



SORBONNE UNIVERSITÉ

MASTER THESIS

Teichmüller theory and Thurston Earthquake flow

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Contents

1	Introduction	2
2	Notations	3
3	Teichmuller Theory	4
3.1	First definitions	4
3.2	Flow on Teichmüller space	6
3.3	Decomposition of hyperbolic surface	8
3.4	The collaring theorem	9
4	Isomorphisme of Mirzhakani	12
4.1	Tightening map	12
4.2	Correspondance between foliations and quadratic differentials	14
4.3	Shear Cordinate	14
5	Mixing rate	18
6	Example of the once ponctured torus	19

1 Introduction

Since Bernhard Riemann, mathematicians knew that only a finite number of parameters can describe a geometric surface. Considering this, we can be interested in the set of all geometries we can give to a given surface, modulo composition by map isotopic to the identity, this set is called the Teichmüller space. Moreover other problems arise shortly after this definition. How can we deform in the natural way a geometry of a surface into another? What does it mean that two geometries are close to each other? What are the natural boundaries of the Teichmüller space?

Oswald Teichmüller, a German mathematician, gave answers to this question in the year preceding the second World War. He created the first metric on this space by finding a solution to an extremal problem: between two hyperbolic geometries on the same surface there is a function which minimizes the deformation. The answer is not only yes, but this function is unique. It naturally creates a distance in the now called Teichmüller space by considering the logarithm of the deformation of the extremal function.

Thurston then added other important steps to this theory. He underlined the role of lamination which are a generalisation of simple closed curves. And he created the earthquake flow which turned to play an important role in Teichmüller theory. Kerckhoff used this tool to show the Nielsen realisation conjecture in 1983 ?? which states that every finite subgroup of the mapping class group has a fixed point in the Teichmüller space.



Figure 1: The mathematician Oswald Teichmüller

An important question in Hyperbolic geometry is the asymptotic number of closed geodesics. To begin we can ask the number $\pi(X, L)$ of geodesics on a hyperbolic surface of length less than L . The answer was found by Delsarte, Huber and Selberg and is called the prime number theorem for hyperbolic surfaces (because of the resemblance to the prime number theorem). It states that

$$\pi(X, L) \equiv e^L/L$$

as $L \rightarrow \infty$. A much harder question was to find the number, $\sigma(X, L)$, of simple (which don't intersect themselves) closed geodesics of length less than L on a hyperbolic surface X . It was found years later, in Mirzakhani's PhD, and we have

$$\sigma(X, L) \equiv C_X L^{6g-6}$$

As $L \rightarrow \infty$ where g is the genus of the surface X and C_X is a constant which depends on the geometry X . To do that Miriam Mirzakhani conjugated the earthquake flow to the horocycle flow. This step gave that the Earthquake flow is ergodic and allowed us to use Birkhoff's theorem to understand asymptotic quantities.

The question is now to give an error term to this quantity and to do that we need to understand better the earthquake flow.

In this master thesis, I will first give an introduction to Teichmüller theory and some useful tools. Then we will review the proof of the Mirzakhani conjugacy between the horocyclic flow and the earthquake flow. Finally we will discuss a special case which can be the most simple example of hyperbolic surface, that is the once punctured torus.

2 Notations

\mathcal{ML}	measured lamination
$\mathcal{MF}(S)$	space of all equivalence classes of measured foliations.
\mathcal{QD}	bundle of nonzero quadratic differential.
\mathcal{T}_g	Teichmuller space of surface of genus g
$Mod(S)$	The modular group of a surface S
$\mathcal{P}^1\mathcal{M}_g$	Product of \mathcal{T}_g and $\mathcal{MF}(S)$ quotiented by the modular group.
$\mathcal{GC}(S)$	the space of geodesic currents
\mathbb{D}	the Poincaré disk
\mathbb{S}	the unit circle seen as the boundary of \mathbb{D}
$\bar{\mathbb{D}}$	$\mathbb{D} \cup \mathbb{S}$
\mathbf{S}	set of all simple closed curve of a surface
$D_\gamma(\alpha)$	Dehn's twist of α around γ

3 Teichmuller Theory

3.1 First definitions

To begin we will in this section give the very definition to introduce the theory of Teichmuller space

Definition 3.1. Teichmuller space Let S be a surface of genus g , a marking of S is a couple (X, f) made of a closed Riemann surface X and of one homeomorphism $f : S \rightarrow X$ which preserve the orientation. On the set of the marking S , we have a equivalence relation, $(X_1, f_1) \sim (X_2, f_2)$ if there exist $\alpha : X_1 \rightarrow X_2$ such that $f_2 \circ \alpha \circ f_1^{-1}$ be an homeomorphism of S preserving the orientation and isotope to the identity map. The set of the marking quotient by the previous relation is the Teichmuller space and is written \mathcal{T}_g .

