

GENERIC DYNAMICS OF 4-DIMENSIONAL C^2 HAMILTONIAN SYSTEMS

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ABSTRACT. We study the dynamical behaviour of Hamiltonian flows defined on 4-dimensional compact symplectic manifolds. We find the existence of a C^2 -residual set of Hamiltonians for which every regular energy surface is either Anosov or it is in the closure of energy surfaces with zero Lyapunov exponents a.e. This is in the spirit of the Bochi-Mañé dichotomy for area-preserving diffeomorphisms on compact surfaces [2] and its continuous-time version for 3-dimensional volume-preserving flows [1].

1. INTRODUCTION AND STATEMENT OF THE RESULTS

The computation of Lyapunov exponents is one of the main problems in the modern theory of dynamical systems. They give us fundamental information on the asymptotic exponential behaviour of the linearized system. It is therefore important to understand these objects in order to study the time evolution of orbits. In particular, Pesin's theory deals with non-vanishing Lyapunov exponents systems (non-uniformly hyperbolic). This setting jointly with a C^α regularity, $\alpha > 0$, of the tangent map allows us to derive a very complete geometric picture of the dynamics (stable/unstable invariant manifolds). On the other hand, if we aim at understanding both local and global dynamics, the presence of zero Lyapunov exponents creates lots of obstacles. The case of conservative systems is not different. As an example, the celebrated KAM theory guarantees persistence of invariant quasiperiodic motion on tori yielding zero Lyapunov exponents.

In this paper we study the dependence of the Lyapunov exponents on the dynamics of Hamiltonian flows. Despite the fact that the theory of Hamiltonian systems ask, in general, for more refined topologies, here we work in the framework of the C^1 topology of the Hamiltonian vector field. Our motivation comes from a recent result of Bochi [2] for area-preserving diffeomorphisms on compact surfaces, followed by its continuous time counterpart [1] for volume-preserving flows on compact 3-manifolds. We point out that these results are based on the outlined approach of Mañé [9, 10]. Furthermore, Bochi and Viana (see [3]) generalized the result in [2] and proved also a version for linear cocycles

and symplectomorphisms in any finite dimension. For a survey of the theory see [4] and references therein.

Here we prove that zero Lyapunov exponents for 4-dimensional Hamiltonian systems are very common, at least for a C^2 -residual subset. This picture changes radically for the C^∞ topology, the setting of most Hamiltonian systems coming from applications. In this case Markus and Meyer showed that there exists a residual of C^∞ Hamiltonians neither integrable nor ergodic [11].

Let (M, ω) be a compact symplectic manifold. We will be interested on the Hamiltonian dynamics of real-valued C^s , $2 \leq s \leq +\infty$, functions on M that are constant on the boundary ∂M . These functions are referred to as Hamiltonians on M and their set will be denoted by $C^s(M, \mathbb{R})$ which we endow with the C^2 -topology. Moreover, we include in this definition the case of M without boundary $\partial M = \emptyset$. We assume M and ∂M (when it exists) to be both smooth.

Given a Hamiltonian H , any scalar $e \in H(M) \subset \mathbb{R}$ is called an energy of H and $H^{-1}(\{e\}) = \{x \in M : H(x) = e\}$ the corresponding invariant energy level set. An energy surface \mathcal{E} is a connected component of $H^{-1}(\{e\})$. Notice that $\partial M \neq \emptyset$ corresponds to some energy surface. If in addition we fix a point p on the manifold M , we denote by $\mathcal{E}_p(H)$ the energy surface in $H^{-1}(\{H(p)\})$ passing through p .

Theorem 1. *Let (M, ω) be a 4-dim compact symplectic manifold. There exists a C^2 -residual subset \mathfrak{R} of $C^2(M, \mathbb{R})$ such that, if $H \in \mathfrak{R}$ and $p \in M$, then the Hamiltonian flow of H on $\mathcal{E}_p(H)$ is either*

- *Anosov, or else*
- *it is in the closure of energy surfaces with zero Lyapunov exponents a.e.*

A Hamiltonian flow is Anosov on an energy surface if its dynamic behaviour is uniformly hyperbolic when restricted to this set (cf. section 2.5). Geodesic flows on negative curvature surfaces are well-known systems yielding Anosov energy levels. An example of a mechanical system which is Anosov on each positive energy level was obtained by Hunt and MacKay [8].

We prove another dichotomy result for the transversal linear Poincaré flow on the tangent bundle (see section 2.3). This projected tangent flow can present a weaker form of hyperbolicity, a dominated splitting (see section 2.6).

Theorem 2. *Let (M, ω) be a 4-dimensional compact symplectic manifold. There exists a C^2 -dense subset \mathfrak{D} of $C^2(M, \mathbb{R})$ such that, if $H \in \mathfrak{D}$, there exists an invariant decomposition $M = D \cup Z \pmod{0}$ satisfying:*

- *$D = \bigcup_{n \in \mathbb{N}} D_{m_n}$, where D_{m_n} is a set with m_n -dominated splitting for the transversal linear Poincaré flow of H , and*

- *the Hamiltonian flow of H has zero Lyapunov exponents for $x \in Z$.*

The results above follow closely the strategy applied in [1] for volume-preserving flows. Besides the decomposition of the manifold into invariant sets for each energy, the main novelty here is the construction of Hamiltonian perturbations. Once those are built, we use abstract arguments developed in [2] and [1] to conclude the proofs. Nevertheless, for completeness, we will present all the ingredients in the Hamiltonian framework.

At this point it is interesting to recall a related C^2 -generic dichotomy by Newhouse [13]. That states the existence of a C^2 -residual set of all Hamiltonians on a compact symplectic $2d$ -manifold, for which an energy surface through any $p \in M$ is Anosov or is in the closure of 1-elliptical periodic orbits. For another related result, in the topological point of view, we mention a recent theorem by Vivier [17]: any 4-dimensional Hamiltonian vector field admitting a robustly transitive regular energy surface is Anosov.

In section 2 we introduce the main tools for the proofs of the above theorems (section 3). These are based on Proposition 3.1 for which we devote the rest of the paper. The fundamental point is the construction of the perturbations of the Hamiltonian in section 4. Finally, we conclude the proof in section 5 by an abstract construction already contained in [1], which works equally in the present setting.

2. PRELIMINARIES

2.1. Basic notions. Let M be a $2d$ -dimensional manifold endowed with a symplectic structure, i.e. a closed and nondegenerate 2-form ω . The pair (M, ω) is called a symplectic manifold which is also a volume manifold by Liouville's theorem. Let μ be the so-called Lebesgue measure associated to the volume form $\omega^d = \omega \wedge \cdots \wedge \omega$.

A diffeomorphism $g: (M, \omega) \rightarrow (N, \omega')$ between two symplectic manifolds is called a symplectomorphism if $g^*\omega' = \omega$. The action of a diffeomorphism on a 2-form is given by the pull-back $(g^*\omega')(X, Y) = \omega'(g_*X, g_*Y)(g)$. Here X and Y are vector fields on M and the push-forward $g_*X = DgX$ is a vector field on N . Notice that a symplectomorphism $g: M \rightarrow M$ preserves the Lebesgue measure μ since $g^*\omega^d = \omega^d$.

For any smooth Hamiltonian function $H: M \rightarrow \mathbb{R}$ there is a corresponding Hamiltonian vector field $X_H: M \rightarrow TM$ determined by $\iota_{X_H}\omega = dH$ being exact, where $\iota_v\omega = \omega(v, \cdot)$ is a 1-form. Notice that H is C^s iff X_H is C^{s-1} . The Hamiltonian vector field generates the Hamiltonian flow, a smooth 1-parameter group of symplectomorphisms φ_H^t on M satisfying $\frac{d}{dt}\varphi_H^t = X_H \circ \varphi_H^t$ and $\varphi_H^0 = \text{id}$. Since $dH(X_H) = \omega(X_H, X_H) = 0$, X_H is tangent to the energy level sets

$H^{-1}(e)$. In addition, the Hamiltonian flow is globally defined with respect to time because $H|_{\partial M}$ is constant or, equivalently, X_H is tangent to ∂M .

If $v \in T_x H^{-1}(e)$, i.e. $dH(v)(x) = \omega(X_H, v)(x) = 0$, then its push-forward by φ_H^t is again tangent to $H^{-1}(e)$ on $\varphi_H^t(x)$ since

$$dH(D\varphi_H^t v)(\varphi_H^t(x)) = \omega(X_H, D\varphi_H^t v)(\varphi_H^t(x)) = \varphi_H^{t*} \omega(X_H, v)(x) = 0.$$

We consider also the tangent flow $D\varphi_H^t : TM \rightarrow TM$ that satisfies the linear variational equation (the linearized differential equation)

$$\frac{d}{dt} D\varphi_H^t = DX_H(\varphi_H^t) D\varphi_H^t$$

with $DX_H : M \rightarrow TTM$.

We say that x is a *regular* point if $dH(x) \neq 0$ (x is not critical). We denote the set of regular points by $\mathcal{R}(H)$ and the set of critical points by $\text{Crit}(H)$. We call $H^{-1}(e)$ a regular energy level of H if $H^{-1}(e) \cap \text{Crit}(H) = \emptyset$. A regular energy surface is a connected component of a regular energy level.

