
3. $f$ is a Bernoulli diffeomorphism.

For surface diffeomorphisms this theorem was proved by A. Katok in [K]. In [B], for any compact smooth Riemannian manifold $\mathcal{K}$ of dimension $\geq 5$, M. Brin constructed a $C^\infty$ Bernoulli diffeomorphism which preserves the Riemannian volume and has all but one Lyapunov exponents nonzero. Thus, combining the results of [B, BFK, K] one obtains that any manifold $\mathcal{K}$ admits a diffeomorphism with $\ell$ zero exponents, where

$$\ell = \begin{cases} 
0, & \text{if } \dim \mathcal{K} = 2 \\
2, & \text{if } \dim \mathcal{K} = 4 \\
1, & \text{otherwise}
\end{cases}$$

In this paper we show how to perturb the diffeomorphism to remove zero exponents. Let us review some main ingredients in the construction of hyperbolic Bernoulli diffeomorphisms.

Key words and phrases. Lyapunov exponents, Bernoulli diffeomorphism, accessibility.

D.D was partially supported by the Sloan Foundation and by the National Science Foundation grant #DMS-0072623. Ya.P. was partially supported by the National Science Foundation grant #DMS-9704564 and by the NATO grant CRG 970161.
(1) Let \( f \) be a diffeomorphism of \( K \) preserving a smooth volume \( m \) and let \( T\mathcal{K} = E \oplus F \) be the splitting of \( T\mathcal{K} \) into two invariant subbundles. We say that \( F \) dominates \( E \) (and write \( E < F \)) if there exists \( \theta < 1 \) such that

\[
\max_{v \in E, \|v\|=1} \|df(v)\| \leq \theta \min_{v \in F, \|v\|=1} \|df(v)\|.
\]

If \( f \) admits a dominated splitting then so does any diffeomorphism which is sufficiently close to \( f \). Shub and Wilkinson [SW] has shown that if \( T\mathcal{K} = E_1 \oplus E_2 \oplus E_3 \) where \( E_1 < E_2 < E_3 \) then the function

\[
f \rightarrow \int \log \det (df|E_2)(x) \, dm(x)
\]

is not locally constant (see also [D]).

(2) If for any sufficiently small perturbation of \( f \) the subspace \( E_2 \) does not admit further splitting then using results of Mané [M1] (see also [M2]) and Bochi [Bo] one can approximate \( f \) by a diffeomorphism \( g \) such that all Lyapunov exponents of \( g \) along \( E_2 \) are close to each other. We will use this observation in the case \( \dim \mathcal{K} = 4 \).

(3) The results in (1) and (2) can be used for constructing non-uniformly hyperbolic systems on manifolds carrying diffeomorphisms with dominated decomposition. However, not every manifold has this property. On the other hand, results in [B, BFK] allow one to construct on any manifold a diffeomorphism which is partially hyperbolic away from a singularity set. In this paper we extend results in (1) and (2) above to such diffeomorphisms with singular splitting.

(4) The above results allow us to construct systems having non-zero exponents on a set of positive measure. We then establish local ergodicity using the approach of [P] (see also [BP, BV] for detailed exposition and extensions of this approach).

(5) Finally, we use some ideas from [BrP] concerning transitivity of foliations to pass from local to global ergodicity.

The structure of the paper is the following. We begin with case \( \dim \mathcal{K} \geq 5 \) since in the multi-dimensional case there is more room to perturb and so the proof is simpler. Then we describe modifications needed if \( \dim \mathcal{K} = 3 \) or 4. In Sections I-III we review constructions of Katok [K] and Brin [B2] and establish some additional properties of the corresponding diffeomorphisms which are used in our analysis. In Section IV we explain how to get rid of zero Lyapunov exponent while in Section V we establish some crucial properties of our perturbation including transitivity and absolute continuity. In Section VI we observe the Bernoulli property of our diffeomorphism and thus complete the proof in the case \( \dim \mathcal{K} \geq 5 \). We then proceed in Section VII with modifications needed in dimensions three and four. Section VIII reviews Mane’s work on discontinuity of Lyapunov exponents needed in the four dimensional case.

Finally, let us mention that open sets of hyperbolic Bernoulli diffeomorphisms on some manifolds are constructed in [ABV, BV, D, SW].
Preliminaries and Notations. In this paper we deal with various partially (uniformly and non-uniformly) hyperbolic diffeomorphisms and we adopt the following notations (see [BP] for details). A diffeomorphism $F$ of a compact smooth Riemannian manifold $\mathcal{K}$ is called nonuniformly partially hyperbolic on a set $X \subset \mathcal{K}$ if for every $x \in X$ the tangent space at $x$ admits an invariant splitting

$$T_x\mathcal{K} = E^s_F(x) \oplus E^c_F(x) \oplus E^u_F(x)$$

(0.1)

into stable, central, and unstable subspaces. This means that there exist numbers $0 < \lambda^s < \lambda^c_1 \leq 1 \leq \lambda^c_2 < \lambda^u$ and Borel functions $C(x) > 0$ and $K(x) > 0$, $x \in X$ such that

(1) for $n > 0$,

$$\|d_x F^n v\| \leq C(x)(\lambda^s)^n e^{\varepsilon n}\|v\|, \quad v \in E^s(x),$$

$$\|d_x F^{-n} v\| \leq C(x)(\lambda^u)^{-n} e^{-\varepsilon n}\|v\|, \quad v \in E^u(x),$$

$$C(x)^{-1}(\lambda^c_1)^n e^{-\varepsilon n}\|v\| \leq \|d_x F^n v\| \leq C(x)(\lambda^c_2)^n e^{\varepsilon n}\|v\|, \quad v \in E^c(x);$$

(2)

$$\angle(E^s(x), E^u(x)) \geq K(x), \quad \angle(E^s(x), E^c(x)) \geq K(x), \quad \angle(E^u(x), E^c(x)) \geq K(x);$$

(3) for $m \in \mathbb{Z}$,

$$C(F^m(x)) \leq C(x) e^{\varepsilon |m|}, \quad K(F^m(x)) \geq K(x) e^{-\varepsilon |m|}.$$

Throughout the paper we deal with the case

$$\lambda^c_2 - \lambda^c_1 \leq \varepsilon$$

for sufficiently small $\varepsilon > 0$. We denote by

$$\chi(x, v) = \lim_{n \to -\infty} \frac{1}{n} \log \|dF^n v\|$$

(0.2)

the Lyapunov exponent of $v$ at $x$ and by $\chi^i_F(x)$ the values of the Lyapunov exponents at $x$. We also adopt the notation $\chi^i_F(x)$ for the Lyapunov exponent along the central direction in the case it is one-dimensional and $\chi^i_F(x, F) \geq \chi^c_2(x, F)$ for the two Lyapunov exponents along the central direction in the case it is two-dimensional (only these two cases will be considered). Given $\varepsilon > 0$, set

$$\Lambda^+(x, F, \varepsilon) = \sum_{\chi^i_F(x) > \varepsilon} \chi^i_F(x), \quad \Lambda^-(x, F, \varepsilon) = \sum_{\chi^i_F(x) < \varepsilon} \chi^i_F(x).$$

(0.3)

Denote by $V^s_F(x)$ and $V^u_F(x)$ the local stable and unstable manifolds at $x$. They can be characterized as follows: there is a neighborhood $U(x)$ of the point $x$ such that for any $n > 0$,

$$V^s_F(x) = \{ y \in U(x) : d(F^{-n}(x), F^{-n}(y)) \leq C(x)(\lambda^u)^{-n} e^{-\varepsilon n} d(x, y) \},$$

(4.4)

$$V^u_F(x) = \{ y \in U(x) : d(F^n(x), F^n(y)) \leq C(x)(\lambda^s)^n e^{\varepsilon n} d(x, y) \}. $$
Finally, we define the global stable and unstable manifolds at \( x \) by
\[
W^s_F(x) = \bigcup_{n \geq 0} F^n(V_F^u(F^{-n}(x))),
\]
\[
W^u_F(x) = \bigcup_{n \geq 0} F^{-n}(V_F^s(F^n(x))).
\]  

(0.5)

Given a subset \( X \subset \mathcal{K} \) we call two points \( p, q \in \mathcal{K} \) accessible via \( X \), if there are points \( z_0 = p, z_1, \ldots, z_{\ell - 1}, z_{\ell} = q, z_i \in X \) such that \( z_i \in V_F^\alpha(z_{i-1}) \) for \( i = 1, \ldots, \ell \) and \( \alpha \in \{s, u\} \). The collection of points \( z_0, z_1, \ldots, z_{\ell} \) is called the path connecting \( p \) and \( q \) and is denoted by \([p, q]_F = [z_0, z_1, \ldots, z_{\ell}]_F\). The diffeomorphism \( F \) is said to have the accessibility property on \( X \) if any two points \( p, q \in X \) are accessible.

Recall that a partition \( \xi \) of a Borel subset \( X \subset \mathcal{K} \) is called a foliation of \( X \) with \( C^1 \) leaves if there exist continuous functions \( \delta: X \to (0, \infty) \) and \( q: X \to (0, \infty) \) and an integer \( k > 0 \) such that for each \( x \in X \)

1. there exists a smooth immersed \( k \)-dimensional manifold \( W(x) \) containing \( x \) for which \( \xi(x) = W(x) \cap X \) where \( \xi(x) \) is the element of the partition \( \xi \) containing \( x \); the manifold \( W(x) \) is called the (global) leaf of the foliation at \( x \); the connected component of the intersection \( W(x) \cap B(x, \delta(x)) \) that contains \( x \) is called the local leaf at \( x \) and is denoted by \( V(x) \); the number \( \delta(x) \) is called the size of \( V(x) \);
2. there exists a continuous map \( \phi_x: X \cap B(x, q(x)) \to C^1(D, M) \) (where \( D \subset \mathbb{R}^k \) is the unit ball) such that \( V(y), y \in X \cap B(x, q(x)) \) is the image of the map \( \phi_x(y): D \to \mathcal{K} \).

In this paper we will only consider foliations with \( C^1 \) leaves and for simplicity we will call them foliations.

**Acknowledgment.** We would like to thank M. Brin, B. Fayad, A. Katok, M. Shub, M. Viana, and A. Wilkinson for useful discussions.

**I. The Katok Example**

Consider the two-dimensional unit disk \( \mathcal{D}^2 = \{(u_1, u_2) \in \mathbb{R}^2 : u_1^2 + u_2^2 \leq 1\} \). Any diffeomorphism \( g: \mathcal{D}^2 \to \mathcal{D}^2 \) can be written in the form \( g(u_1, u_2) = (g_1(u_1, u_2), g_2(u_1, u_2)) \).

We describe classes of functions and diffeomorphisms which are “sufficiently flat” near the boundary \( \partial \mathcal{D}^2 \). The sequence \( \rho = (\rho_0, \rho_1, \ldots) \) of real-valued continuous functions on \( \mathcal{D}^2 \) is called admissible if every function \( \rho_n \) is non-negative and is strictly positive inside the disk. We denote by \( C^\infty_\rho(\mathcal{D}^2) \) the class of functions \( \phi \in C^\infty(\mathcal{D}^2) \) which satisfy the following property: for every \( n \geq 0 \) there exists \( \varepsilon_n > 0 \) such that for every \( (u_1, u_2) \in \mathcal{D}^2 \) with \( u_1^2 + u_2^2 \geq (1 - \varepsilon_n)^2 \) we have

\[
\left| \frac{\partial^n \phi(u_1, u_2)}{\partial^{i_1} u_1 \partial^{i_2} u_2} \right| < \rho_n(u_1, u_2)
\]

for all non-negative integers \( i_1, i_2, i_1 + i_2 = n \). We also denote by

\[
\text{Diff}^\infty_\rho(\mathcal{D}^2) = \{ g \in \text{Diff}^\infty(\mathcal{D}^2) : g_i(u_1, u_2) - u_i \in C^\infty_\rho(\mathcal{D}^2), i = 1, 2 \}.
\]
**Proposition 1.1.** (see [K].) For every admissible sequence of functions $\rho$ on $D^2$ there exists a diffeomorphism $g \in \text{Diff}_\rho^\infty(D^2)$ which satisfies Statements 1 and 2 of the Main Theorem.