Remark. If $g \geq 2$, for every closed curve α of S , there is only one closed geodesic of X freely isotope to $f(\alpha)$. Moreover if α is simple, so is the geodesic. We will note $l_\alpha(X)$ its hyperbolic length and we will take the weakest topologie on \mathcal{T}_g which make this map continuous.

This give a map $L : \mathcal{T}_g \rightarrow \mathbb{R}^{\mathbf{S}}$, where \mathbf{S} is the set of all simple closed curve of a given surface. We can ask if this map is injective, i.e. that a geometry is given by the length of the set of simple closed curve. The answer is yes and more precisely one can choose only $9g - 9 + 3n$ curve so that this map is injective [1] Theorem 10.7. This give the intuition that Teichmuller space can be only by using a finite set of parameter. We will see after that other coordinates which have nice properties for other utilisations.

Definition 3.2. Modular Space The modular group is the group of homeomorphism of S which respect orientation quotiented by the one isotopic to the identity map. We will call this group Mod_g It act discretely on the Teichmuller space \mathcal{T}_g and the quotient is called the moduli space and is written \mathcal{M}_g .

The Teichmuller space is the universal covering of the modular space. IN fact the Teichmuller space is homeomorph to a sphere and so is contractible and in particular, connected and simply connected. It is the universal covering of the moduli space.

We can ask ourselves how look this spaces and if we can give an easy representation of them. The fact is that the modular space is not manifold but an orbifold, that is a space which locally look like a ball of a vector space quotiented by a finite group.

A beginning is to give a set of generator of the modular group.

Definition 3.3. Dehn twist Let γ be a simple closed curve. There is a tubular neighborhood of γ called A homeomorph to $[0; 1] \times S^1$. A Dehn's twist around γ is the homeomorphism which is the identity out of A and is $(t, s) \mapsto (t, e^{2i\pi t} s)$ on A .

Remark. The Lickorisk theorem states that the modular group is generated by the Dehn's twist and more precisely that one can choose only $2g + 1$ generators [5].

Definition 3.4. Measured foliation Given a surface S and a finite set of points $P = (p_1, p_2, \dots)$, given a open covering U_i on $S - P$, a collection of C^1 real function ν_i such than $\|d\nu_j\| = \|d\nu_i\|$ on $U_i \cap U_j$, and near each singular point p_s a coordinate neighborhood V with complex coordinate z such that $\|d\nu\| = \|Im(z^{\frac{k}{2}} dz)\|$ for some positive integer k called the degree of the singular point, leaves of the foliations are the graphs immersed S in along $d\nu$ is constant. In addition if each boundary circle pf S is contained in a singular leaf, then ti is called a measurd foliation.

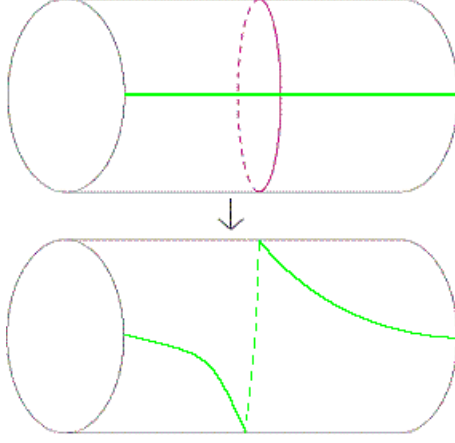


Figure 2: A Dehn twist

The height $h_\gamma(\|d\nu\|)$ of a (free homotopy class) of a loop γ on S is the infimum in the homotopy class of the integral by $\|d\nu\|$

$$h_\gamma(\|d\nu\|) = \inf_{\gamma \equiv \gamma'} \int_g \alpha \|d\nu\|$$

The topology on the measured lamination that we will use is the weakest that make the height functions continuous.

Remark. We won't actually study the set of measured lamination but the equivalence class of

$$h_\gamma(\|d\nu\|) = h_\gamma(\|d\mu\|), \text{ for each loop } \gamma \in S$$

. We can equivalently use Whitehead equivalence relation on singular foliations by collapsing critical intervals to points and taking isotopy of foliation.

Let $\mathcal{MF}(S)$ be the space of all equivalence classes of measured foliations.

Definition 3.5. Lamination A lamination is a closed set made of an union (non necessarily finite) of geodesic. For each point x in λ a lamination passed only one geodesic of the lamination. We will write this space $\mathcal{ML}(x)$.

Definition 3.6. Geodesic currents Let \mathcal{M}_∞ be the space of unordered pairs of distinct points in \mathbb{S}^1

$$\mathcal{M}_\infty := (z, w) \in \mathbb{S}^1 \times \mathbb{S}^1, z \neq w / (z, w) \equiv (w, z)$$

Let G be a discrete torsion-free group in $PSL(2, \mathbb{R})$ such that $\mathbb{H}/G = S$ is a hyperbolic surface. A geodesic current μ on S is a G -invariant Radon measure on \mathcal{M}_∞ . We will note $\mathcal{GC}(S)$ the space of geodesic currents.