Given any regular energy level or surface \mathcal{E} , we induce a volume form $\omega_{\mathcal{E}}$ on the $(2d-1)$ -dimensional manifold \mathcal{E} in the following way. For each $x \in \mathcal{E}$,

$$\omega_{\mathcal{E}}(x) = \iota_Y \omega^d(x) \quad \text{on } T_x \mathcal{E},$$

defines a $(2d-1)$ non-degenerate form if $Y \in T_x M$ satisfies $dH(Y)(x) = 1$, i.e. transversal to \mathcal{E} . Notice that this definition does not depend on Y (up to normalization) as long as it is transversal to \mathcal{E} at x . Moreover, $dH(D\varphi_H^t Y)(\varphi_H^t(x)) = d(H \circ \varphi_H^t)(Y)(x) = 1$. Thus, $\omega_{\mathcal{E}}$ is φ_H^t -invariant, and the measure $\mu_{\mathcal{E}}$ induced by $\omega_{\mathcal{E}}$ is again invariant. In order to obtain finite measures, we need to consider compact energy levels.

On the manifold M we also fix any Riemannian structure which induces a norm $\|\cdot\|$ on the fibers $T_x M$. We will use the standard norm of a bounded linear map A given by $\|A\| = \sup_{\|v\|=1} \|Av\|$.

The symplectic structure guarantees by Darboux theorem the existence of an atlas $\{h_j : U_j \rightarrow \mathbb{R}^{2d}\}$ satisfying $h_j^* \omega_0 = \omega$ with

$$\omega_0 = \sum_{i=1}^d dy_i \wedge dy_{d+i}. \quad (2.1)$$

On the other hand, when dealing with volume manifolds (N, Ω) of dimension p , Moser's theorem [12] gives an atlas $\{h_j : U_j \rightarrow \mathbb{R}^p\}$ such that $h_j^*(dy_1 \wedge \cdots \wedge dy_p) = \Omega$.

2.2. Oseledets' theorem for 4-dim Hamiltonian systems. Unless indicated, for the rest of this paper we fix a 4-dimensional compact symplectic manifold (M, ω) . Take $H \in C^2(M, \mathbb{R})$. Since the time-1 map of any tangent flow derived from a Hamiltonian vector field is measure invariant, we obtain a version of Oseledets' theorem [14] for

Hamiltonian systems. Given μ -a.e. point $x \in M$ we have two possible splittings:

(1) $T_x M = E_x$ with E_x 4-dimensional and

$$\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|D\varphi_H^t(x) v\| = 0, \quad v \in E_x.$$

(2) $T_x M = E_x^+ \oplus E_x^- \oplus E_x^0 \oplus \mathbb{R}X_H(x)$, where $\mathbb{R}X_H(x)$ denotes the vector field direction, each one of these subspaces being 1-dimensional and

- $\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|D\varphi_H^t(x)|_{E_x^0 \oplus \mathbb{R}X_H(x)}\| = 0$;
- $\lambda^+(H, x) = \lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|D\varphi_H^t(x)|_{E_x^+}\| > 0$;
- $\lambda^-(H, x) = \lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|D\varphi_H^t(x)|_{E_x^-}\| < 0$.

Moreover,

$$\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log |\det D\varphi_H^t(x)| = \sum_{i \in \{0, +, -\}} \lambda^i(H, x) \dim(E_x^i). \quad (2.2)$$

The splitting of the tangent bundle is called *Oseledets splitting* and the real numbers $\lambda^\pm(H, x)$ are called the *Lyapunov exponents*. In the case (1) we say that the Oseledets splitting is trivial. The full measure set of the *Oseledets points* is denoted by $\mathcal{O}(H)$.

The vector field direction $\mathbb{R}X_H(x)$ is trivially an Oseledets's direction with zero Lyapunov exponent. It is a well-known fact that the spectrum of a linear symplectomorphism, and in particular $D\varphi_H^t(x)$, is symmetric. Thus the Lyapunov exponents are symmetric: $\lambda^-(H, x) = -\lambda^+(H, x)$, equal to zero in the conjugated direction E^0 to X_H .

2.3. The transversal linear Poincaré flow of a Hamiltonian.

For each $x \in \mathcal{R}$ (we omit H when there is no ambiguity) take the orthogonal splitting $T_x M = \mathbb{R}X_H(x) \oplus N_x$, where $N_x = (\mathbb{R}X_H(x))^\perp$ is the normal fiber at x . Consider the automorphism of vector bundles

$$\begin{aligned} D\varphi_H^t: T_{\mathcal{R}} M &\rightarrow T_{\mathcal{R}} M \\ (x, v) &\mapsto (\varphi_H^t(x), D\varphi_H^t(x) v). \end{aligned} \quad (2.3)$$

Of course that, in general, the subbundle $N_{\mathcal{R}}$ is not $D\varphi_H^t$ -invariant. So we relate to the $D\varphi_H^t$ -invariant quotient space $\tilde{N}_{\mathcal{R}} = T_{\mathcal{R}} M / \mathbb{R}X_H(\mathcal{R})$ with an isomorphism $\phi_1: N_{\mathcal{R}} \rightarrow \tilde{N}_{\mathcal{R}}$ (which is also an isometry). The unique map

$$P_H^t: N_{\mathcal{R}} \rightarrow N_{\mathcal{R}}$$

such that $\phi_1 \circ P_H^t = D\varphi_H^t \circ \phi_1$ is called the *linear Poincaré flow* for H . Denoting by $\Pi_x: T_x M \rightarrow N_x$ the canonical projection, the linear map $P_H^t(x): N_x \rightarrow N_{\varphi_H^t(x)}$ is

$$P_H^t(x) v = \Pi_{\varphi_H^t(x)} \circ D\varphi_H^t(x) v.$$

We now consider

$$\mathcal{N}_x = N_x \cap T_x H^{-1}(e),$$

where $T_x H^{-1}(e) = \ker dH(x)$ is the tangent space to the energy level set with $e = H(x)$. Thus, $\mathcal{N}_{\mathcal{R}}$ is invariant under P_H^t . So we define the map

$$\Phi_H^t: \mathcal{N}_{\mathcal{R}} \rightarrow \mathcal{N}_{\mathcal{R}}, \quad \Phi_H^t = P_H^t|_{\mathcal{N}_{\mathcal{R}}},$$

called the *transversal linear Poincaré flow* for H such that

$$\Phi_H^t(x): \mathcal{N}_x \rightarrow \mathcal{N}_{\varphi_H^t(x)}, \quad \Phi_H^t(x) v = \Pi_{\varphi_H^t(x)} \circ D\varphi_H^t(x) v$$

is a linear symplectomorphism for the symplectic form induced on $\mathcal{N}_{\mathcal{R}}$ by ω .

If $x \in \mathcal{R} \cap \mathcal{O}$, the Oseledets splitting on $T_x M$ induces a $\Phi_H^t(x)$ -invariant splitting $\mathcal{N}_x = \mathcal{N}_x^+ \oplus \mathcal{N}_x^-$ where $\mathcal{N}_x^\pm = \Pi_x(E_x^\pm)$.

2.4. Lyapunov exponents. Our next lemma explicits that the dynamics of $D\varphi_H^t$ and Φ_H^t are coherent so that the Lyapunov exponents for both cases are related.

Lemma 2.1. *Given $x \in \mathcal{R} \cap \mathcal{O}$, the Lyapunov exponents of the Φ_H^t -invariant decomposition are equal to the ones of the $D\varphi_H^t$ -invariant decomposition.*

Proof. If the Oseledets' splitting is trivial there is nothing to prove. Otherwise, equation (2.2) implies subexponential decrease of the angle α_t at time t between any subspaces of the Oseledets' splitting along μ -a.e. orbits:

$$\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log(\sin \alpha_t) = 0. \quad (2.4)$$

Let

$$n^+ = \alpha X_H(x) + v^+ \in \mathcal{N}_x^+$$

with $v^+ \in E_x^+$ and $\alpha \in \mathbb{R}$. We want to study the asymptotic behavior of $\|\Phi_H^t(x) n^+\|$. From the following two equalities

- $\Pi_{\varphi_H^t(x)} D\varphi_H^t(x) X_H(x) = \Pi_{\varphi_H^t(x)} X_H \circ \varphi_H^t(x) = 0$,
- $\|\Pi_{\varphi_H^t(x)} D\varphi_H^t(x) v^+\| = \sin(\theta_t) \|D\varphi_H^t(x) v^+\|$,

we get

$$\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|\Phi_H^t(x) n^+\| = \lim_{t \rightarrow \pm\infty} \frac{1}{t} \log [\sin(\theta_t) \|D\varphi_H^t(x) v^+\|],$$

where θ_t is the angle between $X_H \circ \varphi_H^t(x)$ and $E_{\varphi_H^t(x)}^+$. By (2.4), we obtain

$$\begin{aligned} \lim_{t \rightarrow \pm\infty} \frac{1}{t} \log [\sin(\theta_t) \|D\varphi_H^t(x) v^+\|] &= \lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|D\varphi_H^t(x) v^+\| \\ &= \lambda^+(H, x). \end{aligned}$$

We proceed analogously for \mathcal{N}_x^- . □

Below we state the Oseledets theorem for the transversal linear Poincaré flow.