We outline the proof of Proposition 1.1. Let $g_0$ be a hyperbolic automorphism of the 2-torus $T^2$ which has four fixed points $x_1 = (0,0), x_2 = (1/2,0), x_3 = (0,1/2), x_4 = (1/2,1/2)$ (for example, the automorphism generated by the matrix $\begin{pmatrix} 5 & 8 \\ 8 & 13 \end{pmatrix}$ is appropriate). The desired diffeomorphism $g$ is constructed via the following commutative diagram

\[
\begin{array}{ccccccc}
T^2 & \overset{\varphi_0}{\longrightarrow} & T^2 & \overset{\varphi_1}{\longrightarrow} & T^2 & \overset{\varphi_2}{\longrightarrow} & S^2 & \overset{\varphi_3}{\longrightarrow} & D^2 \\
\downarrow g_0 & \downarrow g_1 & \downarrow g_2 & \downarrow g_3 & \downarrow g \\
T^2 & \overset{\varphi_0}{\longrightarrow} & T^2 & \overset{\varphi_1}{\longrightarrow} & T^2 & \overset{\varphi_2}{\longrightarrow} & S^2 & \overset{\varphi_3}{\longrightarrow} & D^2
\end{array}
\]

where $S^2$ is the unit sphere. The map $g_1$ is obtained by slowing down $g_0$ near the points $x_i$. Its construction depends upon a real-valued function $\psi$ which is defined on the unit interval $[0,1]$ and has the following properties:

1. $\psi$ is $C^\infty$ except for the point 0;
2. $\psi(0) = 0$ and $\psi(u) = 1$ for $u \geq r$ where $0 < r < 1$ is a number;
3. $\psi'(u) \geq 0$;
4. \[\int_0^1 \frac{du}{\psi(u)} < \infty.\]

The next condition on the function $\psi$ expresses a “very slow” rate of convergence of the integral $\int_0^1 \frac{du}{\psi(u)}$ near zero. More precisely, for $i = 1, 2, 3, 4$ consider the disk $D^i_r$ centered at $x_i$ of radius $r$ and endowed with the coordinate system $(s_1, s_2)$, i.e.,

\[D^i_r = \{(s_1, s_2) : s_1^2 + s_2^2 \leq r\}.

Choose numbers $r_0 > r_1 > r > 0$ such that

\[D^i_{r_0} \cap D^j_{r_0} = \emptyset, \quad i \neq j, \quad (g_0(D^i_{r_1}) \cup g_0^{-1}(D^j_{r_1})) \subset D^i_{r_0}, \quad D^i_r \subset \text{Int}(g_0(D^i_{r_1})).\]

We also set $D = \bigcup_{i=1}^4 D^i_{r_1}$. Let $\beta(u)$ be the inverse of the function

\[\gamma(u) = \sqrt{\int_0^u \frac{d\tau}{\psi(\tau)}}.

Consider the following two functions defined near the origin:

\[H_1(s_1, s_2) = (\log \alpha)\beta \left( \sqrt{s_1^2 + s_2^2} \right) \frac{s_1 s_2}{s_1^2 + s_2^2},\]
and
\[ H_2(s_1, s_2) = (\log \alpha) \beta \left( \frac{s_2}{\sqrt{s_1^2 + s_2^2}} \right) - \frac{s_2}{\sqrt{s_1^2 + s_2^2}}, \]
as well as the function \( H \) defined near \( \partial D^2 \) by
\[ H(x_1, x_2) = (\log \alpha) \beta \left( \frac{x_2}{\sqrt{x_1^2 + x_2^2}} \right) - \frac{x_2}{\sqrt{x_1^2 + x_2^2}}, \]
where \( \alpha \) is the largest eigenvalue of the matrix generating \( g_0 \). We assume that the function \( \psi \) is chosen such that the following condition holds:

\[(1.5) \text{ for any sequence } \kappa \text{ of admissible germs near the origin in } \mathbb{R}^2 \text{ and any sequence } \rho \text{ of admissible functions on } D^2 \text{ there is a sequence } \theta \text{ of admissible germs near } 0 \in \mathbb{R}^+ \text{ such that } H_1, H_2 \in C^\kappa_0(\mathbb{R}^+, 0) \text{ and } H \in C^\rho(\mathbb{D}^2). \]

Denote by \( \tilde{g}_\psi^i \) the time-one map generated by the vector field \( v_\psi \) in \( D_{r_0}^i \), \( i = 1, 2, 3, 4 \) given as follows:
\[ \dot{s}_1 = (\log \alpha)s_1\psi(s_1^2 + s_2^2), \quad \dot{s}_2 = -(\log \alpha)s_2\psi(s_1^2 + s_2^2). \]
One can show that \( \tilde{g}_\psi^i(D_{r_1}^i) \subset D_{r_0}^i \) and \( \tilde{g}_\psi^i \) coincides with \( g_0 \) in some neighborhood of the boundary \( \partial D_{r_0}^i \). Therefore, the map
\[ g_1(x) = \begin{cases} g_0(x) & \text{if } x \in T^2 \setminus D, \\ \tilde{g}_\psi^i(x) & \text{if } x \in D \end{cases} \]
defines a homeomorphism of the torus \( T^2 \) which is a \( C^\infty \) diffeomorphism everywhere except for the points \( x_i, i = 1, 2, 3, 4 \). The map \( g_1 \) leaves invariant a smooth probability measure \( d\nu = \kappa_0^{-1}\kappa \, dm \) where the density \( \kappa \) is a positive \( C^\infty \) function except for inﬁnities at \( x_i \). It is defined by the formula
\[ \kappa(x) = \begin{cases} \psi^{-1}(s_1^2(x) + s_2^2(x)) & \text{if } x \in D, \\ 1 & \text{otherwise} \end{cases} \]
and
\[ \kappa_0 = \int_{T^2} \kappa \, dm. \]
We summarize the properties of the map \( g_1 \) in the following lemma.

**Lemma 1.2.** (see [K]).

1. The map \( g_1 \) is topologically conjugate to \( g_0 \) via a homeomorphism \( \varphi_0 \) which transfers the stable \( W^s_{g_0}(x) \) and unstable \( W^u_{g_0}(x) \) (global) curves of \( g_0 \) into smooth curves which are stable \( W^s_{g_1}(x) \) and unstable \( W^u_{g_1}(x) \) curves of \( g_1 \).
2. There exist continuous families of stable cones \( K^{-}_{g_1}(x) \) and unstable cones \( K^+_{g_1}(x) \), \( x \in T^2 \setminus \{x_1, x_2, x_3, x_4\} \) such that
\[ g_1^{-1}(K^{-}_{g_1}(x)) \subset K^{-}_{g_1}(g_1^{-1}(x)), \quad g_1(K^+_{g_1}(x)) \subset K^+_{g_1}(g_1(x)). \]
For every $x \in T^2 \setminus \{x_1, x_2, x_3, x_4\}$ we define the stable and unstable one-dimensional subspaces at $x$ by

$$E^{-}_{g_1}(x) = \bigcap_j g_1^{-j}(K^0_{g_1}(g_1^{j}(x))), \quad E^{+}_{g_1}(x) = \bigcap_j g_1^{j}(K^+_{g_1}(g_1^{-j}(x))).$$

**Lemma 1.3.** (see [K].)

1. The subspaces $E^{-}_{g_1}(x)$ and $E^{+}_{g_1}(x)$ depend continuously on $x$.

2. The map $g_1$ is uniformly hyperbolic on $T^2 \setminus D$; more precisely, there is a number $\lambda > 1$ such that for every $x \in T^2 \setminus D$,

$$\|dg_1|E^{-}_{g_1}(x)\| \leq \frac{1}{\lambda}, \quad \|dg_1^{-1}|E^{+}_{g_1}(x)\| \leq \frac{1}{\lambda}.$$

Once the maps $\varphi_1$, $\varphi_2$, and $\varphi_3$ are constructed the maps $g_2$, $g_3$, and $g$ are defined to make the above diagram commutative. We follow [K] and describe a particular choice of maps $\varphi_1$, $\varphi_2$, and $\varphi_3$.

In a neighborhood of each point $x_i$, $i = 1, 2, 3, 4$ the map $\varphi_1$ is given by

$$\varphi_1(s_1, s_2) = \frac{1}{\sqrt{s_0(s_1^2 + s_2^2)}} \left( \int_0^{s_1^2 + s_2^2} \frac{du}{\psi(u)} \right)^{\frac{1}{2}} (s_1, s_2)$$

and it is the identity in $T^2 \setminus D$. Thus, it is a homeomorphism which is a $C^\infty$ diffeomorphism except for the points $x_i$; it carries the measure $\nu$ into the Lebesgue measure and it commutes with the involution $J(t_1, t_2) = (1 - t_1, 1 - t_2)$.

The map $\varphi_2 : T^2 \to S^2$ is a double branched covering and is regular and $C^\infty$ everywhere except for the points $x_i$, $i = 1, 2, 3, 4$ where it branches; it commutes with the involution $J$ and preserves the Lebesgue measure; there is a local coordinate system $(\tau_1, \tau_2)$ in a neighborhood of each point $p_i = \varphi_2(x_i)$ such that

$$\varphi_2(s_1, s_2) = \left( \frac{s_1^2 - s_2^2}{\sqrt{s_1^2 + s_2^2}}, \frac{2s_1 s_2}{\sqrt{s_1^2 + s_2^2}} \right).$$

In a neighborhood of the point $p_4$ the map $\varphi_3$ is given by

$$\varphi_3(\tau_1, \tau_2) = \left( \frac{\tau_1 \sqrt{1 - \tau_1^2 - \tau_2^2}}{\sqrt{\tau_1^2 + \tau_2^2}}, \frac{\tau_2 \sqrt{1 - \tau_1^2 - \tau_2^2}}{\sqrt{\tau_1^2 + \tau_2^2}} \right).$$

and it is extended to a $C^\infty$ diffeomorphism $\varphi_3$ between $S^2 \setminus \{p_4\}$ and Int $D^2$ which preserves the Lebesgue measure.

This concludes the construction of the diffeomorphism $g$ in Proposition 1.1.
II. SOME ADDITIONAL PROPERTIES OF THE DIFFEOMORPHISM IN THE KATOK’S EXAMPLE

We first observe the following crucial properties of the map \( g_1 \).

**Proposition 2.1.** There are constants \( \gamma_0 > 0 \) and \( C > 0 \) such that for every \( \gamma_0 \geq \gamma > 0 \) one can find a point \( x_0 \in T^2 \setminus D \) for which

\[
g_1^j(B(x_0, \gamma)) \cap B(x_0, \gamma) = \emptyset, \quad -N < j < N, \quad j \neq 0,
\]

\[
g_1^j(B(x_0, \gamma)) \cap D = \emptyset, \quad -N < j < N,
\]

where \( N = N(\gamma) = -\frac{\log \gamma}{\log \lambda} - C \).

**Proof.** Note that the statement holds true for the linear hyperbolic automorphism \( g_0 \) and the desired result now follows from Lemma 1.2. \( \square \)

We now describe some additional properties of the map \( g \).

Let \( U \) be a sufficiently small neighborhood of the singularity set \( Q = \{q_1, q_2, q_3\} \cup \partial D^2 \) where \( q_i = \varphi_3(p_i), i = 1, 2, 3 \).

**Proposition 2.2.**

1. The Lyapunov exponents of \( g \) are nonzero almost everywhere with respect to the Lebesgue measure \( m \).
2. There exist continuous families of stable cones \( K_g^-(x) \) and unstable cones \( K_g^+(x) \), \( x \in D^2 \setminus Q \) such that

\[
g^{-1}(K_g^-(x)) \subset K_g^-(g^{-1}(x)), \quad g(K_g^+(x)) \subset K_g^+(g(x))
\]

and the inclusions are strict on the closure of the set \( D^2 \setminus U \).
3. The distributions

\[
E_g^-(x) = \bigcap_j g^{-j}(K_g^-(g^j(x))), \quad E_g^+(x) = \bigcap_j g^j(K_g^+(g^{-j}(x)))
\]

are one-dimensional \( dg \)-invariant and continuous on \( D^2 \setminus Q \); moreover, the map \( g \) is uniformly hyperbolic on \( D^2 \setminus U \): there is a number \( \lambda > 1 \) such that for \( x \in D^2 \setminus U \),

\[
\|dg|E_g^-(x)\| \leq \frac{1}{\lambda}, \quad \|dg^{-1}|E_g^+(x)\| \leq \frac{1}{\lambda};
\]

furthermore, there is an invariant set \( X \) of full measure such that for every \( x \in X \),

\[
E_g^s(x) = E_g^-(x), \quad E_g^u(x) = E_g^+(x),
\]

where \( E_g^s(x) \) and \( E_g^u(x) \) are given by (0.1).
(4) The map $g$ possesses two one-dimensional foliations, $W_g^-$ and $W_g^+$, of the set $D^2 \setminus Q$ such that

$$T_x W_g^-(x) = E_g^s(x), \quad T_x W_g^+(x) = E_g^u(x), \quad x \in D^2 \setminus Q;$$

the sizes of local leaves $V_g^-(x)$ and $V_g^+(x)$ are bounded away from zero on the set $D^2 \setminus U$; moreover, for every $x \in X$,

$$W_g^s(x) = W_g^-(x), \quad W_g^u(x) = W_g^+(x),$$

where $W_g^s(x)$ and $W_g^u(x)$ are given by (0.5) (with $F = g$).