Theorem 2.2. *Let $H \in C^2(M, \mathbb{R})$. For μ -a.e. $x \in M$ there exists the upper Lyapunov exponent*

$$\lambda^+(H, x) = \lim_{t \rightarrow +\infty} \frac{1}{t} \log \|\Phi_H^t(x)\| \geq 0$$

and $x \mapsto \lambda^+(H, x)$ is measurable. For μ -a.e. x with $\lambda^+(H, x) > 0$, there is a splitting $\mathcal{N}_x = \mathcal{N}_x^+ \oplus \mathcal{N}_x^-$ which varies measurably with x such that:

$$\lim_{t \rightarrow \pm\infty} \frac{1}{t} \log \|\Phi_H^t(x) v\| = \begin{cases} \lambda^+(H, x), & v \in \mathcal{N}_x^+ \setminus \{0\} \\ -\lambda^+(H, x), & v \in \mathcal{N}_x^- \setminus \{0\} \\ \pm\lambda^+(H, x), & v \notin \mathcal{N}_x^+ \cup \mathcal{N}_x^- \end{cases}$$

2.5. Hyperbolic structure. Let $H \in C^2(M, \mathbb{R})$. Given any compact and φ_H^t -invariant set $\Lambda \subset H^{-1}(e)$, we say that Λ is a *hyperbolic set* for φ_H^t if there exist $m \in \mathbb{N}$ and a $D\varphi_H^t$ -invariant splitting $T\Lambda = E^+ \oplus E^- \oplus E$ such that for all $x \in \Lambda$ we have:

- $\|D\varphi_H^m(x)|_{E_x^-}\| \leq \frac{1}{2}$ (uniform contraction),
- $\|D\varphi_H^{-m}(x)|_{E_x^+}\| \leq \frac{1}{2}$ (uniform expansion)
- and E is the direction of the vector field and its conjugated space.

If Λ is a regular energy surface, then $\varphi_H^t|_\Lambda$ is said to be *Anosov*. Notice that there are no minimal hyperbolic sets larger than energy level sets.

Similarly, we can define a hyperbolic structure for the linear Poincaré flow Φ_H^t . The next lemma relates the hyperbolicity of Φ_H^t with the hyperbolicity of the tangent flow. It is an immediate consequence of a result by Doering [7] for the linear Poincaré flow extended to our Hamiltonian setting and the transversal linear Poincaré flow.

Lemma 2.3. *Let Λ be an φ_H^t -invariant and compact set. Then Λ is hyperbolic for φ_H^t iff Λ is hyperbolic for Φ_H^t .*

We end this section with a well-known result about the measure of hyperbolic sets for C^2 (or more general C^{1+}) dynamical systems, proved by Bowen [6], Bochi-Viana [4] and Bessa [1] in several contexts. Here it is stated for Hamiltonian functions, meaning a higher differentiability degree.

Lemma 2.4. *Let $H \in C^3(M, \mathbb{R})$ and a regular energy surface \mathcal{E} . If $\Lambda \subset \mathcal{E}$ is hyperbolic, then $\mu_{\mathcal{E}}(\Lambda) = 0$ or $\Lambda = \mathcal{E}$ (i.e. Anosov).*

2.6. Dominated splitting. We now study a weaker form of hyperbolicity. Let $\Lambda \subset M$ be an φ_H^t -invariant set. A splitting of the bundle $\mathcal{N}_\Lambda = \mathcal{N}_\Lambda^- \oplus \mathcal{N}_\Lambda^+$ has a *dominated splitting* for the transversal linear

Poincaré flow if it is Φ_H^t -invariant, continuous and we may find a *uniform* $m \in \mathbb{N}$ such that

$$\frac{\|\Phi_H^m(x)|\mathcal{N}_x^-\|}{\|\Phi_H^m(x)|\mathcal{N}_x^+\|} \leq \frac{1}{2}, \quad x \in \bar{\Lambda}. \quad (2.5)$$

If Λ has a dominated splitting, then we may extend the splitting to its closure, except to critical points. Moreover, the angle between \mathcal{N}^- and \mathcal{N}^+ is bounded away from zero on Λ . Due to our low dimensional assumption, the decomposition is unique. For more details about dominated splitting see [5].

The above definition of dominated splitting is equivalent to the existence of $C > 0$ and $0 < \theta < 1$ so that

$$\frac{\|\Phi_H^t(x)|\mathcal{N}_x^-\|}{\|\Phi_H^t(x)|\mathcal{N}_x^+\|} \leq C\theta^t, \quad x \in \bar{\Lambda}, \quad t \geq 0. \quad (2.6)$$

The proof of the next lemma hints to the fact that the 4-dimensional setting is crucial in obtaining hyperbolicity from the dominated splitting structure.

Lemma 2.5. *Let $H \in C^2(M, \mathbb{R})$ and a regular energy surface \mathcal{E} . If $\Lambda \subset \mathcal{E}$ has a dominated splitting for Φ_H^t , then $\bar{\Lambda}$ is hyperbolic.*

Proof. Since \mathcal{E} is compact it is at a fixed distance away from critical points, hence there is $K > 1$ such that

$$\frac{1}{K} \leq \|X_H(x)\| \leq K, \quad x \in \mathcal{E}.$$

On the other hand, because X_H is volume-preserving on the 3-dimensional submanifold \mathcal{E} , we get

$$\sin(\gamma_0) \|X_H(x)\| = \sin(\gamma_t) \|X_H \circ \varphi_H^t(x)\| \frac{\|\Phi_H^t(x)|\mathcal{N}_x^+\|}{\|\Phi_H^t(x)|\mathcal{N}_x^-\|}. \quad (2.7)$$

Here γ_t is the angle between the subspaces \mathcal{N}^- and \mathcal{N}^+ at $\varphi_H^t(x)$, which is bounded from below by some $\beta > 0$ for any $x \in \bar{\Lambda}$. We can now rewrite (2.7) as

$$\begin{aligned} \|\Phi_H^t(x)|\mathcal{N}_x^-\|^2 &= \frac{\sin(\gamma_0)}{\sin(\gamma_t)} \frac{\|X_H(x)\|}{\|X_H \circ \varphi_H^t(x)\|} \frac{\|\Phi_H^t(x)|\mathcal{N}_x^-\|}{\|\Phi_H^t(x)|\mathcal{N}_x^+\|} \\ &\leq K^2 \frac{\sin(\gamma_0)}{\sin(\beta)} C\theta^t, \end{aligned}$$

where we also have used (2.6). Thus we have uniform contraction on \mathcal{N}_x^- .

The above procedure can be adapted for \mathcal{N}_x^+ to find uniform expansion, hence $\bar{\Lambda}$ is hyperbolic for Φ_H^t . Lemma 2.3 concludes the proof. \square

Combining Lemmas 2.4 and 2.5 we get the following.

Proposition 2.6. *Let $H \in C^3(M, \mathbb{R})$ and a regular energy surface \mathcal{E} . If $\Lambda \subset \mathcal{E}$ has a dominated splitting for Φ_H^t , then $\mu_{\mathcal{E}}(\Lambda) = 0$ or Λ is Anosov.*

In particular, there is a C^2 -dense set of C^2 -Hamiltonians for which the above holds.

Remark 2.7. *It is an open problem to decide whether for every $H \in C^3(M, \mathbb{R})$ the following holds: an invariant set Λ containing critical points of H and admitting a dominated splitting can only be of zero measure or Anosov.*

3. PROOF OF THE MAIN THEOREMS

3.1. Integrated Lyapunov exponent. Let $H \in C^2(M, \mathbb{R})$. We take any measurable φ_H^t -invariant subset Γ of M and we define the integrated upper Lyapunov exponent over Γ by

$$\text{LE}(H, \Gamma) = \int_{\Gamma} \lambda^+(H, x) d\mu(x). \quad (3.1)$$

The sequence

$$a_n(H) = \int_{\Gamma} \log \|\Phi_H^n(x)\| d\mu(x)$$

is subadditive ($a_{n+m} \leq a_n + a_m$), hence $\lim_{n \rightarrow \infty} \frac{a_n(H)}{n} = \inf_{n \geq 1} \frac{a_n(H)}{n}$. That is,

$$\text{LE}(H, \Gamma) = \inf_{n \geq 1} \frac{1}{n} \int_{\Gamma} \log \|\Phi_H^n(x)\| d\mu(x). \quad (3.2)$$

Since $H \mapsto \frac{1}{n} \int_{\Gamma} \log \|\Phi_H^n(x)\| d\mu(x)$ is continuous for each n , we conclude that $\text{LE}(\cdot, \Gamma)$ is upper semicontinuous for any C^2 Hamiltonians having a common invariant set Γ .

3.2. Decay of Lyapunov exponent. For a given Hamiltonian H we define the open set

$$\Gamma_m(H) = M \setminus D_m(H),$$

where $D_m(H)$ has m -dominated splitting for Φ_H^t . This means that $\Gamma_m(H)$ is the set of points absent of m -dominated splitting. Furthermore, fixed $m \in \mathbb{N}$, there exists $\tilde{m} \in \mathbb{N}$ such that for all $m' \geq \tilde{m}$ we have $\Gamma_{m'}(H) \subset \Gamma_m(H)$. On the other hand, if $H' = H$ on $D_m(H)$, then $\Gamma_m(H') \subset \Gamma_m(H)$. The equivalent relations for $D_m(H)$ are immediate.

The next proposition is fundamental because it allows us to decay the integrated Lyapunov exponent over a full measure subset of $\Gamma_m(H)$.

Proposition 3.1. *Let $H \in C^2(M, \mathbb{R})$ and $\epsilon, \delta > 0$. Then there exists $m \in \mathbb{N}$ and $\tilde{H} \in C^\infty(M, \mathbb{R})$, ϵ - C^2 -close to H , such that $\tilde{H} = H$ on $D_m(H)$ and*

$$\text{LE}(\tilde{H}, \Gamma_m(H)) < \delta. \quad (3.3)$$

Notice that it is enough to show the result for $H \in C^\infty(M, \mathbb{R})$ since C^∞ is C^2 -dense in C^s , $s \geq 2$. Moreover, we assume that

$$\text{LE}(H, \Gamma_m(H)) > 0,$$

otherwise the claim holds trivially. We postpone the proof of this proposition to section 5 and complete the ones of our main results.

3.3. Proof of Theorem 1. Here we look at the product set

$$\mathcal{M} = M \times C^2(M, \mathbb{R})$$

endowed with the standard product topology. The subset

$$A = \{(p, H) \in \mathcal{M} : \mathcal{E}_p(H) \text{ is Anosov}\}$$

is open by structural stability of Anosov systems. Moreover, for each $(p, H) \in A$ there is a tubular neighbourhood of $\mathcal{E}_p(H)$ in M , consisting of regular energy surfaces supporting Anosov flows.

On the complementary of the closure of A , denoted by

$$B = \mathcal{M} \setminus \overline{A},$$

we can measure the distance in energy of its points to A . More specifically, there is a continuous positive function

$$\eta : B \rightarrow \mathbb{R}^+$$

guaranteeing for $(p, H) \in B$ that $\mathcal{V}_{\eta(p, H)}$ is a connected component of

$$\bigcup_{x \in M : |H(x) - H(p)| < \eta(p, H)} \mathcal{E}_x(H)$$

containing p and made entirely of non-Anosov energy surfaces.

Now, for each $k \in \mathbb{N}$ write

$$A_k = \left\{ (p, H) \in B : \text{LE}(H, \mathcal{V}_{\eta(p, H)}) < \frac{1}{k} \right\}.$$

This is an open set because the function in its definition is upper semi-continuous.

Lemma 3.2. A_k is dense in B .

Proof. Let $(p, H) \in B$. We want to find an arbitrarily close pair (p, H) in A_k . Notice that we will not need to approximate on the first component, the point on the manifold, but only on the Hamiltonian.

By Robinson's version of the Kupka-Smale theorem [15] there exists a set KS of C^r -Hamiltonians, $r \geq 2$, with finite critical points. Since C^r functions are C^2 -dense in C^2 , it is sufficient to prove the claim by restricting to $(M \times \text{KS}) \cap B$. Moreover, small perturbations of a Hamiltonian in KS will have regular energy surfaces through p . Therefore, we have a dense subset $D \subset M \times \text{KS}$ such that $\mathcal{E}_p(H)$ is regular for $(p, H) \in D$ and away from Anosov. This means that in fact we only need to show the claim for D .

Let $(p, \widehat{H}) \in D$ and $\varepsilon > 0$ such that $(p, \widetilde{H}) \in \mathcal{V}_{\eta(p, \widehat{H})} \subset B$ for any \widetilde{H} that is ε - C^2 -close to \widehat{H} . Proposition 3.1 guarantees that for all $\delta > 0$ we find $H \in C^\infty(M, \mathbb{R})$ which is ε - C^2 -close to \widehat{H} and satisfying $H = \widehat{H}$ on $D_m(\widehat{H})$ (hence $\Gamma_m(H) \subset \Gamma_m(\widehat{H})$) and

$$\text{LE}(H, \Gamma_m(\widehat{H})) < \delta.$$

Notice that $\mu(\Gamma_m(H) \cap \mathcal{V}_{\eta(p, H)}) = \mu(\mathcal{V}_{\eta(p, H)})$ for all $m \in \mathbb{N}$. Otherwise, if there was an energy surface $\mathcal{E} \subset \mathcal{V}_{\eta(p, H)}$ and $m \in \mathbb{N}$ such that $\mu_{\mathcal{E}}(D_m(H) \cap \mathcal{E}) > 0$, by Proposition 2.6 it would be Anosov, thus contradicting that $(p, H) \in B$.

Therefore, since the upper Lyapunov exponent is non-negative,

$$\begin{aligned} \text{LE}(H, \mathcal{V}_{\eta(p, H)}) &= \text{LE}(H, \Gamma_m(H) \cap \mathcal{V}_{\eta(p, H)}) \\ &\leq \text{LE}(H, \Gamma_m(\widehat{H})) < \delta. \end{aligned} \tag{3.4}$$

The choice $\delta = 1/k$ yields $(p, H) \in A_k$. \square

From the above, $A \cup A_k$ is open and dense. Finally,

$$\begin{aligned} \mathfrak{A} &= \bigcap_{k \in \mathbb{N}} (A \cup A_k) = A \cup \bigcap_{k \in \mathbb{N}} A_k \\ &= A \cup \left\{ (p, H) \in B : \int_{\mathcal{V}_{\eta(p, H)}} \lambda^+(H, x) d\mu(x) = 0 \right\} \end{aligned}$$

is residual. We can thus write $\mathfrak{A} = \mathfrak{M} \times \mathfrak{R}$, where \mathfrak{M} is residual in M and \mathfrak{R} is C^2 -residual in $C^2(M, \mathbb{R})$, having the following property: if $p \in \mathfrak{M}$ and $H \in \mathfrak{R}$, then $\mathcal{E}_p(H)$ is Anosov or

$$\int \int \lambda^+ d\mu_{\mathcal{E}} dH = 0.$$

The latter implies that dH -a.e. the Lyapunov exponents on each energy surface \mathcal{E} in \mathcal{V}_{η} are $\mu_{\mathcal{E}}$ -a.e. equal to zero. Recall that we can split the measure μ into $\mu_{\mathcal{E}}$ on the energy surfaces and dH corresponding to the 1-form transversal to \mathcal{E} .

The above can easily be extended to hold for every $p \in M$. That completes the proof of Theorem 1.

3.4. Proof of Theorem 2. It is enough to show that we can arbitrarily C^2 -approximate any $H \in C^\infty(M, \mathbb{R})$ by $H' \in C^2(M, \mathbb{R})$ satisfying

$$\text{LE}(H', Z) = 0$$

for some Z to be determined, without domination and whose mod 0-complementary is dominated. We use an inductive scheme built on (3.3) and the fact that $\text{LE}(\cdot, \Gamma)$ is an upper semicontinuous function, to define a convenient sequence $H_n \in C^\infty(M, \mathbb{R})$ with C^2 -limit H' .

Choose $\epsilon_n = \epsilon_0 2^{-n}$ for some $\epsilon_0 > 0$. By Proposition 3.1 we construct the sequence of Hamiltonians H_n in the following way:

- (1) $H_0 = H$,
- (2) H_n and H_{n-1} are ϵ_n - C^2 -close,
- (3) $H_n = H_{n-1}$ on $D_{m_n}(H_{n-1})$,
- (4) $\text{LE}(H_n, \Gamma_{m_n}(H_{n-1})) \leq 2^{-n}$.

That is, each term H_n of the sequence is the perturbation of the previous one H_{n-1} as given by Proposition 3.1. Then, the C^2 -limit H' exists and is ϵ_n - C^2 -close to any H_n .

Because $\text{LE}(\cdot, \Gamma)$ is upper semicontinuous, for any $\theta > 0$ we can find $\eta > 0$ such that

$$\text{LE}(H', \Gamma) \leq (1 + \theta) \text{LE}(H_*, \Gamma)$$

as long as H' and H_* are η - C^2 -close.

Take now $\epsilon_0 < 2\eta$. So, for any $n \in \mathbb{N}$,

$$\begin{aligned} \text{LE}(H', \cap_i \Gamma_{m_i}(H_{i-1})) &\leq \text{LE}(H', \Gamma_{m_n}(H_{n-1})) \\ &\leq (1 + \theta) \text{LE}(H_n, \Gamma_{m_n}(H_{n-1})) \\ &\leq (1 + \theta) 2^{-n}. \end{aligned}$$

Therefore, $\text{LE}(H', \cap_i \Gamma_{m_i}(H_{i-1})) = 0$ and the Lyapunov exponents vanish on

$$Z = \bigcap_{i \in \mathbb{N}} \Gamma_{m_i}(H_{i-1}) \pmod{0}.$$

Consider an increasing subsequence m_{n_k} . The complementary set of $\cap_i \Gamma_{m_{n_i}}(H_{n_i-1})$ is

$$D = \bigcup_{i \in \mathbb{N}} D_i, \quad \text{where } D_i = D_{m_{n_i}}(H_{n_i-1}).$$

By the inductive scheme above, $D_i \subset D_{i+1}$ and $H' = H_{n_i}$ on D_i . So, H' has an m_{n_i} -dominated splitting on D_i .