(5) There is $\gamma_0 > 0$ such that for every $\gamma_0 > \gamma > 0$ one can find a point $x_0 \in D^2 \setminus U$ such that

$$g^j(B(x_0, \gamma)) \cap B(x_0, \gamma) = \emptyset, \quad -N < j < N, \quad j \neq 0,$$

$$g^j(B(x_0, \gamma)) \cap U = \emptyset, \quad -N < j < N,$$

where $N = N(\gamma) = \frac{\log \gamma}{\log \lambda} - C$ and $C > 0$ is a constant.

Proof. The result follows immediately from Lemmas 1.2, 1.3, 1.4, and Proposition 2.1.

Remarks. 1. A. Katok has shown that the leaves $W_g^-(x)$ and $W_g^+(x)$ depend Lipschitz continuously over $x \in D^2 \setminus Q$ (private communication).

2. One can show that the set $T^2 \setminus (\varphi_1 \circ \varphi_2 \circ \varphi_3)^{-1}(X)$ is the union of the stable and unstable separatrices of the fixed points $x_1, x_2, x_3$, and $x_4$.

III. THE DESCRIPTION OF BRIN’S EXAMPLE

We outline Brin’s construction from [B].

Given a positive integer $n \geq 5$ set $k = \lfloor \frac{n-3}{2} \rfloor$ and consider the $(n - 3) \times (n - 3)$ block diagonal matrix $A = (A_i)$, where $A_i = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$ for $i < k$ and

$$A_k = \begin{cases} \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix} & \text{if } n \text{ is odd,} \\
\begin{pmatrix} 2 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 1 & 2 \end{pmatrix} & \text{if } n \text{ is even.} \end{cases}$$

It is easy to see that $\det A = 1$ and that $A$ generates a volume preserving hyperbolic automorphism of the torus $T^{n-3}$. Let $T^t$ be the suspension flow over $A$ with the roof function

$$H = H_0 + \varepsilon H(x),$$
where $H_0$ is a constant and the function $H(x)$ is such that $|H(x)| \leq 1$. The flow $T^t$ is an Anosov flow on the phase space $\mathcal{Y}^{n-2}$ which is diffeomorphic to the product $\mathcal{T}^{n-3} \times [0,1]$, where the tori $\mathcal{T}^{n-3} \times 0$ and $\mathcal{T}^{n-3} \times 1$ are identified by the action of $A$.

One can choose the function $H(x)$ such that the flow $T^t$ has the accessibility property.

Consider the following skew product map $R$ of the manifold $\mathcal{M} = \mathcal{D}^2 \times \mathcal{Y}^{n-2}$

$$ R(z) = R(x,y) = (g(x), T^\alpha(x)(y)), \quad z = (x, y), \quad (3.1) $$

where the diffeomorphism $g$ is constructed in Proposition 1.1 and $\alpha : \mathcal{D}^2 \to \mathbb{R}$ is a non-negative $C^\infty$ function which is equal to zero in the neighborhood $\mathcal{U}$ of the singularity set $\mathcal{Q}$ and is strictly positive otherwise.

We define the singularity set for the map $R$ by $\mathcal{S} = \mathcal{Q} \times \mathcal{Y}^{n-2}$, where $\mathcal{Q}$ is the singularity set of the map $g$ (see Proposition 2.2). We also set $\mathcal{N} = (\mathcal{D}^2 \setminus \mathcal{U}) \times \mathcal{Y}^{n-2}$ and $\mathcal{Z} = \mathcal{X} \times \mathcal{Y}^{n-2}$, where the sets $\mathcal{U}$ and $\mathcal{X}$ are defined in Proposition 2.2.

**Proposition 3.1.** The following statements hold.

1. The map $R$ possesses four continuous cone families $K_R^c(z)$, $K_R^{+c}(z)$, and $K_R^{-c}(z)$, $z \in \mathcal{M} \setminus \mathcal{S}$ such that

$$ R^{-1}(K_R^c(z)) \subset K_R^c(R^{-1}(z)), \quad R(K_R^{+c}(z)) \subset K_R^{+c}(R(z)), $$

$$ R^{-1}(K_R^{-c}(z)) \subset K_R^{-c}(R^{-1}(z)), \quad R(K_R^{+c}(z)) \subset K_R^{+c}(R(z)) \quad (3.2) $$

and inclusions are strict on the closure of the set $\mathcal{N}$; moreover, there exists $\mu > 1$ such that for all $z \in \mathcal{N}$,

$$ \|dR(v)\| > \mu \|v\| \quad \text{for all } v \in K^+(z), $$

$$ \|dR(v)\| < \frac{1}{\mu} \|v\| \quad \text{for all } v \in K^-(z). \quad (3.3) $$

2. For every $z \in \mathcal{Z}$ the formulae

$$ E_R^s(z) = \bigcap_j R^{-j}(K_R^c(R^j(z))), \quad E_R^u(z) = \bigcap_j R^j(K_R^{-c}(R^{-j}(z))); $$

determine $dR$-invariant stable and unstable continuous distributions such that

$$ T_z \mathcal{M} = E_R^s(z) \oplus E_R^{+c}(z) \oplus E_R^u(z), $$

where $E_R^c(z)$ is the one-dimensional central direction;

3. For every $z \in \mathcal{N} \cap \mathcal{Z}$,

$$ \|dR|E_R^s(z)\| \leq \frac{1}{\mu}, \quad \|dR^{-1}|E_R^u(z)\| \leq \frac{1}{\mu}. $$

4. For every $z = (x, y) \in \mathcal{Z}$,

$$ \pi_1 E_R^s(z) = E^s_g(x), \quad \pi_1 E_R^u(z) = E^u_g(x), $$

$$ \pi_2 E_R^s(z) = E^s_T'(y), \quad \pi_2 E_R^u(z) = E^u_T'(y), $$

where $\pi_1 : T_z \mathcal{M} \to T_x \mathcal{D}^2$ and $\pi_2 : T_z \mathcal{M} \to T_y \mathcal{Y}^{n-2}$ are the natural projections.

5. $m \{ x \in \mathcal{M} : R^n(x) \in \mathcal{U} \text{ for all } n \in \mathbb{Z} \} = 0.$
Proof. For every $z = (x, y) \in (\mathcal{U} \setminus \mathcal{S}) \times \mathcal{Y}^{n-2}$ we set
\[ K_R^+(z) = K_g^-(x) \times K_{T^1}^+(y), \quad K_R^-(z) = K_g^+(x) \times K_{T^1}^-(y). \]
Now for every $z \in \mathcal{N}$ one can find numbers $n_1 = n_1(z)$ and $n_2 = n_2(z)$ such that
\[ R^{n_1}(z), R^{-n_2}(z) \in (\mathcal{U} \setminus \mathcal{S}) \times \mathcal{Y}^{n-2}. \]
Set
\[ K_R^+(z) = dR^{n_2} K_R^+(R^{-n_2}(z)), \quad K_R^-(z) = dR^{-n_1} K_R^-(R^{n_1}). \]
It is not difficult to show that $K_R^+(z)$ and $K_R^-(z)$ do not depend on the choice of numbers $n_1$ and $n_2$ and by Proposition 2.2 (see Statement 1), have all the desired properties. We show that the distribution $E_R^u(z)$ is continuous over $z \in Z$. Indeed, let $z_n \in Z$ be a sequence of points which converges to a point $z \in Z$. By Statements 2 and 3 of Proposition 2.2, given $\delta > 0$, one can find a number $m = m(z)$ such that the cone $R^m(K_R^+(R^{-m}(z_n)))$ is contained in the cone around $E_R^u(z)$ of angle $\delta$. Therefore, for all sufficiently large $n$ the cones $R^m(K_R^+(R^{-m}(z_n)))$ are contained in the cone around $E_R^u(z)$ of angle $2\delta$. Since $E_R^u(z_n) \subset R^m(K_R^+(R^{-m}(z_n)))$ the continuity of the distribution $E_R^u(z)$, $z \in Z$ follows. Similar arguments show the continuity of the distribution $E_R^s(z)$ over $z \in Z$. Statement 3 follows from Statement 3 of Proposition 2.2 and Statement 4 is obvious. The last statement is a consequence of Statement 1 of Lemma 1.2 and the properties of the maps $\varphi_1, \varphi_2$, and $\varphi_3$ (see Section 1).

Proposition 3.2. The distributions $E_R^s(z)$ and $E_R^u(z)$ generate two foliations, $W_R^s$ and $W_R^u$, of $Z$; the sizes of local leaves $V_R^s(z)$ and $V_R^u(z)$ are bounded away from zero on the set $\mathcal{N} \cap Z$.

Proof. We follow arguments in [B]. Let $z = (x, y) \in Z$. Set
\[ W_R^s(z) = \bigcup_{\hat{x} \in W_g^s(x)} (\hat{x}, W_{T^1}^s(T^t(\hat{x}))(y)), \]
\[ W_R^u(z) = \bigcup_{\hat{x} \in W_g^u(x)} (\hat{x}, W_{T^1}^u(T^t(\hat{x}))(y)), \]
where
\[ t(\hat{x}) = \sum_{n=0}^{\infty} (\alpha(g^n(\hat{x})) - \alpha(g^n(x))), \]
\[ t(\hat{x}) = \sum_{n=0}^{\infty} (\alpha(g^n(\hat{x})) - \alpha(g^n(x))). \tag{3.4} \]
Note that each series in (3.4) converges for every $x \in Z$. Indeed, since the point $(\varphi_1 \circ \varphi_2 \circ \varphi_3)^{-1}(x)$ does not lie on a separatrix of any of the fixed points $x_1, x_2, x_3$, and $x_4$ the series converges exponentially fast. The desired properties of the foliations $W_R^s$ and $W_R^u$ follow from Propositions 2.2 and 3.1.

Remark. We shall show below (see Proposition 5.1) that the distributions $E_R^s(z)$ and $E_R^u(z)$ as well as foliations $W_R^s(z)$ and $W_R^u(z)$ can be extended to continuous distributions on and foliations of $\mathcal{M} \setminus \mathcal{S}$.

We proceed with Brin’s construction.
Lemma 3.3. (see [B]). There exists a smooth embedding of the manifold $\mathcal{Y}^{n-2}$ into $\mathbb{R}^n$.\(^1\)

We now state the main result in [B].

**Proposition 3.4.** Given a compact smooth Riemannian manifold $\mathcal{K}$ of dimension $n \geq 5$ there exists a $C^\infty$ diffeomorphism $h$ of $\mathcal{K}$ such that

1. $h$ preserves the Riemannian volume on $\mathcal{K}$;
2. for almost every $z \in \mathcal{K}$ there exists a decomposition
   \[ T_z \mathcal{K} = E^s_h(z) \oplus E^c_h(z) \oplus E^u_h(z) \]
   into $dh$ invariant stable, central, and unstable subspaces such that $\dim E^c_h(z) = 1$ and the Lyapunov exponents at the point $z$ of a vector $v \in T_z \mathcal{K}$
   \[
   \chi(z,v) \begin{cases} 
   < 0 & \text{if } v \in E^s_h(z), \\
   = 0 & \text{if } v \in E^c_h(z), \\
   > 0 & \text{if } v \in E^u_h(z);
   \end{cases}
   \]
3. $h$ satisfies the essential accessibility property and is a Bernoulli diffeomorphism.