4. PERTURBING THE HAMILTONIAN

4.1. A symplectic straightening-out lemma. Here we present an improved version of a lemma by Robinson [16] that provides us with symplectic flowbox coordinates useful to perform local perturbations to our original Hamiltonian.

Consider the canonical symplectic form on \mathbb{R}^{2d} given by ω_0 as in (2.1). The Hamiltonian vector field of any smooth $H: \mathbb{R}^{2d} \rightarrow \mathbb{R}$ is then

$$X_H = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \nabla H,$$

where I is the $d \times d$ identity matrix. Let the Hamiltonian function $H_0: \mathbb{R}^{2d} \rightarrow \mathbb{R}$ be given by $y \mapsto y_{d+1}$, so that

$$X_{H_0} = \frac{\partial}{\partial y_1}.$$

Theorem 4.1 (Symplectic flowbox coordinates). *Let (M^{2d}, ω) be a C^s symplectic manifold, a Hamiltonian $H \in C^s(M, \mathbb{R})$, $s \geq 2$, and $x \in M$. If $x \in \mathcal{R}(H)$, there exists a neighborhood $U \subset M$ of x and a local C^{s-1} -symplectomorphism $g: (U, \omega) \rightarrow (\mathbb{R}^{2d}, \omega_0)$ such that $H = H_0 \circ g$ on U .*

Proof. Fix $e = H(x)$. Choose any C^s function $G: M \rightarrow \mathbb{R}$ such that $G(x) = 0$ and

$$\omega(X_H, X_G)(x) \neq 0. \quad (4.1)$$

This defines a transversal Σ to X_H at x in the following way. If $U \subset M$ is a small enough neighborhood of x in M (U will always be allowed to remain as small as needed), then

$$\Sigma = G^{-1}(0) \cap U$$

is a C^s regular connected submanifold of dimension $2d - 1$. Notice also that (4.1) holds in U .

Locally there is a C^s regular $(2d - 2)$ -dimensional hypersurface of $H^{-1}(e)$ where H and G are both constant: $\Sigma_e = \Sigma \cap H^{-1}(e)$. Notice that for $m \in \Sigma_e$

$$\begin{aligned} T_m \Sigma_e &= \{v \in T_m M : dH(v)(m) = dG(v)(m) = 0\} \\ &= \ker(\iota_{X_H} \omega(m)) \cap \ker(\iota_{X_G} \omega(m)). \end{aligned} \quad (4.2)$$

Since $\omega(X_H, X_G) \neq 0$, we have $X_G(m), X_H(m) \notin T_m \Sigma_e$ and

$$T_m M = T_m \Sigma_e \oplus \mathbb{R} X_H(m) \oplus \mathbb{R} X_G(m).$$

Now, consider the closed 2-form $\omega_e = \omega|_{\Sigma_e}$ defined on $T\Sigma_e \times T\Sigma_e$. To show that (Σ_e, ω_e) is a C^s symplectic manifold it is enough to check that ω_e is non-degenerate. So, suppose there is $v \in T_m \Sigma_e$ such that $\omega_e(w, v) = 0$ for any $w \in T_m \Sigma_e$. As in addition $\omega(X_H, v)(m) = \omega(X_G, v)(m) = 0$, $m \in \Sigma_e$, due to the fact that ω is non-degenerate we have to have $v = 0$. Thus, ω_e is non-degenerate. So, Darboux's theorem assures us the existence of a local diffeomorphism $h: \Sigma_e \rightarrow \mathbb{R}^{2d-2}$ such that

$$h^* \omega'_0 = \omega_e \quad \text{where} \quad \omega'_0 = \sum_{i=2}^d dy_i \wedge dy_{d+i}. \quad (4.3)$$

The next step is to extend the above symplectic coordinates from Σ_e to U . For this purpose we use the parametrization by the flows φ_H^t and ϕ^t generated by X_H and $Y := \omega(X_H, X_G)^{-1} X_G$, respectively. The time reparametrization in the definition of Y is necessary to normalize the pull-back of the form as it will become clear later.

The transversality condition (4.1) is again used in solving the equation $G \circ \varphi_H^{\tau(m)}(m) = 0$, $m \in U$, with respect to a function $\tau: U \rightarrow \mathbb{R}$. That is, we want to find τ and U such that $\varphi_H^{\tau(m)}(m) \in \Sigma$ for each $m \in U$.

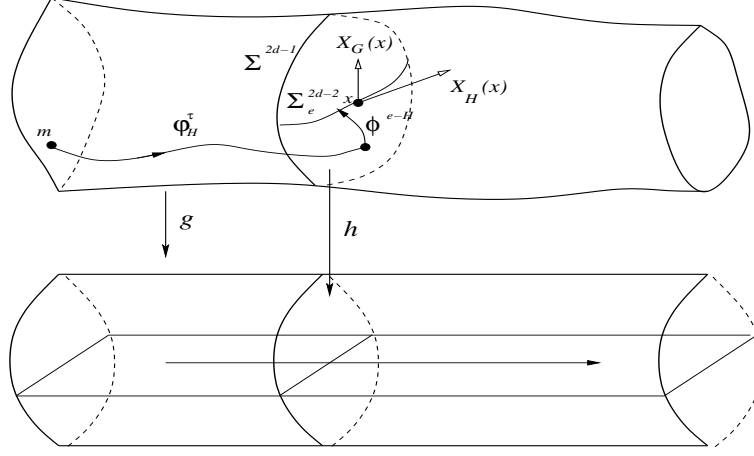


FIGURE 1. Illustration to the Symplectic flowbox coordinates.

By the implicit function theorem, since $G \circ \varphi_H^0(m) = 0$ and

$$\frac{d}{dt}G \circ \varphi_H^t(m)|_{t=0} = dG(X_H)(m) = \omega(X_G, X_H)(m) \neq 0,$$

there exists U and a unique $\tau \in C^{s-1}(U, \mathbb{R})$ as required. Moreover, ϕ^t preserves the level sets of G as $\mathcal{L}_Y G = \omega(X_G, Y) = 0$, and

$$\mathcal{L}_Y H = \frac{d}{dt}H \circ \phi^t(m) = \omega(X_H, Y) \circ \phi^t(m) = 1.$$

Thus, $H \circ \phi^t(m) = H(m) + t$ and in particular $H \circ \phi^{e-H(m)}(m) = e$ meaning that $\phi^{e-H(m)}(m) \in H^{-1}(e)$ for $m \in U$.

So, we define the map $g: U \rightarrow \mathbb{R}^{2d}$ given by

$$g(m) = (-\tau(m), h_1 \circ \phi^{e-H(m)} \circ \varphi_H^{\tau(m)}(m), H(m), h_2 \circ \phi^{e-H(m)} \circ \varphi_H^{\tau(m)}(m)),$$

where $h = (h_1, h_2)$ as in (4.3) and $h_i: \Sigma_e \rightarrow \mathbb{R}^{d-1}$. In particular, $H_0 \circ g = H$. It remains to prove that g is a C^{s-1} -symplectomorphism.

It follows that g is C^{s-1} and it has a C^{s-1} inverse $g^{-1}: g(U) \rightarrow U$ given by

$$g^{-1}(y) = \varphi_H^{y_1} \circ \phi^{y_{d+1}-e} \circ h^{-1}(\hat{y}),$$

where $\hat{y} = (y_2, \dots, y_d, y_{d+2}, \dots, y_{2d})$. In addition, for $y \in g(U)$,

$$\begin{aligned} g_*^{-1} X_{H_0}(y) &= \dot{\varphi}_H^{y_1} \circ \phi^{y_{d+1}-e} \circ h^{-1}(\hat{y}) \\ &= X_H \circ \varphi_H^{y_1} \circ \phi^{y_{d+1}-e} \circ h^{-1}(\hat{y}) \\ &= X_H \circ g^{-1}(y). \end{aligned} \quad (4.4)$$

Hence, $g_* X_H = X_{H_0}$. Similarly, we can show that $g_* Y = \frac{\partial}{\partial y_{d+1}}$ when restricting to Σ .

Notice that on $g(\Sigma_e)$ we have $g_*^{-1} \frac{\partial}{\partial y_j} = h_*^{-1} \frac{\partial}{\partial y_j}$ for $j \notin \{1, d+1\}$. Furthermore, taking in addition $k \notin \{1, d+1\}$,

$$\begin{aligned} (g^{-1*} \omega) \left(\frac{\partial}{\partial y_j}, \frac{\partial}{\partial y_k} \right) &= (h^{-1*} \omega) \left(\frac{\partial}{\partial y_j}, \frac{\partial}{\partial y_k} \right) = \omega_0 \left(\frac{\partial}{\partial y_j}, \frac{\partial}{\partial y_k} \right), \\ (g^{-1*} \omega) \left(\frac{\partial}{\partial y_1}, \frac{\partial}{\partial y_{d+1}} \right) &= \omega(X_H, Y) \circ g^{-1} = 1. \end{aligned}$$

Since $Dh^{-1} \frac{\partial}{\partial y_j} \in T\Sigma_e$, and H and G are constant on Σ_e ,

$$(g^{-1*} \omega) \left(\frac{\partial}{\partial y_1}, \frac{\partial}{\partial y_j} \right) = \omega \left(X_H, Dh^{-1} \frac{\partial}{\partial y_j} \right) = dH \left(Dh^{-1} \frac{\partial}{\partial y_j} \right) = 0$$

and analogously $(g^{-1*} \omega) \left(\frac{\partial}{\partial y_{d+1}}, \frac{\partial}{\partial y_j} \right) = 0$. Therefore $g^{-1*} \omega$ has to be the canonical 2-form, i.e. $g^* \omega_0 = \omega$ on Σ_e .

Now, we show that $g^* \omega_0 = \omega$ also holds on Σ . Using Cartan's formula for the Lie derivative $\mathcal{L}_v = \iota_v d + d\iota_v$ with respect to a vector field v and the identities $df^* = f^*d$ and $f^* \iota_v \omega = \iota_{f_*^{-1}v} f^* \omega$, then

$$\mathcal{L}_Y g^* \omega_0 = g^* d\iota_{\partial/\partial y_{d+1}} \omega_0 = g^* d^2(-y_1) = 0.$$

As we also have $\mathcal{L}_{X_G} \omega = 0$ and $\mathcal{L}_Y \omega = 0$, the forms $g^* \omega_0$ and ω are constant and coincide along the flow of Y passing through Σ_e , i.e. on Σ .

In order to see that we can have $g^* \omega_0 = \omega$ on all of U , we compute

$$\mathcal{L}_{X_H} g^* \omega_0 = d\iota_{X_H} \omega_0 = d(dH_0) = 0.$$

Recall that $\mathcal{L}_{X_H} \omega = 0$. So, $g^* \omega_0 = \omega$ along the flow of X_H through Σ , thus on all U . This concludes the proof that g is a symplectomorphism. \square

4.2. Hamiltonian local perturbation. In the next lemma we introduce the main tool to perturb $2d = 4$ -dimensional Hamiltonians. We will then be able to perturb the transversal linear Poincaré flow in order to rotate its action by a small angle. As we shall see later, that is all we need to interchange \mathcal{N}^+ with \mathcal{N}^- using the lack of dominance.

For functions on \mathbb{R}^4 consider the C^k -norm, with $k \geq 0$ integer,

$$\|f\|_{C^k} = \sup_y \max_{0 \leq |\sigma| \leq k} \left| \frac{\partial^{|\sigma|} f(y)}{\partial^{\sigma_1} y_1 \dots \partial^{\sigma_4} y_4} \right|,$$

where $\sigma = (\sigma_1, \dots, \sigma_4) \in \mathbb{N}_0^4$ with $|\sigma| = \sum_i \sigma_i$. Define the ‘‘tube’’

$$V_{a,b,c} = \{(y_1, y_2, y_3, y_4) \in \mathbb{R}^4 : a < y_1 < b, \sqrt{y_2^2 + y_4^2} < c\}.$$

Moreover, take the 2-dim plane $\Sigma_0 = \{(0, y_2, 0, y_4) \in \mathbb{R}^4\}$ and the orthogonal projection $\pi_0: \mathbb{R}^4 \rightarrow \Sigma_0$. Notice that the transversal linear Poincaré flow of $H_0(y) = y_3$ on Σ_0 is given by $\Phi_{H_0}^t(0) = \pi_0$.

Lemma 4.2. *Given $0 < \kappa < 1$ and $\epsilon > 0$, there exists $\alpha > 0$ such that for every $0 < r < 1$ we can find $H \in C^\infty(\mathbb{R}^4, \mathbb{R})$ satisfying*

- $H = H_0$ outside $V_{0,1,r(1-\kappa)}$,
- $\|H - H_0\|_{C^2} < \epsilon$ and
- $\Phi_H^1(0) := \pi_0 D\varphi_H^1(0) = R_\alpha$ on Σ_0 , where

$$R_\alpha = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \cos \alpha & 0 & -\sin \alpha \\ 0 & 0 & 0 & 0 \\ 0 & \sin \alpha & 0 & \cos \alpha \end{bmatrix}.$$

Proof. Consider the Hamiltonian flow $\varphi_{H_0}^t(y) = (y_1 + t, y_2, y_3, y_4)$. We want to ϵ - C^2 -perturb H_0 to get a Hamiltonian flow that rotates on the (y_2, y_4) -plane while the orbit is inside $V_{\xi, \xi', r(1-\kappa)}$ for some fixed $0 < \xi < \xi' < 1$. Outside the slightly larger tube $V_{0,1,r}$ we impose no perturbation.

In order to construct a C^∞ perturbation on those terms, we need to consider two bump functions. It is possible to find C^∞ maps $\ell: \mathbb{R} \rightarrow \mathbb{R}$ along the time direction and $\Omega: \mathbb{R}_0^+ \rightarrow \mathbb{R}$ for the plane (y_2, y_4) , such that

$$\ell(y_1) = \begin{cases} 0, & y_1 \leq 0 \text{ or } y_1 \geq 1 \\ 1, & \xi \leq y_1 \leq \xi' \end{cases} \quad \text{and} \quad \Omega'(\rho) = \begin{cases} 0, & \rho \geq r \\ 1, & 0 \leq \rho \leq r(1-\kappa), \end{cases}$$

$\Omega(0) = 0$, $\|\ell\|_{C^0} = \|\Omega'\|_{C^0} = 1$ and $\|\Omega''\|_{C^0} \leq \frac{2}{\kappa r}$. Therefore take the Hamiltonian

$$H(y) = H_0(y) - \alpha \ell'(y_1) \phi(\rho), \quad (4.5)$$

where $\phi(\rho) = \rho \Omega(\rho) - \int_0^\rho \Omega$ and $\rho = \sqrt{y_2^2 + y_4^2}$. This choice of H implies that

$$\nabla H(y) = (-\alpha \ell''(y_1) \phi(\rho), -\alpha y_2 \ell'(y_1) \Omega'(\rho), 1, -\alpha y_4 \ell'(y_1) \Omega'(\rho)). \quad (4.6)$$

So, X_H generates the flow

$$\begin{aligned} \varphi_H^t(y) = & (y_1 + t, \\ & \rho \cos(\theta + \alpha \Omega'(\rho)[\ell(y_1 + t) - \ell(y_1)]), \\ & y_3 + \alpha \phi(\rho)[\ell'(y_1 + t) - \ell'(y_1)], \\ & \rho \sin(\theta + \alpha \Omega'(\rho)[\ell(y_1 + t) - \ell(y_1)]), \end{aligned} \quad (4.7)$$

where $\theta = \arctan(y_4/y_2)$. Notice that $\frac{d}{dt}\rho^2 = 0$ so that ρ is φ_H^t -invariant. That is, on the (y_2, y_4) -plane the motion consists of a rotation. In addition, if $\rho < r(1-\kappa)$,

$$\varphi_H^1(0, y_2, y_3, y_4) = (1, \rho \cos(\theta + \alpha), y_3, \rho \sin(\theta + \alpha))$$

and $\pi_0 D\varphi_H^1(0)v = R_\alpha v$, $v \in \Sigma_0$.

Finally, we need to estimate the C^2 -norm of the perturbation. First notice that

$$\|\phi\|_{C^0} \leq 2r\|\Omega\|_{C^0}.$$

From (4.5) and (4.6) we get

$$\|H - H_0\|_{C^1} \ll \alpha r, \quad (4.8)$$

where we are using the notation $A \ll B$ to mean that there is a constant $C > 0$ such that $A \leq CB$. The second order derivatives are

$$\begin{aligned} \frac{\partial^2 H}{\partial y_1^2} &= -\alpha \ell'''(y_1) \phi(\rho) \\ \frac{\partial^2 H}{\partial y_2 \partial y_4} &= -\alpha \frac{y_2 y_4}{\rho} \ell''(y_1) \Omega''(\rho) \\ \frac{\partial^2 H}{\partial y_1 \partial y_j} &= -\alpha y_j \ell''(y_1) \Omega'(\rho) \\ \frac{\partial^2 H}{\partial y_j^2} &= -\alpha \ell'(y_1) \left[\Omega'(\rho) + \frac{y_j^2}{\rho} \Omega''(\rho) \right], \quad j = 2, 4. \end{aligned} \quad (4.9)$$

The remaining ones vanish. So,

$$\|D^2(H - H_0)\|_{C^0} \ll \alpha \max\{r, \kappa^{-1}\}. \quad (4.10)$$

Hence, there is $\alpha \ll \epsilon / \max\{1, \kappa^{-1}\}$ such that $\|H - H_0\|_{C^2} < \epsilon$. \square

Remark 4.3. *It is not possible to find an α as above if we require C^3 -closeness. This can easily be seen in the proof by computing the third order derivatives. E.g. $\frac{\partial^3 H}{\partial y_2^3}$ contains the term $\alpha \ell'(y_1) y_2^2 \rho^{-2} \Omega''(\rho)$ that can not be controlled by a bound of smaller order than α/r .*

4.3. Realizing Hamiltonian systems. In this section we define the central objects for the proof of Proposition 3.1, the achievable or *realizable* linear flows. These will be constructed by perturbations of Φ_H^t . We start with a point $x \in \mathcal{O}(H)$ with lack of hyperbolic behavior and mix the directions \mathcal{N}_x^+ and \mathcal{N}_x^- to cause the decay of the upper Lyapunov exponent. In fact we are interested in ‘‘a lot’’ of points (related to the Lebesgue measure on transversal sections). Therefore, we perturb the Hamiltonian to make sure that ‘‘many’’ points y near x have $\Phi_H^t(y)$ close to $\Phi_H^t(x)$. For this reason we must be very careful in our procedure.