**Proof.** Using Lemma 3.3 one can construct a smooth embedding $\chi_1 : \mathcal{K} \rightarrow \mathcal{B}^n$ (where $\mathcal{B}^n$ is the unit ball in $\mathbb{R}^n$) which is a diffeomorphism except for the boundary $\partial \mathcal{D}^2 \times \mathcal{Y}^{n-2}$. Then using results in [K] one can find a smooth embedding $\chi_2 : \mathcal{B}^n \rightarrow \mathcal{K}$ which is a diffeomorphism except for the boundary $\partial \mathcal{B}^n$. Since the map $R$ is identity on the boundary $\partial \mathcal{D}^2 \times \mathcal{Y}^{n-2}$ the map $h = (\chi_1 \circ \chi_2) \circ R \circ (\chi_1 \circ \chi_2)^{-1}$ has all the properties stated in Proposition 3.4.

\[\square\]

IV. The Perturbation of The Diffeomorphism in Brin’s Example

Fix a number $\gamma > 0$ and a point $y_0 \in \mathcal{Y}^{n-2}$ and set $\Delta = B(x_0, \gamma) \times B(y_0, \gamma)$ (where the point $x_0$ is chosen in Proposition 2.2, see Statement 5).

In this section we prove the following result.

**Proposition 4.1.** Given $\varepsilon > 0$, there is a $C^\infty$ diffeomorphism $P : \mathcal{M} \rightarrow \mathcal{M}$ such that

1. $P$ preserves the Riemannian volume $m$;
2. $d_{C^1}(P,R) \leq \varepsilon$ where the map $R$ is defined by (3.1); moreover, $P|_{(\mathcal{M} \setminus \Delta)} = R|_{(\mathcal{M} \setminus \Delta)}$;
3. for almost every $z \in \mathcal{M}$ there exists a decomposition
   \[ T_z \mathcal{M} = E^s_P(z) \oplus E^c_P(z) \oplus E^u_P(z) \]
   into $dP$ invariant subspaces such that $\dim E^c_P(z) = 1$ and the Lyapunov exponent at the point $z$ of a vector $v \in T_z \mathcal{M}$
   \[
   \chi(z,v) \begin{cases} 
   < 0 & \text{if } v \in E^s_P(z), \\
   > 0 & \text{if } v \in E^u_P(z);
   \end{cases}
   \]

\(^1\)The proof of this statement in [B] needs some minor corrections. The manifold $\mathcal{Y}^{n-2}$ is of codimension two. Although not every codimension two manifold has trivial normal bundle $\mathcal{Y}^{n-2}$ does. This can easily be seen from its construction. Similar observation should be made wherever triviality of the normal bundle is used.
(4) the Lyapunov exponent $\chi^c_P(z)$ in the central direction satisfies

$$\int_{\mathcal{M}} \chi^c_P(z) \, dm < 0.$$ 

Proof. Let $\varphi : \mathcal{Y}^{n-2} \to \mathcal{Y}^{n-2}, x \in \mathcal{M}$ be a family of volume preserving $C^\infty$ diffeomorphisms satisfying

$$d_{C^1}(\varphi, Id) \leq \varepsilon, \quad \varphi(x) = x \quad \text{for } (x, y) \in \mathcal{M} \setminus \Delta. \quad (4.1)$$

A particular choice of such a family of diffeomorphisms will be specified below (see Lemma 4.4). Set

$$\varphi(x, y) = (x, \varphi(x)), \quad P = \varphi \circ R. \quad (4.2)$$

It is easy to see that the map $P$ is $C^\infty$, volume preserving, and

$$P| (\mathcal{M} \setminus \Delta) = R| (\mathcal{M} \setminus \Delta), \quad d_{C^1}(P, R) \leq \varepsilon. \quad (4.3)$$

It follows from Proposition 3.1 and the first relation in (4.3) that for every $z \in \mathcal{M} \setminus \mathcal{S},$

$$P^{-1}(K_R^-(z)) \subset K_R^-(P^{-1}(z)), \quad P(K_R^+(z)) \subset K_R^+(P(z)) \quad (4.4)$$

and inclusions are strict on the set $\mathcal{M} \setminus \mathcal{S}$. Therefore, the formulae

$$E^s_P(z) = \bigcap_j P^{-j}(K_R^-(P^j(z))), \quad E^u_P(z) = \bigcap_j P^j(K_R^+(P^{-j}(z))) \quad (4.5)$$

define subspaces at every point $z \in Z$. Clearly, these subspaces are $dP$-invariant. Moreover, since the first coordinate of the point $P(x, y)$ depends only on $x$ (see (4.2)) we obtain that

$$\pi_1 E^s_P(z) = E^s_q(x), \quad \pi_1 E^u_P(z) = E^u_q(x), \quad (4.6)$$

where $z = (x, y)$ (recall that $\pi_1 : T_z\mathcal{M} \to T_xD^2$ is the natural projection).

Remark. We shall show below (see Proposition 5.1) that for any sufficiently small gentle perturbation $P$ of the map $R$ the distributions $E^s_P$ and $E^u_P$ can be extended to a continuous distributions $\tilde{E}^s_P$ and $\tilde{E}^u_P$ on the set $\mathcal{M} \setminus \mathcal{S}$ (but not just the set $Z$). However, the property (4.6) holds true only due to the special form of the perturbation (see (4.2)). This property is crucial for our further study (see Proposition 5.2).

Lemma 4.2.

(1) For every sufficiently small $\gamma > 0$ and $z = (x, y) \in Z$ with $x \in B(x_0, \gamma)$ we have that

$$\angle(E^s_P(z), E^u_R(z)) \leq C\gamma \log \frac{1}{\gamma},$$

$$\angle(E^s_R(z), dP^{-1}E^s_R(P(z))) \leq C\gamma \log \frac{1}{\gamma}. \quad (4.7)$$

(2) There is a number $\nu > 1$ such that for every $z \in \mathcal{N} \cap Y,$

$$\|dP|E^s_P(z)\| \leq \frac{1}{\nu}, \quad \|dP^{-1}|E^u_P(z)\| \leq \frac{1}{\nu}. \quad (4.8)$$
Proof of the lemma. The second statement follows immediately from the first one and Statement 3 of Proposition 3.1. We will prove the first inequality in (4.7), the proof of the second one is similar. Consider the point

\[ z^* = (x^*, y^*) = R^{-(N-1)}(P^{-1}(z)), \]

where \( N = N(\gamma) \) is defined in Proposition 2.2 (see Statement 5). By (4.3),

\[ d(\mathcal{E}_P^u(z^*), \mathcal{E}_R^u(z^*)) \leq \delta, \]

where \( d \) is the distance in the Grassmanian manifold and \( \delta = \delta(\varepsilon) > 0 \) is sufficiently small. Since \( P_j(z^*) = R_j(z^*) \) for \( 0 \leq j \leq N - 1 \) \((4.9)\)

we obtain using Statement 3 of Proposition 3.1 that

\[ d(dR^{N-1}\mathcal{E}_P^u(z^*), dR^{N-1}\mathcal{E}_R^u(z^*)) \leq \frac{\delta}{\mu_{N-1}}. \]

Using again (4.9) we rewrite the last inequality as

\[ d(\mathcal{E}_P^u(P^{-1}(z)), \mathcal{E}_R^u(P^{-1}(z))) \leq \frac{\delta}{\mu_{N-1}} \leq \delta \mu^{\log \mu \log \log \delta}. \]

Applying \( dP \) we obtain the desired result. \( \square \)

Since the maps \( R \) and \( P \) preserve the Riemannian volume we have for every \( z \in \mathcal{M} \setminus \mathcal{S}, \)

\[ \Lambda^+(z, R, \varepsilon) + \Lambda^-(z, R, \varepsilon) + \chi_R(z) = \Lambda^+(z, R, \varepsilon) + \Lambda^-(z, R, \varepsilon) = 0, \]

\[ \Lambda^+(z, P, \varepsilon) + \Lambda^-(z, P, \varepsilon) + \chi_P^c(z) = 0, \]

(see (0.3) for the definition of the terms). It follows that

\[
\begin{align*}
\int_{\mathcal{M}} \chi_P^c(z) \, dm &= \int_{\mathcal{M}} \Lambda^+(z, R, \varepsilon) \, dm - \int_{\mathcal{M}} \Lambda^+(z, P, \varepsilon) \, dm \\
&\quad + \int_{\mathcal{M}} \Lambda^-(z, R, \varepsilon) \, dm - \int_{\mathcal{M}} \Lambda^-(z, P, \varepsilon) \, dm.
\end{align*}
\] (4.10)

Lemma 4.3. We have

\[
\begin{align*}
\int_{\mathcal{M}} \Lambda^+(z, P, \varepsilon) \, dm - \int_{\mathcal{M}} \Lambda^+(z, R, \varepsilon) \, dm &= \int_{\Delta} \left( \log \left[ \det(\Phi^u)(z) \right] + O \left( \frac{\log \mu}{\varepsilon \log \log \delta} \right) \right) \, dm, \\
\int_{\mathcal{M}} \Lambda^-(z, P, \varepsilon) \, dm - \int_{\mathcal{M}} \Lambda^-(z, R, \varepsilon) \, dm &= - \int_{\Delta} \left( \log \left[ \det(\Phi^{-1})^s(z) \right] + O \left( \frac{\log \mu}{\varepsilon \log \log \delta} \right) \right) \, dm,
\end{align*}
\]

where

\[ \Phi^u(z) = d\varphi|E^u_R(z), \quad (\Phi^{-1})^s(z) = d\varphi|E^s_R(z). \] (4.11)
Proof of the lemma. We will establish the first relation. The proof of the second one is similar. Consider the induced maps \( \tilde{R} \) and \( \tilde{P} \) generated by the maps \( R \) and \( P \) respectively on the set \( \Delta \). These maps are well-defined for almost every \( z \in \Delta \). Let \( \tilde{\Delta} \) be the set of such points. By Kac’s formula

\[
\int_M \Lambda^+(z, R, \varepsilon) \, dm = \int_{\tilde{\Delta}} \Lambda^+(z, \tilde{R}, \varepsilon) \, dm,
\]

\[
\int_M \Lambda^+(z, P, \varepsilon) \, dm = \int_{\tilde{\Delta}} \Lambda^+(z, \tilde{P}, \varepsilon) \, dm.
\]

It follows

\[
\int_M [\Lambda^+(z, P, \varepsilon) - \Lambda^+(z, R, \varepsilon)] \, dm = \int_{\tilde{\Delta}} [\Lambda^+(z, \tilde{P}, \varepsilon) - \Lambda^+(z, \tilde{R}, \varepsilon)] \, dm.
\]

Fix \( z = (x, y) \in \tilde{\Delta} \). Every vector \( v \in E_P^u(z) \) can be written in the form \( v = v_R + w \) where \( v_R \in E_P^u(z) \) and \( w \in E_R^s(z) \oplus E_R^c(z) \). Denote by \( N = N(z) \) the first return time of the point \( z \) to \( \tilde{\Delta} \) under the map \( R \). By (4.2) we have that the first return time of \( Z \) to \( \tilde{\Delta} \) under the map \( P \) is also \( N \). Moreover, by Lemma 4.2,

\[
dP^N v = d\phi dR^N (v_R + w) = \|dR^N v_R\| d\phi \left( \frac{dR^N v_R}{\|dR^N v_R\|} \right) (1 + O(\mu^{-N}))
\]

\[
= (1 + O(\mu^{-N})) \|dR^N v_R\| \left[ \Phi^u \frac{dR^N v_R}{\|dR^N v_R\|} + w^* \right],
\]

where \( w^* \) is a vector in \( E_R^s(z) \oplus E_R^c(z) \). Notice that

\[
\int_{\tilde{\Delta}} \Lambda^+(z, \tilde{P}, \varepsilon) \, dm = \int_{\tilde{\Delta}} \log \det (d\tilde{P}|E_P^u(z)) \, dm,
\]

\[
\int_{\tilde{\Delta}} \Lambda^+(z, \tilde{R}, \varepsilon) \, dm = \int_{\tilde{\Delta}} \log \det (d\tilde{R}|E_R^u(z)) \, dm.
\]

It follows that

\[
\int_{\tilde{\Delta}} (\Lambda^+(z, \tilde{P}, \varepsilon) - \Lambda^+(z, \tilde{R}, \varepsilon)) \, dm \quad \text{d}(\Lambda^+(z, \tilde{P}, \varepsilon) - \Lambda^+(z, \tilde{R}, \varepsilon)) \, dm
\]

\[
= \int_{\tilde{\Delta}} \log \frac{\det \Phi^u(P^N|E_P^u(z))}{\det \Phi^u(R^N|E_R^u(z))} \, dm
\]

\[
= \int_{\tilde{\Delta}} (\log \det \Phi^u(R^N(z)) + O(\mu^{-N})) \, dm
\]

\[
= \int_{\tilde{\Delta}} \left( \log \det \Phi^u(R^N(z)) + O \left( \frac{\log \mu}{\log 1/\mu} \right) \right) \, dm.
\]

The desired result now follows.
For \( z = (x, y) \in Z \) we set
\[
\Phi^u(z) = \frac{\partial \phi_x}{\partial y}(E_R^u(z) \cap T_z \mathcal{Y}^{n-2}), \quad (\Phi^{-1})^s(z) = \frac{\partial \phi_x}{\partial y}(E_R^s(z) \cap T_z \mathcal{Y}^{n-2}).
\]

It follows from the definition of the map \( \varphi \) (see (4.2)) that
\[
det \Phi^u(z) = \det \Phi^u(z), \quad \det \Phi^s(z) = \det \Phi^s(z).
\]

Therefore, using (4.10) and Lemma 4.3 we obtain that
\[
\int_{\mathcal{M}} \chi^c (z) dm = \int_{\Delta} \left( \log \det \Phi^u(z) - \log \det (\Phi^{-1})^s(z) \right) + O \left( \gamma \frac{\log \log \lambda}{\log \lambda} \right) dm. \tag{4.12}
\]

**Lemma 4.4.** There is a family of diffeomorphisms \( \varphi_x : \mathcal{Y}^{n-2} \rightarrow \mathcal{Y}^{n-2} \) satisfying (4.1) and such that
\[
\int_{\Delta} \left[ -\log \det \Phi^u(z) + \log \det (\Phi^{-1})^s(z) \right] dm \leq -C\varepsilon^2 \gamma^{n-2} + O(\varepsilon^3) \gamma^{n-2} + o(1)O(\gamma^n),
\]
where \( C > 0 \) is a constant.

**Proof of the lemma.** Choose a coordinate system \( \{x, y\} = \{x_1, x_2, y_1, y_2, \ldots, y_{n-2}\} \) in \( \Delta \) such that
\[
\begin{align*}
(1) & \quad dm = dx \; dy; \\
(2) & \quad E^c_{\tau}(y_0) = \frac{\partial}{\partial y_2}, \quad E^s_{\tau}(y_0) = \left\langle \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right\rangle, \quad E^u_{\tau}(y_0) = \left\langle \frac{\partial}{\partial y_{k+1}}, \ldots, \frac{\partial}{\partial y_{n-2}} \right\rangle \quad \text{for some } k, 2 \leq k < n-2;
\end{align*}
\]
Let \( \psi(t) \) be a \( C^\infty \) function with compact support. Set \( \tau = \frac{1}{r^2}(\|x\|^2 + \|y\|^2) \) and define
\[
\varphi_x^{-1}(y) = (x, y_1 \cos(\varepsilon \psi(\tau)) + y_2 \sin(\varepsilon \psi(\tau)), -y_1 \sin(\varepsilon \psi(\tau)) + y_2 \cos(\varepsilon \psi(\tau)), y_3, \ldots, y_{n-2}). \tag{4.13}
\]
Since the distributions \( E_R^u(z) \) and \( E_R^s(z) \) are continuous (see Statement 2 of Proposition 2.2) by (4.11) we find that
\[
\int_{\Delta} \log \det \Phi^u(z) dm = o(1) \; m(\Delta) = o(1)O(\gamma^n) \tag{4.14}
\]
and
\[
\int_{\Delta} \log \det (\Phi^{-1})^s(z) dm = \int_{\Delta} \log \det \left( d\phi_x^{-1} \; E_R^s \right)(z) dm.
\]

\[
= \int_{\Delta} \log \det \left( d\phi_x^{-1} \left\langle \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right\rangle \right)(x, y) \; dx \; dy + o(1) \; m(\Delta) \tag{4.15}
\]

\[
= \int_{\Delta} \log \det \left( d\phi_x^{-1} \left\langle \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right\rangle \right)(x, y) \; dx \; dy + o(1)O(\gamma^n).
\]
It is easy to see that
\[
\det \left( d\varphi_x^{-1}\left| \left( \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right) \right. \right) (x, y) = -\frac{2y_1 y_2}{\gamma^2} \varepsilon \psi' (\tau) \cos (\varepsilon \psi (\tau)) + \cos (\varepsilon \psi (\tau)) - \frac{2y_2^2}{\gamma^2} \varepsilon \psi' (\tau) \cos (\varepsilon \psi (\tau)).
\]

It follows that
\[
\log \det \left( d\varphi_x^{-1}\left| \left( \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right) \right. \right) (x, y) = -\frac{2y_1 y_2}{\gamma^2} \varepsilon \psi' (\tau) - \frac{2y_1^2 y_2^2}{\gamma^4} \varepsilon^2 (\psi' (\tau))^2 - \frac{1}{2} \varepsilon^2 (\psi (\tau))^2 - \frac{2y_2^2}{\gamma^2} \varepsilon^2 \psi (\tau) \psi' (\tau) + \mathcal{O} (\varepsilon^3).
\]

Making the coordinate change \( \eta = \frac{y}{\gamma} \) we compute that
\[
\int_{\Delta} \log \det \left( d\varphi_x^{-1}\left| \left( \frac{\partial}{\partial y_2}, \ldots, \frac{\partial}{\partial y_k} \right) \right. \right) (x, y) \, dx dy = -\gamma^{n-2} \int_{B(x_0, \gamma)} dx \int_{\mathbb{R}^{n-2}} \left[ -2\eta_1 \eta_2 \varepsilon \psi (\tau)' \right] d\eta + \gamma^{n-2} \int_{B(x_0, \gamma)} dx \int_{\mathbb{R}^{n-2}} \left[ -2\eta_1^2 \eta_2^2 \varepsilon^2 (\psi (\tau)')^2 \right] d\eta + \gamma^{n-2} \int_{B(x_0, \gamma)} dx \int_{\mathbb{R}^{n-2}} \left[ -\frac{1}{2} \varepsilon^2 (\psi (\tau))^2 - 2\varepsilon^2 \psi (\tau) \psi (\tau)' \eta_2^2 \right] d\eta + \mathcal{O} (\varepsilon^3) \gamma^{n-2}. \tag{4.16}
\]

Since the function \( \psi \) has compact support the first integral in (4.16) is zero. Integrating by parts we obtain that
\[
\int_{\mathbb{R}^{n-2}} \varepsilon^2 \psi (\tau) \psi (\tau)' \eta_2^2 d\eta = -\frac{1}{4} \int_{\mathbb{R}^{n-2}} \varepsilon^2 (\psi (\tau))^2 d\eta.
\]

Hence, the third integral in (4.16) is also zero. The second integral is a strictly negative number of order \( \mathcal{O}(\varepsilon^2 \gamma^{n-2}) \). The desired result follows.

Using Lemma 4.4 and (4.12) we obtain that
\[
\int_{\mathcal{M}} \chi_{\tilde{P}}^c (z) \, dm = -C \varepsilon^2 \gamma^{n-2} + \mathcal{O}(\varepsilon^3) \gamma^{n-2} + o(1) \mathcal{O}(\gamma^n) + \mathcal{O} \left( \left( \frac{\log K}{\varepsilon} \right)^{k+n} \right).
\]

In order to complete the proof of the proposition we choose the number \( \gamma \) so small that \( \gamma^2 \leq \varepsilon^3 \).  \( \Box \)
V. Absolute Continuity And Orbit Density of The Perturbation

In this section we establish some additional crucial properties of the diffeomorphism $P$ given by (4.2).

**Definition.** A perturbation $P$ of the map $R$ is called gentle if $P = R$ on $U \times \gamma^{n-2}$.

If $P$ is a gentle perturbation of $R$ which is sufficiently close to $R$ then $P$ satisfies (3.2) and (3.3). In what follows we assume that $P$ has these properties. Set

\[
E_P^+(z) = \bigcap_j dP^j(K_R^+(P^{-j}(z))), \quad E_P^-(z) = \bigcap_j dP^{-j}(K_R^-(P^j(z))),
\]

\[
E_P^{+c}(z) = \bigcap_j dP^j(K^{+c}(P^{-j}(z))), \quad E_P^{-c}(z) = \bigcap_j dP^{-j}(K^{-c}(P^j(z))),
\]

\[
E_P^{+c}(z) = E_P^{+c}(z) \bigcap E_P^{-c}(z).
\]

**Proposition 5.1.** The following statements hold:

1. $E_P^+(z)$, $E_P^-(z)$, $E_P^{+c}(z)$, $E_P^{-c}(z)$, and $E_P^{c}(z)$ are $dP$ invariant distributions which depend continuously over $z \in \mathcal{M} \setminus \mathcal{S}$;

2. the distributions $E_P^-(z)$ and $E_P^+(z)$ are integrable and the corresponding global leaves $W_P^-(z)$ and $W_P^+(z)$ form foliations of the set $\mathcal{M} \setminus \mathcal{S}$;

3. for every $z \in \mathbb{Z}$ we have

\[
E_P^s(z) = E_P^-(z), \quad E_P^u(z) = E_P^+(z), \quad W_P^s(z) = W_P^-(z), \quad W_P^u(z) = W_P^+(z),
\]

where the distributions $E_P^s(z)$, $E_P^u(z)$ and the foliations $W_P^s(z)$, $W_P^u(z)$ are defined by (0.1) and (0.5) respectively; moreover, the sizes of local leaves $V_P^s(z)$ and $V_P^u(z)$ are uniformly bounded away from zero on the set $\mathcal{N}$;

4. the distributions and the foliations depend continuously on $P$.

**Proof.** Consider the set

\[\mathcal{M}^+ = \{ z \in \mathcal{M} \setminus \mathcal{S} : P^n(z) \to \mathcal{S} \text{ as } n \to +\infty \}.$

Note that

(a) for every $z \in \mathcal{M} \setminus \mathcal{M}^+$ there exists a sequence of numbers $n_k \to +\infty$ such that

\[P^{n_k}(z) \in \mathcal{N};
\]

(b) for every $z \in \mathcal{M}^+$ there exists a number $n_0 = n_0(z)$ such that for every $n \geq n_0$ if we write $P_n(z) = (x_n, y_n)$ then $x_n = g^{n-n_0}x_{n_0}$.

It follows from (a) and (b) that $E_P^-(z)$ is a $dP$ invariant distribution. We shall show that it is continuous. Fix $z \in \mathcal{M} \setminus \mathcal{S}$ and $\varepsilon > 0$. Let $z_m$ be a sequence of points which converges to $z$. There exists $n > 0$ such that $dP^{-n}(K_R^-(P^n(z)))$ is contained in a cone around $E_P^-(z)$ of angle $\varepsilon$. By (a), (b), and the continuity of the cone family $K_R$ one can find $M > 0$ such that for every $m \geq M$ the angle of the cone $dP^{-n}(K_R^-(P^n(z_m)))$ does not exceed $2\varepsilon$. Since $E_P^-(z_m) \subset dP^{-n}(K_R^-(P^n(z_m)))$ we conclude that the Grassmanian distance between $E_P^-(z_m)$ and $E_P^-(z)$ does not exceed $3\varepsilon$. 

18
We shall show that the distribution $E_P^-(z)$ is integrable. Fix $z \in \mathcal{M} \setminus \mathcal{M}^+$. Consider a $u$-admissible manifold $V^-$ at $z$, i.e., a local smooth submanifold passing through $z$ and such that $T_wV^- \subset K^-_R(w)$ for every $w \in V^-$. We have for $z \in \mathcal{M}^+$,

$$W^-_P(z) = \bigcup_{n_i \geq 0} P^{-n_k}(V^-(P^{n_k}(z))) = W^s_P(z).$$

For $z \in \mathcal{M}^+$ the existence of the manifold $W^-(z)$ follows from Property (a) and Proposition 2.2. The desired properties of the foliation $W^-_P$ follow from continuity of the distribution $E^-(z)$, Lemma 4.2 (see 4.8), and Proposition 2.2. Using similar arguments one can establish the desired properties of other distributions in (5.1) and the corresponding foliations.