Consider a Darboux atlas $\{h_j: U_j \rightarrow \mathbb{R}^4\}_{j \in \{1, \dots, \ell\}}$. For each $x \in \mathcal{R}(H)$ choose j such that $x \in U_j$, and take the 3-dimensional normal section to the flow \mathfrak{N}_x . In the sequel we abuse notation to write \mathfrak{N}_x for $h_j(\mathfrak{N}_x \cap U_j)$, so that we work in \mathbb{R}^4 instead of M . Furthermore, denote by $B(x, r)$ the open ball in \mathfrak{N}_x about x with small enough radius r .

Consider the standard Poincaré map

$$\mathcal{P}_H^t(x): U \rightarrow \mathfrak{N}_{\varphi_H^t(x)},$$

where $U \subset \mathfrak{N}_x$ is chosen sufficiently small. Given $T > 0$, the self-disjoint set

$$\mathcal{F}_H^T(x, U) = \left\{ \mathcal{P}_H^t(x) y \in M : y \in U, t \in [0, T] \right\},$$

is called a T -length flowbox at x associated to the Hamiltonian H .

There is a natural way to define a measure $\bar{\mu}$ in the transversal sections by considering the invariant volume form $\iota_{X_H}\omega^d$. We easily obtain an estimate on the time evolution of the measure of transversal sets: for $\nu, t > 0$ there is $r > 0$ such that for any measurable $A \subset B(x, r)$ we have

$$|\bar{\mu}(A) - \alpha(t)\bar{\mu}(\mathcal{P}_H^t(x)A)| < \nu, \quad (4.11)$$

where

$$\alpha(t) = \frac{\|X_H(\varphi_H^t(x))\|}{\|X_H(x)\|}.$$

Definition 4.4. *Let a Hamiltonian $H \in C^{s+1}(M, \mathbb{R})$, $s \geq 2$, $T, \epsilon > 0$, $0 < \kappa < 1$ and a non-periodic point $x \in M$. The flow L of symplectic linear maps:*

$$L^t(x): \mathcal{N}_x \rightarrow \mathcal{N}_{\varphi_H^t(x)}, \quad 0 \leq t \leq T, \quad L^0(x) = I,$$

is (ϵ, κ) -realizable length T linear flow at x if the following holds:

For $\gamma > 0$ there is $r > 0$ such that for any open set $U \subset B(x, r)$ we can find

- (1) $K \subset U$ with $\bar{\mu}(U \setminus K) \leq \kappa \bar{\mu}(U)$, and
- (2) $\tilde{H} \in C^s(M, \mathbb{R})$ ϵ - C^2 -close to H , verifying
 - (a) $\varphi_H^t = \varphi_{\tilde{H}}^t$ outside $\mathcal{F}_H^T(x, U)$,
 - (b) $DX_H(y) = DX_{\tilde{H}}(y)$ for $y \in U \cup \mathcal{P}_H^T(x)U$, and
 - (c) $\|\Phi_{\tilde{H}}^T(y) - L^T(x)\| < \gamma$ with $y \in K$.

Let us add a few words about this definition: (2a) and (2b) guarantee that the support of the perturbation is restricted to the flowbox and it C^1 “glues” to its complementary; (2c) says that a large percentage of points (given numerically by (1)) have the transversal linear Poincaré flow of \tilde{H} (as in (2)) very close to the abstract linear action of the central point x along the orbit. Notice that the realizability is with respect to the C^2 topology. Moreover, there is no need for the point to be non-periodic as long as the period is larger than T .

Remark 4.5. *Using Vitali covering arguments we may replace any open set U of Definition 4.4 by open balls. That turns out to be very useful because the basic perturbation Lemma 4.2 works for balls.*

It is an immediate consequence of the definition that the transversal linear Poincaré flow of H is itself a realizable linear flow. In addition, the concatenation of two realizable linear flows is still a realizable linear flow as it is shown in the following lemma.

Lemma 4.6. *Let $H \in C^2(M, \mathbb{R})$ and $x \in M$ non-periodic. If L_1 is (ϵ, κ_1) -realizable of length T_1 at x and L_2 is (ϵ, κ_2) -realizable of length*

T_2 at $\varphi_H^{T_1}(x)$ so that $\kappa = \kappa_1 + \kappa_2 < 1$, then the concatenated linear flow

$$L^t(x) = \begin{cases} L_1^t(x), & 0 \leq t \leq T_1 \\ L_2^{t-T_1}(\varphi_H^{T_1}(x)) L_1^{T_1}(x), & T_1 < t \leq T_1 + T_2 \end{cases}$$

is (ϵ, κ) -realizable of length $T_1 + T_2$ at x .

Remark 4.7. Notice that concatenation of realizable flows worsens κ .

Proof. For $\gamma > 0$, take $r_1, r_2, K_1, K_2, \tilde{H}_1, \tilde{H}_2$ the obvious variables in the definition for L_1 and L_2 . We want to find the corresponding ones r, K, \tilde{H} for L satisfying the properties of realizable flows. Let $x_2 = \varphi_H^{T_1}(x)$.

- First, choose $r \leq r_1$ such that

$$U_2 := \mathcal{P}_H^{T_1}(x) U \subset B(x_2, r_2)$$

with $U = B(x, r)$.

- Now, we construct \tilde{H} as

$$\tilde{H} = \begin{cases} \tilde{H}_1 & \text{on } \mathcal{F}_H^{T_1}(x, U) \\ \tilde{H}_2 & \text{on } \mathcal{F}_H^{T_2}(x_2, U_2) \\ H & \text{otherwise.} \end{cases}$$

Notice that $\mathcal{F}_H^{T_1+T_2}(x, U) = \mathcal{F}_H^{T_1}(x, U) \cup \mathcal{F}_H^{T_2}(x_2, U_2)$.

- Consider $K = K_1 \cap \mathcal{P}_H^{-T_1}(x) (K_2 \cap U_2)$. Hence,

$$\begin{aligned} \bar{\mu}(U \setminus K) &\leq \bar{\mu}(U \setminus K_1) + \bar{\mu}(U \setminus \mathcal{P}_H^{-T_1}(x) (K_2 \cap U_2)) \\ &\leq (\kappa_1 + 1) \bar{\mu}(U) - \bar{\mu}(\mathcal{P}_H^{-T_1}(x) (K_2 \cap U_2)). \end{aligned}$$

Now, by (4.11) applied to $A = \mathcal{P}_H^{-T_1}(x) (K_2 \cap U_2)$ we know that

$$\begin{aligned} \bar{\mu}(\mathcal{P}_H^{-T_1}(x) (K_2 \cap U_2)) &\geq \alpha(T_1) \bar{\mu}(K_2 \cap U_2) \\ &= \alpha(T_1) [\bar{\mu}(U_2) - \bar{\mu}(U_2 \setminus K_2)] \\ &\geq \alpha(T_1)(1 - \kappa_2) \bar{\mu}(U_2). \end{aligned}$$

On the other hand, using (4.11) for $A = U$, $\bar{\mu}(U_2) \geq \alpha(T_1)^{-1} \bar{\mu}(U)$. Combining all the above estimates we get

$$\bar{\mu}(U \setminus K) \leq (\kappa_1 + \kappa_2) \bar{\mu}(U).$$

- The choice of \tilde{H} yields that $DX_H = DX_{\tilde{H}}$ on U because that is true for \tilde{H}_1 . The same on $\mathcal{P}_H^{T_1+T_2}(x) U$ related to \tilde{H}_2 .
- In order to check that \tilde{H} is C^s it is enough to look at U_2 . That follows from the same reason as the previous item.

- Finally, there is $C > 0$ verifying for $y \in K$ and writing $y_2 = \mathcal{P}_H^{T_1}(x)y$,

$$\begin{aligned} \|\Phi_{\tilde{H}}^{T_1+T_2}(y) - L^{T_1+T_2}(x)\| &\leq \|\Phi_{\tilde{H}}^{T_2}(y_2)[\Phi_{\tilde{H}}^{T_1}(y) - L^{T_1}(x)]\| \\ &\quad + \|[\Phi_{\tilde{H}}^{T_2}(y_2) - L^{T_2}(x_2)]L^{T_1}(x)\| \\ &< C\gamma. \end{aligned}$$

□

The next lemma is the basic mechanism to perform perturbations in time length 1, for which we use Lemma 4.2 to realize the map $\Phi_H^t(x) \circ R_\alpha$. In fact, we will not be needing more than length 1 realizable flows, since we can concatenate them (keeping in mind Remark 4.7). Each length 1 piece contributes to rotations by the same angle α , independently of x , as shown below.