It is easy to see that the perturbation $P$ given by (4.2) is gentle and hence, Proposition 5.1 applies. Furthermore, due the special form of the perturbation we will obtain an additional crucial information.

For every $z = (x, y) \in \mathcal{M} \setminus \mathcal{S}$ we define “traces” of stable and unstable global leaves for the maps $R$ and $P$ on the fiber $(\mathcal{Y}^{n-2})_x$ by

$$\tilde{W}^s_R(y) = W^s_R(z) \cap (\mathcal{Y}^{n-2})_x, \quad \tilde{W}^-_P(y) = W^-_P(z) \cap (\mathcal{Y}^{n-2})_x$$

$$\tilde{W}^u_R(y) = W^u_R(z) \cap (\mathcal{Y}^{n-2})_x, \quad \tilde{W}^+_P(y) = W^+_P(z) \cap (\mathcal{Y}^{n-2})_x.$$

**Proposition 5.2.**

1. For every $z \in \mathcal{M} \setminus \mathcal{S}$ the collections of manifolds $\tilde{W}^s_R(y), \tilde{W}^u_R(y), \tilde{W}^-_P(y), \tilde{W}^+_P(y)$ form four foliations of $(\mathcal{Y}^{n-2})_x$; for $x \in \mathcal{N}$, the sizes of local leaves $\tilde{V}^s_R(y), \tilde{V}^u_R(y), \tilde{V}^-_P(y), \tilde{V}^+_P(y)$ are uniformly bounded away from zero.

2. Given $\delta > 0$ there exists $\varepsilon > 0$ such that if $d_{C^1}(P, R) \leq \varepsilon$ then for every $z = (x, y) \in \mathcal{N}$,

$$\rho(\tilde{V}^s_R(y), \tilde{V}^-_P(y)) \leq \delta, \quad \rho(\tilde{V}^u_R(y), \tilde{V}^+_P(y)) \leq \delta.$$

**Proof.** The result follows from Propositions 3.1, 3.2, 5.1, and Lemma 4.2.

We now establish the absolute continuity property. Choose a point $z_0 \in \mathcal{N}$ and consider the local manifolds $V^+_P(z), z \in B(z_0, r) \cap \mathcal{Z}$ for sufficiently small number $r > 0$. Since the manifolds depend continuously on $z \in \mathcal{N} \cap \mathcal{Z}$ there is a local submanifold $W$ passing through $z_0$ and transversal to $V^+_P(z)$. Set

$$A = \bigcup_{z \in B(z_0, r) \cap \mathcal{Z}} V^+_P(z).$$

Denote by $\xi$ the partition of $A$ by $V^+_P(z), z \in B(z_0, r) \cap \mathcal{Z}$. Note that the factor space $A/\xi$ can be identified with $W \cap A$. Finally, we denote by $m^+_\xi$ and $m_W$ the Lebesgue measure on $V^+_P(z)$ and respectively on $W$ induced by the Riemannian metric. Since the set $\mathcal{Y}$ has full measure for almost every point $z_0 \in \mathcal{Z}$ we have that $m_W(W \cap A) = 1$. 19
Proposition 5.3. The foliation $W^+_P$ of the set $\mathcal{N} \cap Z$ is absolutely continuous: for almost every point $z \in \mathcal{N} \cap Z$,

1. the conditional measure on the element $V^+(z)$ of this partition is absolutely continuous with respect to the measure $m^+_z$;
2. the factor measure on the factor space $A/\xi$ is absolutely continuous with respect to the measure $m_W$.

A similar statement holds for the foliation $W^-_P$ of $\mathcal{N} \cap Z$.

Proof. If the map $P$ were (fully) non-uniformly hyperbolic the desired result would follow from Theorem 14.1 in [BP] (see Lemma 14.4). It requires a simple and standard modification to generalize the arguments there to partially non-uniformly hyperbolic case.

Our next statement establishes essential accessibility property of the map $P$.

Proposition 5.4. If the perturbation $P$ is sufficiently close to $R$ then any two points $p, q \in Z \cap \mathcal{N}$ are accessible.

Proof. Let $p = (p_1, p_2)$ and $q = (q_1, q_2)$. One can connect points $p_1$ and $q_1$ by a path $[x_0, \ldots, x_\ell]_g$ such that $x_0 = p_1, x_\ell = q_1$, and each point $x_i \in X$. Without loss of generality we may assume that $x_1 \in V^-_g(x_0)$. The local stable manifold $V^-_P(p)$ intersect the fiber $(Y^{n-2})_{x_0}$ at a single point $y_1 \in Z$. Proceeding by induction we construct points $y_0, \ldots, y_\ell$, such that each point $z_i = (x_i, y_i) \in Z, i = 0, 1, \ldots, \ell$ and the path $[z_0, z_1, \ldots, z_\ell]_P$ connects the points $p$ and $z_\ell$. Note also that $y_\ell \in (Y^{n-2})_q$. Fix a number $r > 0$ and consider the interval $[y^-, y^+]$ on the trajectory $T_t(q_2)$ centered at $q_2$ of radius $r$. Since the flow $T_t$ has the accessibility property (see Section 3) for every $s \in [y^-, y^+]$ one can find a path $[y_\ell, s]_{T_t}$. Moreover, paths corresponding to different $s$ are homotopic to each other. By Propositions 3.2 and 5.2 and Statement 4 of Proposition 3.1, one can find a family of homotopic paths $[z_\ell, (q_1, s)]_P$ such that $s$ runs an interval on the trajectory $T_t(q_2)$. For sufficiently small $\varepsilon$, this interval contains a subinterval centered at $q_2$ of length $r - \delta > 0$. The desired result follows.

We now show that the map $P$ is topologically transitive; indeed, we prove a stronger statement.

Proposition 5.5. For almost every point $z \in \mathcal{N}$ the trajectory $\{P^n(z)\}$ is dense in $\mathcal{N}$ (i.e., $\{P^n(z)\} \supset \mathcal{N}$).

Proof. Consider a maximal set $E_0 \subset \mathcal{N}$ of points $z$ for which

1. $z$ is topologically recurrent, i.e., for any $r > 0$ there exits $n \in \mathbb{Z}$ such that $P^n(z) \in B(z, r)$;
2. for any $w \in E_0$ the points $z$ and $w$ are accessible;

Lemma 5.6. $m(E_0) = 1$.

Proof of the lemma. Since the set of topologically recurrent points has full measure the desired result follows from Propositions 5.3 and 5.4.
Lemma 5.7. There exists the set $E$ such that $m(E) = 1$, $E$ satisfies (5.2) and (5.3) as well as

\[(5.4) \forall z \in E \text{ the sets } V^\alpha_P(z) \cap E, \alpha \in \{-,+,\} \text{ have full measure with respect to the Riemannian volume on } V^\alpha_P(z).\]

**Proof of the lemma.** Given a set $F \subset M$ let

$$F^* = \{ z \in F \text{ such that } F \cap V^\alpha_P(z), \alpha \in \{+,\} \text{ have full measure with respect to the Riemann volume on } V^\alpha_P(z) \}. $$

Define inductively $E_n = E_{n-1}$. From the absolute continuity of $W^\pm_P$ we obtain using induction that $m(E_n) = 1$. Let $E = \bigcap_{n=0}^\infty E_n$. Then $m(E) = 1$ and (5.2) and (5.3) are satisfied since $E \subset E_0$. Also if $z \in E$ then for each $n z \in E_{n+1}$, so $V^\alpha_J(z) \cap E_n, \alpha \in \{+,\} \text{ have full measure. Thus } V^\alpha_J(z) \cap E$ has full measure. \qed

Choose any two points $z, w \in E$ and let $[z_0, \ldots, z_\ell]$ be a path connecting them.

**Lemma 5.8.** Given $\delta > 0$, there are points $z'_j \in E, j = 0, \ldots, \ell$ such that $z'_0 = z$, and $d(z_j, z'_j) \leq \delta$ for $j = 1, \ldots, \ell$.

**Proof of the lemma.** Without loss of generality we may assume that $z_1 \in V^+_P(z_0)$. If $z_1 \in E$ we set $z'_1 = z_1$. Otherwise, fix $0 < \delta_1 \leq \delta$ and let $z'_1 \in E$ be a point such that $z'_1 \in V^+_P(z_0)$ and $d(z_1, z'_1) \leq \delta_1$ (such a point exists for every $\delta_1$ in view of (5.4)). If $\delta_1$ is sufficiently small, for any $0 < \delta_2 \leq \delta_1$ one can find a point $z'_2 \in E$ such that $z'_2 \in V^-_P(z'_1)$ and $d(z_2, z'_2) \leq \delta_2$. Since the length of the path $\ell$ is uniformly bounded over $z$ and $w$ it remains to use induction to complete the proof. \qed

We proceed with the proof of the proposition. Choose $z, w \in E$ and let $z'_j \in E, j = 0, \ldots, \ell$ be points constructed in Lemma 5.8. Fix $\delta > 0$ and numbers $0 < \delta_1 < \cdots < \delta_\ell \leq \delta$. There is $m_1 > 0$ such that $d(P^{n_1}(z_0), P^{n_1}(z'_1)) \leq \frac{1}{2}\delta_1$ for every $n \geq m_1$. By (5.2), there is $n_1 \geq m_1$ for which $d(P^{n_1}(z_1), z_1) \leq \frac{1}{2}\delta_1$. It follows that $d(P^{n_1}(z_0), z'_1) \leq \delta_1$.

There is $m_2 > 0$ such that for every $n \geq m_2$, $d(P^{-n}(z'_1), P^{-n}(z'_2)) \leq \frac{1}{3}\delta_2$. By (5.2), there is $n_2 \geq m_2$ for which $d(P^{-n_2}(z'_2), z'_2) \leq \frac{1}{3}\delta_2$. It follows that $d(P^{-n_2}(z'_1), z'_2) \leq \frac{2}{3}\delta_2$. Note that if $\delta_1$ is chosen sufficiently small (depending only on $n_2$) and $n_1$ is chosen accordingly then $d(P^{n_1-n_2}(z_0), z'_2) \leq \delta_2$. Proceeding by induction we find numbers $n_i, i = 1, \ldots, \ell$ such that

$$d(P^{n_1-n_2+\cdots-n_\ell}(z_0), z'_\ell)) \leq \delta_\ell. $$

This implies that for almost every point $z \in \mathcal{N} \cap E$ the orbit $\{ P^n(z) \}$ is everywhere dense. The desired result for almost every point $z \in \mathcal{M}$ follows from Statement 2 of Proposition 4.1 and Statement 5 of Proposition 3.1. \qed

**VI. Proof of The Main Theorem: The Case dim$\mathcal{K} \geq 5$**

Consider the set $\mathcal{L}$ of points for which $\chi^c(z) < 0$ and hence, all values of the Lyapunov exponent at $z$ are nonzero. It is well-known that ergodic components of $P|\mathcal{L}$ have positive measure. Let $Q$ be such a component. In view of Statement 5 of Proposition 3.1 the set $Q \cap \mathcal{N}$ has positive measure. Let $z_0$ be a Lebesgue point of the set $Q \cap \mathcal{N}$. Fix $r > 0$ and consider the set $A$ defined by (5.2). Using Proposition 5.3 and applying the standard Hopf argument (see the proof of Theorem 13.1 in [BP]) one can show that $Q \supset A$ for sufficiently small $r$. This implies that $Q$ is open (mod 0) and so is the set $\mathcal{L}$. Applying Proposition 5.5
we conclude that $P|_{\mathcal{L}}$ is ergodic. Note that the same arguments can be used to show that the map $P^n$ is ergodic for all $n$. Hence, $P$ is a Bernoulli diffeomorphism. It also follows from Proposition 5.4 that $m(\mathcal{L}) = 1$.

Set $f = (\chi_1 \circ \chi_2) \circ P \circ (\chi_1 \circ \chi_2)^{-1}$ where the maps $\chi_1$ and $\chi_2$ are constructed in Proposition 3.4. It follows that the map $f$ satisfies all the desired properties.

Remark. Let us mention another approach for establishing ergodicity of $P$. Using the theory of invariant foliations one can show that if $P$ is sufficiently close to $R$ then $\tilde{W}^\pm(z, P)$ are uniformly close to $\tilde{W}^{u,s}(z, R)$ for all $z \in Z$. Let $\Omega \subset \mathcal{N}$ be such that there exist $\Omega^\alpha$, $\alpha = +, -$ which consist of the whole leaves of $\tilde{W}^\alpha(P)$ such that $m_{\mathcal{N}}(\Omega \Delta \Omega^\alpha) = 0$ (where $m_{\mathcal{N}}$ is the restriction of the Lebesgue measure to $\mathcal{N}$). It follows from [PS] that $m_{\mathcal{N}}(\Omega) = 0$ or $m_{\mathcal{N}}(\Omega) = 1$. Hence, if $\Lambda$ is a $P$-invariant set then $m(\Lambda \cap \mathcal{N}_z) = 0$ or $m(\Lambda \cap \mathcal{N}_z) = 1$ for almost all $z \in M$. It follows that $\Lambda$ factors down to a $g$-invariant set. This implies that $P$ is ergodic. In this paper we choose to present another proof since it extends to the case $\dim K = 3$ or 4 as we show below.

VII. Proof of The Main Theorem: The Case $\dim K = 3$ and 4

Consider the manifold $M = D^2 \times T^\ell$ where $\ell = 1$ if $\dim K = 3$ and $\ell = 2$ if $\dim K = 4$ and the skew product map $R$

$$R(z) = R(x, y) = (g(x), R_{\alpha(x)}(y)), \quad z = (x, y),$$

where the diffeomorphism $g$ is constructed in Proposition 1.1, $R_{\alpha(x)}$ the translation by $\alpha(x)$, and $\alpha : D^2 \to \mathbb{R}$ a non-negative $C^\infty$ function which is equal to zero on the set $\mathcal{U}$ (defined in Proposition 2.2) and is strictly positive otherwise.

We define the singularity set for the map $R$ by $S = Q \times T^\ell$, where $Q$ is the singularity set of the map $g$, and we also set $\mathcal{N} = (D^2 \setminus \mathcal{U}) \times T^\ell$ and $Z = X \times T^\ell$ (see Proposition 2.2).

As before we have four cone families $K^+_R(z), K^{+c}_R(z), K^-_R(z)$, and $K^{-c}_R(z)$ which satisfy (3.2) and (3.3).

We say that the map $R$ is robustly accessible if for all $p, q \in \mathcal{N}$ and any pair of foliations $\mathcal{F}^+$ and $\mathcal{F}^-$ which are close to $W^+_R$ and $W^-_R$ respectively, there exists a path $[p, q] = [z_0 z_1 \ldots z_{\ell}]$ such that $z_{j+1} \in \mathcal{F}^\alpha(z_j), \quad \alpha \in \{+,-\}$.

Proposition 7.1. The function $\alpha(x)$ (see (3.1)) can be chosen such that the map $R$ is robustly accessible.

Proof. By [B1] (see also [BW]), a generic skew product over multiplication by the map

$$\begin{pmatrix} 5 & 8 \\ 8 & 13 \end{pmatrix}$$

of $T^2$ is robustly accessible. Now the statement follows from Statement 1 of Lemma 1.2. \hfill $\square$

Choose the function $\alpha(x)$ such that $R$ is robustly accessible. Then any gentle perturbation of $R$ has the accessibility property. Repeating the proof of Proposition 5.5 we obtain the following result.

Corollary 7.2. Any gentle perturbation $P$ of $R$ which is sufficiently close to $R$ has no open invariant sets.
We consider a gentle perturbation $P$ of $R$ in the form $P = \varphi \circ R$. We wish to choose $\varphi$ such that
\[
\int_{\mathcal{M}} \log \det(dP|E_P^c)(z) \, dm(z) = -\rho < 0. \tag{7.2}
\]
Indeed, in the case $\mathcal{M} = \mathcal{D} \times S^1$, consider a coordinate system $\xi = \{\xi_1, \xi_2, \xi_3\}$ in a small neighborhood of a point $z_0$ such that
\begin{align*}
(1) & \quad dm = d\xi; \\
(2) & \quad E_R^c(z_0) = \frac{\partial}{\partial \xi_1}, \quad E_R^s(z_0) = \frac{\partial}{\partial \xi_2}, \quad E_R^u(z_0) = \frac{\partial}{\partial \xi_3}.
\end{align*}
Let $\psi(t)$ be a $C^\infty$ function with compact support. Set $\tau = \frac{\|\xi\|^2}{\gamma}$ and define
\[
\varphi^{-1}(\xi) = (\xi_1 \cos (\varepsilon \psi(\tau)) + \xi_2 \sin (\varepsilon \psi(\tau)), -\xi_1 \sin (\varepsilon \psi(\tau)) + \xi_2 \cos (\varepsilon \psi(\tau)), \xi_3).
\]
The proof of (7.2) is similar to the proof of Lemma 4.4 (with $\gamma$ chosen such that $\gamma \leq \varepsilon^3$). In the case $\mathcal{M} = \mathcal{D} \times T^2$ write $\mathcal{M} = (\mathcal{D} \times S^1) \times S^1$ and let $\varphi = \varphi \times 1$ where $\varphi$ is the above map (note that the distributions $E_R^s$, $E_R^u$, and $E_R^c$ are translation invariant).

In case $\dim \mathcal{K} = 3$ the remaining part of the proof repeats the arguments in the case $\dim \mathcal{K} \geq 5$ (see Propositions 5.1, 5.3, 5.4 and 5.5 and Section VI). Note that the embeddings $\chi_1 : \mathcal{M} \to B^3$ and $\chi_2 : B^3 \to \mathcal{K}$ should be chosen according to [BFK].

We now proceed with the case $\dim \mathcal{K} = 4$. We further perturb the map $P$ to $\bar{P}$ to obtain a set of positive measure on which $\bar{P}$ has three negative Lyapunov exponents.

**Proposition 7.3.** Suppose that the support of the map $\varphi$ is sufficiently small. Then for all positive $\varepsilon_1, \varepsilon_2$ there exists a gentle perturbation $\bar{P}$ of $P$ such that $d_{C^1}(P, \bar{P}) \leq \varepsilon_1$ and
\[
\int_{\mathcal{M}} \left[ \chi^c_1(z, \bar{P}) - \chi^c_2(z, \bar{P}) \right] \, dm(z) \leq \varepsilon_2,
\]
where $\chi^c_1(z, \bar{P}) \geq \chi^c_2(z, \bar{P})$ are the Lyapunov exponents of $\bar{P}$ along the subspace $E^c_P(z)$.

**Proof.** See Section VIII. \[\square\]

If $\varepsilon_1$ and $\varepsilon_2$ are sufficiently small then $\chi^c_1(z, \bar{P}) < 0$ and $\chi^c_2(z, \bar{P}) < 0$ on a set of positive measure. Indeed, by (7.2) there exist $\varepsilon_1 > 0$ and $C > 0$ such that for any gentle perturbation $\bar{P}$ of $P$ with $d_{C^1}(P, \bar{P}) \leq \varepsilon_1$ we have
\[
\int_{\mathcal{M}} (\chi^c_1(z, \bar{P}) + \chi^c_2(z, \bar{P})) \, dm \leq -\frac{\rho}{2}
\]
and $|\chi^c_1(z, \bar{P}) + \chi^c_2(z, \bar{P})| \leq C$. Hence, $\chi^c_1(z, \bar{P}) + \chi^c_2(z, \bar{P}) < -\frac{\rho}{4}$ on a set of measure at least $\frac{\rho}{4}$ and $\chi^c_1(z, \bar{P}) - \chi^c_2(z, \bar{P}) > \frac{\rho}{4}$ on a set of measure at most $\frac{8\varepsilon_3}{C}$.

To complete the proof one now proceeds as in the case $\dim \mathcal{K} \geq 5$.

**VIII. Almost Conformality**

We will prove Proposition 7.3. We follow the arguments in [M1, Bo] and split the proof in several steps. In what follows we adopt the following agreement: if at some step we use a statement of the type:
Therefore, the desired result holds for any $\varepsilon_j$ ($j = 1, \ldots, q$) are functions of $\varepsilon_{\ell_i}$ ($i = 1, \ldots, p$) satisfying the condition above.

Consider the set $D = \{z \in \mathcal{M} \setminus \mathcal{S} : \chi_i^1(z, P) \neq \chi_2^\epsilon(z, P)\}$. If $m(D) = 0$ the desired result follows (it suffices to choose $\tilde{P} = P$). From now on we assume that $m(D) > 0$. Let $E_1^c(z)$ and $E_2^c(z)$ be the one-dimensional Lyapunov directions corresponding to $\chi_1^1(z, P)$ and $\chi_2^\epsilon(z, P)$. They are defined for almost every $z \in D$.

**Lemma 8.1.** For every $\varepsilon_3 > 0$ there is a measurable function $n_0 : \mathcal{M} \setminus \mathcal{S} \to \mathbb{N}$ such that for any $z \in \mathcal{M} \setminus \mathcal{S}$ and two one-dimensional subspaces $E', E'' \in E_P^c(z)$ one can find maps

$$L_j(z, E', E'') : E_P^c(P^{j-1}(z)) \to E_P^c(P^{j}(z)), \quad 1 \leq j \leq n_0(z)$$

satisfying

1. $L_j(z, E', E'') = \mathbb{R}_{\beta_j(z, E', E'')} dP|E_P^c(z)$ where $\mathbb{R}_{\beta}$ denotes the rotation by angle $\beta$ and $\beta_j = \beta_j(z, E', E'')$ is such that
   $$\|\beta_j\| = \varepsilon_3, \quad \beta_j = 0 \text{ on } \mathcal{U}, \quad (8.1)$$
2. if
   $$\tilde{L}(z, E', E'') = L_{n_0(z)}(z, E', E'') \circ \cdots \circ L_1(z, E', E'')$$
   then $\tilde{L}(z, E', E'') E' = dP^{n_0(z)}(z)^{E''}$. \(\square\)

**Proof.** Let $A$ be the set of points $z \in \mathcal{M} \setminus \mathcal{S}$ for which the statements of Lemma 8.1 hold. It is easy to see that $A$ is invariant. Since the number $n_0(z)$ does not depend on the choice of subspaces $E'$ and $E''$ by continuity of $dP$ we find that the set $A$ is open. In view of Corollary 7.2 if $A$ is not empty it coincides with $\mathcal{M} \setminus \mathcal{S}$. We shall show that $A \neq \emptyset$.

Let $x \in D^2 \setminus Q$ be a periodic point of the map $g$ of period $r$ whose trajectory does not intersect $\text{supp}(\varphi)$ (such a point always exists if $\text{supp}(\varphi)$ is sufficiently small). We have that $P^r T^2(x) = T^2(x)$ where $T^2(x)$ is a fiber over $x$. Moreover, $P^r | T^2(x)$ is a translation. Therefore, the desired result holds for any $z \in T^2(x)$. \(\square\)

Given positive $\varepsilon_3, \varepsilon_4$, and $N$ define

$$D_1(\varepsilon_3, \varepsilon_4, N) = \{z \in \mathcal{M} : n_0(z, \varepsilon_3) \leq N, \quad \frac{1}{n} \log \|dP^n|E_1^c(z, P)\| - \chi_1^\epsilon(z, P) \leq \varepsilon_4, \quad \ell = 1, 2,$$

$$\angle(E_1^c(P^n(z), P), E_2^\epsilon(P^n(z), P)) \geq e^{-\varepsilon_4|n|} \text{ for any } |n| \geq N\}.$$

**Lemma 8.2.** For any positive $\varepsilon_3, \varepsilon_4, \varepsilon_5$ one can find $N_1 > 0$ such that for any $N \geq N_1$,

$$m(D \setminus D_1(\varepsilon_3, \varepsilon_4, N)) \leq \varepsilon_5.$$

**Proof.** The result follows from the Birkhoff ergodic theorem and Oseledec’ theorem. \(\square\)

Fix $z \in D_1(\varepsilon_3, \varepsilon_4, N)$. Since $\chi_1^\epsilon(z, P) \geq \chi_2^\epsilon(z, P)$ we obtain from the definition of the set $D_1(\varepsilon_3, \varepsilon_4, N)$ that for every point $z$ in this set, $v \in E_2^\epsilon(z, P)$, $\|v\| = 1$, and $|n| \geq N$,

$$\frac{1}{n} \log \|dP^n v\| - \chi_2^\epsilon(z, P) \leq \varepsilon_4 \quad (8.2)$$

and for $v \in E_1^\epsilon(z, P)$, $\|v\| = 1$ such that $\angle(v, E_2^\epsilon(z, P)) \geq e^{-\varepsilon_4}$, and $|n| \geq N$,

$$\frac{1}{n} \log \|dP^n v\| - \chi_1^\epsilon(z, P) \leq 2\varepsilon_4.$$

(8.3)
Lemma 8.3. For any positive $\varepsilon_3, \varepsilon_4, \varepsilon_6, \varepsilon_7$, and $N_2$ there exist positive $N_3$ and $\varepsilon_5$ such that