Lemma 4.8. *Let $H \in C^2(M, \mathbb{R})$, $\epsilon > 0$ and $0 < \kappa < 1$. Then there exists an angle $\alpha = \alpha(H, \epsilon, \kappa)$ such that $\Phi_H^t(x) \circ R_\alpha$ is (ϵ, κ) -realizable of length 1 at any non-periodic point $x \in M$ (or with period larger than 1).*

Proof. Let $\gamma > 0$ and choose $U = B(x', r') \subset B(x, r)$ (recall Remark 4.5). Now, assume that the time arrival of x' is 1 and that the normal section to the flow in x' is the same as the one in x . This is (almost as we like) true since we may decrease r in the choice for the realizable linear flow. Then Lemma 4.2 and a small enough r gives:

- $X_{\tilde{H}} - X_H$ supported in the flowbox $\mathcal{F}_H^1(x', B(x', r))$,
- for every $y \in B(x', r\sqrt[3]{1-\kappa})$,

$$\|\Phi_{\tilde{H}}^1(y) - \Phi_H^1(x) \circ R_\alpha\| < \gamma. \quad (4.12)$$

For the perturbation $g_*X_{\tilde{H}}$ with a C^{s-1} -symplectomorphism g as in Theorem 4.1, we have $DX_{\tilde{H}}(\cdot) = 0$ when computed in the edges of the flowbox, therefore (2a) in Definition 4.4 is valid. We take $K = \overline{B}(x', r\sqrt[3]{1-\kappa})$ and get

$$\frac{\bar{\mu}(K)}{\bar{\mu}(U)} = \frac{\frac{4\pi}{3}(1-\kappa)r'^3}{\frac{4\pi}{3}r^3} = 1 - \kappa.$$

Hence (1) follows. Finally, (2c) is a direct consequence of the continuity of the transversal linear Poincaré flow and (4.12). □

Remark 4.9. *A similar result holds true also for $R_\alpha \circ \Phi_H^t(x)$ using essentially the same proof.*

5. PROOF OF PROPOSITION 3.1

We present here a sketch of how to complete the proof of Proposition 3.1; see [1] for full details. Even if we only need the following results for H of C^∞ class, we present them for C^3 . This highlights the

fact that it can not be C^2 since \tilde{H} has to be one degree of differentiability less. The differentiability loss comes from the symplectomorphism obtained in Theorem 4.1 that rectifies the flow.

5.1. Local. The lemma below states that the absence of dominated splitting is sufficient to interchange the two directions of non-zero Lyapunov exponents along an orbit segment by the means of a realizable flow.

Lemma 5.1. *Let $H \in C^3(M, \mathbb{R})$, $\epsilon > 0$ and $0 < \kappa < 1$. There exists $m \in \mathbb{N}$, such that for every $x \in \mathcal{R}(H) \cap \mathcal{O}(H)$ with a positive Lyapunov exponent and satisfying*

$$\frac{\|\Phi_H^m(x)|\mathcal{N}_x^-\|}{\|\Phi_H^m(x)|\mathcal{N}_x^+\|} \geq \frac{1}{2},$$

there exists a (ϵ, κ) -realizable linear flow L of length m at x such that

$$L^m(x)\mathcal{N}_x^+ = \mathcal{N}_{\varphi_H^m(x)}^-.$$

Proof. The proof is the same as for Lemma 3.15 of [1] in which the constructions of Lemma 4.8 are used, namely the concatenation of rotated Poincaré linear maps. \square

Now we aim at locally decaying the upper Lyapunov exponent.

Lemma 5.2. *Let $H \in C^3(M, \mathbb{R})$ and $\epsilon, \delta > 0$, $0 < \kappa < 1$. There is $T: \Gamma_m(H) \rightarrow \mathbb{R}$ measurable, such that for μ -a.e. $x \in \Gamma_m(H)$ and $t \geq T(x)$, we can find a (ϵ, κ) -realizable linear flow L at x with length t satisfying*

$$\frac{1}{t} \log \|L^t(x)\| < \delta. \quad (5.1)$$

Proof. We follow Lemma 3.18 of [1]. Notice that for μ -a.e. $x \in \Gamma_m(H)$ with $\lambda = \lambda^+(H, x) > 0$ and due to the nice recurrence properties of the function T (see Lemma 3.12 of [2]) we obtain for every (very large) $t \geq T(x)$ that

$$\frac{\|\Phi_H^m(y)|\mathcal{N}_y^-\|}{\|\Phi_H^m(y)|\mathcal{N}_y^+\|} \geq \frac{1}{2}$$

for $y = \varphi_H^s(x)$ with $s \approx t/2$.

Now, by Lemma 5.1 we obtain a (ϵ, κ) -realizable linear flow L_2^t such that $L_2^m \mathcal{N}_y^+ = \mathcal{N}_{\varphi_H^m(y)}^-$. We consider also the realizable linear flows $L_1^t: \mathcal{N}_x \rightarrow \mathcal{N}_y$ and $L_3^t: \mathcal{N}_{\varphi_H^m(y)} \rightarrow \mathcal{N}_{\varphi_H^t(x)}$ given by Φ_H^t for $0 \leq t \leq s$ and $t \geq m$, respectively. Then we use Lemma 4.6 and concatenate $L_1 \rightarrow L_2 \rightarrow L_3$ as L^t , which is a (ϵ, κ) -realizable linear flow at x with length t .

The choice of $t \gg m$ and the exchange of the directions will cause a decay on the norm of L^t . Roughly that is:

- in \mathcal{N}_x^+ the action of L_1 is approximately $e^{\lambda t/2}$,

- in $\mathcal{N}_{\varphi_H^m(y)}^-$ the action of L_3 is approximately $e^{-\lambda t/2}$ and
- L_2 exchange these two rates.

Therefore, $\|L^t(x)\| < e^{t\delta}$. \square

5.2. Global. Notice that, in Lemma 5.2, we obtained $\|L^t(x)\| < e^{t\delta}$. However, we still need to get an upper estimate of the upper Lyapunov exponent. Due to (3.2) this can be done without taking limits, say in finite time computations. In other words, we will be using the inequality

$$\int_{\Gamma_m(H)} \lambda^+(\tilde{H}, x) d\mu(x) \leq \int_{\Gamma_m(H)} \frac{1}{t} \log \|\Phi_{\tilde{H}}^t(x)\| d\mu(x), \quad (5.2)$$

which is true for all $t \in \mathbb{R}$. Therefore, δ is larger than the upper Lyapunov exponent of at least most of the points near x .

To prove Proposition 3.1 we turn Lemma 5.2 global. This is done by a recurrence argument based in the Kakutani towers techniques entirely described in [1] (section 6). In broad terms the construction goes as follows:

- Take a very large $m \in \mathbb{N}$ from Lemma 5.1. Then Lemma 5.2 gives us a measurable function $T: \Gamma_m(H) \rightarrow \mathbb{R}$ depending on κ and δ . Let $\delta^2 = \kappa$.
- For $x_1 \in \Gamma_m(H)$, the realizability of the flow $L^t(x_1)$ guarantees that we have a t -length flowbox at x_1 (a tower \mathcal{T}_1) associated to the perturbed Hamiltonian \tilde{H}_1 . If we take a point in the measurable set K_1 (cf. (1) of Definition 4.4) contained in the base of the tower, then by (2c) of Definition 4.4 and Lemma 5.2, we have $\|\Phi_{\tilde{H}_1}^t(y)\| < e^{2\delta t}$ for all $y \in K_1$.
- Now, for $x_2, \dots, x_j \in \Gamma_m(H)$, where $j \in \mathbb{N}$ is large enough, we define self-disjoint towers \mathcal{T}_i , $i = 1, \dots, j$, which (almost) cover the set $\Gamma_m(H)$ in the measure theoretical sense. We take these towers such that their heights are approximately the same, say h .
- The C^2 Hamiltonian \tilde{H} is defined by glueing together all perturbations \tilde{H}_i , $i = 1, \dots, j$.
- Consider $\mathcal{T} = \cup_i \mathcal{T}_i$, $U = \cup_i U_i$ and $K = \cup_i K_i$. Clearly $K \subset U$. Note that for points in $U \setminus K$ we may not have $\|\Phi_{\tilde{H}_1}^t(\cdot)\| < e^{2\delta t}$.
- Denote by \mathcal{T}^K the subtowers of \mathcal{T} with base K instead of U . By (1) of Definition 4.4 we obtain that $\bar{\mu}(U \setminus K) \leq \kappa \bar{\mu}(U)$, hence $\mu(\mathcal{T} \setminus \mathcal{T}^K) < \mu(\mathcal{T}) \leq \delta^2$.

We claim that it is sufficient to take $t = h\delta^{-1}$ in (5.2). It follows from (5.1) that we only control the iterates that enter the base of \mathcal{T}^K . Since the height of each tower is approximately h the orbits leave \mathcal{T}^K at most δ^{-1} times. For each of those times the chance of not re-entering again is less than δ^2 . So, the probability of leaving \mathcal{T}^K along t iterates

is less than δ . In conclusion, most of the points in $\Gamma_m(H)$ satisfy the inequality (5.1) and Proposition 3.1 is proved.

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