1. for any $\varepsilon_8 > 0$ and $N \geq N_3$ one can find a set $\Omega = \Omega(N)$ for which $P^j(\Omega) \cap \Omega = \emptyset$, $|j| \leq N$ and if $\Omega = \bigcup_{j=0}^N P^j(\Omega)$ then $m(D \setminus \Omega) \leq \varepsilon_8$;

2. if $D_2(\varepsilon_3, \varepsilon_4, \varepsilon_6, N, M) = \{ z \in \tilde{\Omega}: z = P^{j_0}(y) \text{ for some } y \in \Omega, |j_0| \leq N \}$ and maps $L_j(z) = L_j(z, E^c_1(z, P), E^c_2(z, P))$, $j = 1, \ldots, k \leq \varepsilon_6 N_3$ satisfying (8.1) and such that $\hat{L}(z) = L_k(z) \circ \cdots \circ L_1(z)$ moves $E^c_1(z, P)$ into $E^c_2(P^k(z), P)$. Then

$$\exp \left[ n \left( \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} - \varepsilon_9 \right) \right] \leq \left\| \left( dP^{n-k} \circ \hat{L}(z) \circ dP^{n_1} \right)e^c_P(\hat{P}^{-1}(z)) \right\| \leq \exp \left[ n \left( \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} + \varepsilon_9 \right) \right].$$

Proof. The first statement is just the Rokhlin-Halmos Lemma. Note that the measure of each set $R^j(\Omega)$ is of order $\frac{1}{N}$ and that the number

$$\text{Card} \left\{ j : \left| \frac{N - j}{j} - 1 \right| \leq \varepsilon_6 \right\}$$

is of order $\varepsilon_6 N$. The second statement follows.

Lemma 8.4. For any positive $\varepsilon_3, \varepsilon_4, \varepsilon_7$ there exist positive $\varepsilon_6$ such that the following statement holds. Fix $z \in D_1(\varepsilon_3, \varepsilon_4, N_1)$, positive $n_1, n_2$ satisfying

$$\left| \frac{n_2}{n_1} - 1 \right| \leq \varepsilon_6, \quad n = n_1 + n_2 \geq N_3,$$

and maps $L_j(z) = L_j(z, E^c_1(z, P), E^c_2(z, P))$, $j = 1, \ldots, k \leq \varepsilon_6 N_3$ satisfying (8.1) and such that $\hat{L}(z) = L_k(z) \circ \cdots \circ L_1(z)$ moves $E^c_1(z, P)$ into $E^c_2(P^k(z), P)$. Then

$$\exp \left[ n \left( \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} - \varepsilon_9 \right) \right] \leq \left\| \left( dP^{n-k} \circ \hat{L}(z) \circ dP^{n_1} \right)e^c_P(\hat{P}^{-1}(z)) \right\| \leq \exp \left[ n \left( \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} + \varepsilon_9 \right) \right].$$

Proof. Set

$$\mathcal{P} = dP^{n-k} \circ \hat{L}(z) \circ dP^{n_1} \cdot E^c_P(z).$$

Let $e_1 \in E^c_1(z, P)$ and $e_2 \in E^c_2(z, P)$ be a normalized basis in $E^c_P(z)$. Then by (8.2) and (8.3),

$$\frac{1}{n} \log \| \mathcal{P}e_\ell \| = \chi^c_\ell(z, P)n_1 + \chi^c_{3-\ell}(z, P)n_2 + O(\varepsilon_4 n)$$

for $\ell = 1, 2$. Let $\Pi(z) : E^c(z) \to E^c(z)$ be a linear map satisfying $\det \Pi(z) = 1$ and the vectors $\Pi(z)e_1$ and $\Pi(z)e_2$ are orthogonal. Then

$$\log \| \exp \left( n \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} \right) \mathcal{P} \| = \log \| \Pi^{-1}(P^n(z)) \| + \log \| \Pi(P^n(z)) \circ \exp \left( n \frac{\chi^c_1(z, P) + \chi^c_2(z, P)}{2} \right) \mathcal{P} \circ \Pi^{-1}(P^n(z)) \| + \log \| \Pi(P^{-n_1}(z)) \|$$

and each term is of order $O((\varepsilon_6 + \varepsilon_4)n)$. The desired result follows.
Lemma 8.5. For any positive \(\varepsilon_{10}, \varepsilon_{11}, \varepsilon_{12}, \varepsilon_{13}\) there exist positive \(\varepsilon_{3}, \varepsilon_{7}, \varepsilon_{9}, \text{ and } N_{2}\) such that the following holds. Let \(\Omega_{1} = \Omega \setminus D_{2}(\varepsilon_{3}, \varepsilon_{4}, N_{2}, N_{3})\) where \(\Omega = \Omega(N_{3})\) is a tower of height \(N_{3}\) and

\[\Omega_{2} = \{f^{j}(z) : z \in \Omega_{1} \text{ and } j \text{ is the smallest number for which } \left| \frac{N_{3} - j}{j} - 1 \right| \leq \varepsilon_{6} \text{ and } f^{j}(z) \in D_{1}(\varepsilon_{3}, \varepsilon_{4}, N_{2})\}.\]

Let also \(k = \varepsilon_{6}N_{3}\). Then

1. there exists an open set \(\Omega_{3}\) satisfying \(m(\Omega_{3} \Delta \Omega_{2}) \leq \varepsilon_{10}\) and a map \(\hat{P} = P \circ \hat{\varphi}\) such that
   \[\text{supp}(\hat{\varphi}) = \left( \bigcup_{j=0}^{k-1} \hat{P}^{j}(\Omega_{3}) \right) \setminus (\mathcal{U} \times T^2);\]

2. \(d_{C^{1}}(\hat{\varphi}, \text{Id}) \leq \varepsilon_{1};\)
3. there exists \(\Omega_{4} \subset \Omega_{2}\) such that \(m(\Omega_{2} \setminus \Omega_{4}) \leq \varepsilon_{11}\) and for all \(z \in \Omega_{4},\)
   \[\|d\hat{P}^{n}[E_{P}^{c}(z) - \hat{L}(z)]\| \leq \varepsilon_{12} \text{ for some } n \leq k,\]
   where \(\hat{L}(z) : E_{P}^{c}(z) \to E_{P}^{c}(P^{n}(z))\) moves \(E_{P}^{c}(z, P)\) to \(E_{P}^{c}(P^{n}(z), z)\) (see Lemma 8.4);
4. for any \(z \in \Omega,\)
   \[d(E_{P}^{c}(z), E_{P}^{c}(z)) \leq \varepsilon_{13}.\]

Proof. The proof is similar to [Bo]. Consider a finite atlas \(\Phi = \{\Phi_{1}, \ldots, \Phi_{n}\}\) such that in each chart \(\Phi_{i}\) one can introduce a coordinate system \(\{\xi_{1}, \xi_{2}, \xi_{3}, \xi_{4}\}\) satisfying

\[dm = d\xi_{1}d\xi_{2}d\xi_{3}d\xi_{4}.\]

Approximate \(\Omega_{2}\) by the finite union of balls \(\bigcup_{j} B(z_{j}, r_{j})\), with \(r_{j} \leq \rho\) where \(\rho\) is sufficiently small. By coordinate rotation we may assume that \(E_{P}^{c}(z_{j}) = \langle \frac{\partial}{\partial \xi_{1}}, \frac{\partial}{\partial \xi_{2}} > |z_{j} \rangle\). We can apply Lemma 8.4 to each \(z \in \Omega_{2}\) and construct the maps \(L_{1}(z), \ldots, L_{N_{1}}(z)\) such that \(\hat{L}(z) = L_{N_{1}}(z) \circ \cdots \circ L_{1}(z)\) moves \(E_{P}^{c}(z, P)\) to \(E_{P}^{c}(P^{n}(z), P)\). By slightly shrinking the set \(\Omega_{2}\) if necessary we may assume that the maps \(L_{i}(z)\) are continuous on \(\Omega_{2}\). Recall that each map \(L_{\ell}(w)\) is a twist of the form

\[L_{\ell}(w) = \mathbb{R}_{\beta_{i}(w)}(dP|E_{P}^{c}(w)).\]

We define \(\hat{\varphi}\) on each \(B(z_{j}, r_{j})\) to be

\[\hat{\varphi}(\xi_{1}, \xi_{2}, \xi_{3}, \xi_{4}) = \langle \mathbb{R}_{\psi(||\xi||/r_{j})\beta_{1}(z_{j})}^{\beta_{1}(z_{j})}(\eta_{1}, \eta_{2}), \xi_{3}, \xi_{4} \rangle,\]

where \(\{\eta_{1}, \eta_{2}, \eta_{3}, \eta_{4}\} = \exp_{z_{j}}^{-1}(\xi_{1}, \xi_{2}, \xi_{3}, \xi_{4})\) and the function \(\psi(x)\) is supported on \([0, 1]\) and

\[\psi(x) = 1, \quad x \in \left[0, \frac{1}{2}\right].\]
Continuing by induction for each \( \ell \leq N_1 \) we approximate the sets \( P^\ell(B(z_j, r_j)) \) by balls and define \( \hat{\phi} \) on each ball to be an appropriate twist generated by the maps \( L_\ell(z) \). This construction allows us to define \( \hat{\phi} \) in such a way that (8.4) holds for \( n = N_1 \) on a set \( \Delta_1 \) for which \( m(\Delta_1) > c(N_1)m(\Omega_2) \). Here \( c(N_1) \) is a constant which can be made arbitrary close to \( (\frac{1}{16})^{N_1} \) if the approximation by balls is chosen appropriately; we exploit here the fact that in view of (8.5)
\[
\frac{m(B(z, \frac{r}{2}))}{m(B(z, r))} = \frac{1}{16}.
\]
Consider a point \( z \in \Omega_2 \setminus \Delta_1 \). Let \( \tilde{N}_1(z) > N_1 \) be the first moment when the trajectory \( \{P^j(z)\} \) visits the set \( D_1 \). Define \( \hat{\phi} \) along the orbit \( \{f^{j+N_1}(z)\} \) with \( \tilde{N}_1(z) \leq j \leq \tilde{N}_1(z) + N_1 \) to be appropriate twists such that the map \( dP^{\tilde{N}_1(z)-N_1} \circ dP^{N_1} \) moves \( E_1^c(z, P) \) to \( dP^{\tilde{N}_1(z)} \circ dP^{N_1}E_2^c(z, P) \). Thus, we obtain a set \( \Delta_2 \) for which \( m(\Delta_2) > m(\Omega_2 \setminus \Delta_1) \geq c \) and \( n = N_1 + \tilde{N}_1(z) \) on \( \Delta_2 \). Repeating this procedure \( (N_2/N_1) \) times we obtain the required map \( \hat{\phi} \). All properties of the map \( \hat{P} \) can now be verified by the arguments similar to those in Lemma 4.4.

It remains to show that \( \varepsilon_{10}, \varepsilon_{11}, \varepsilon_{12}, \varepsilon_{13} \) can be chosen such that
\[
\left| \frac{1}{N_3} \log \| \hat{P}^{N_3}(z) |E_1^{c}(z)|| dm(z) - \frac{1}{2} \int_{\mathcal{M}} \log \det(d\hat{P}(z)|E_1^{c}(z)) dm(z) \right| \leq \varepsilon_2.
\]
This again is similar to the proof of Lemma 4.4 and we leave the details to the reader.

REFERENCES


Dmitry Dolgopyat
Department of Mathematics
The Pennsylvania State University
University Park, PA 16802
U.S.A.
Email: dolgop@math.psu.edu

Yakov Pesin
Department of Mathematics
The Pennsylvania State University
University Park, PA 16802
U.S.A.
Email: pesin@math.psu.edu