Remark. $\mathcal{GC}(S)$ have a natural topology which is the weak $*$ convergence on continuous functions.

Remark. A multicurve is a formal sum of geodesics $\gamma = \sum a_i \gamma_i$. The space of lamination is in some aspect the closure of the set of all multicurve

Definition 3.7. Intersection number Consider the square $\mathcal{M}_\infty^2 := \mathcal{M}_\infty \times \mathcal{M}_\infty$. In this space we can consider the open subset \mathcal{IM}_∞^2 corresponding to pair pairs of geodesics which have transversal intersections in \mathbb{H} . G act on \mathcal{IM}_∞^2 . If μ and ν are geodesic currents in $\mathcal{GC}(S)$, the product $\mu \times \nu$ define a G -invariant measure on \mathcal{IM}_∞^2 . Finally if we take the mass of the total space \mathcal{IM}_∞^2/G , the result is called the intersection number, $i(\mu, \nu)$

Proposition 3.1.

$$i : \mathcal{GC}(S) \times \mathcal{GC}(S) \rightarrow \mathbb{R}_+$$

is continuous and bilinear

Remark. If α and β are simple closed geodesics (dirac measure in $\mathcal{GC}(S)$), then the intersection number is the number of intersection between α and β . Actually, one can define intersection in this way, first on simple closed geodesic, then by bilinearity on multi-curves and finally by continuity on geodesic current.

Remark. The topology on \mathcal{ML} is the weakest that make $i(.,.)$ a continuous function.

Definition 3.8. Différentielle quadratique Une différentielle quadratique est une section du carré de l'espace tangent canonique à X . Il s'écrit localement comme $\phi = \phi(z)dz^2$

Remark. Si $\phi(p) \neq 0$ on peut trouver une carte contenant p dans laquelle $\phi = dz^2$. Ainsi ϕ détermine une métrique plate sur X et un feuilletage \mathcal{F} correspondant aux lignes horizontales.

Une différentielle quadratique est dite intégrable si

$$\|\phi\| = \int_X |\phi| < \infty$$

Nous noterons $\mathcal{Q}(X)$ l'espace de Banach des différentielles quadratiques intégrables.

3.2 Flow on Teichmüller space

We will define the main object of this paper, earthquake flow.

Definition 3.9. The earthquake flow is family of maps defined for $t \in \mathbb{R}$

$$\begin{aligned} E_t : \mathcal{ML} \times \mathcal{T}_g &\rightarrow \mathcal{ML} \times \mathcal{T}_g \\ (\lambda, X) &\mapsto (\lambda, E_{t\lambda}X) \end{aligned}$$

where $E_{t\lambda}$ is first defined if λ is a simple closed curve. In this case, we open the surface along λ , then twist the left part of t unit and put it together again. Then if γ_1 and γ_2 are two curves that don't intersect, E_{γ_1} and E_{γ_2} commute. So we can define the earthquake map on weighted multicurves by twisting one curve after the other by amount proportional to the weight. Finally as multicurves are dense in the set of lamination we can extend this map for any lamination [3].

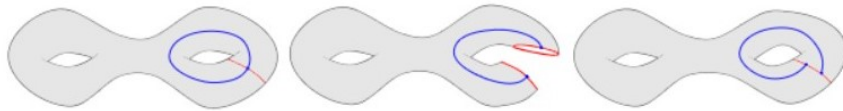


Figure 3: Effect of a twist on a transverse curve, image from [8]

Remark. If the lamination is just a simple closed curve γ then $E_{t\gamma}(X, \gamma)$ is just a Dehn twist around γ . Moreover if we take a decomposition in a pair of pants that contains γ , it is just a translation in the coordinate of the twist of γ .

One could give a precise proof that the extension of the earthquake map from the multicurves to the lamination is rigorous, that is if we take two sequences α_n and α'_n of multicurves which converge to the same lamination, then the sequences of earthquake map along these multicurves converge to the same map.

Remark. The earthquake flow is an isometry outside the support of the lamination and is continuous outside the atomic part, i.e. the simple closed geodesics of the lamination.

Thurston show that given two point in the Teichmüller space, there is a lamination λ such that the earthquake flow from one point with respect to λ reach the other point (also in [3]).

We can ask ourselves what is an invariant measure of this flow.

Definition 3.10. The Weil-Peterson form is the form

$$\omega_{WP} = \sum dl_i \wedge d\tau_i$$

Where (l_1, \dots, τ_1) are the Fenchel-Nielsen according to a pant decomposition.

This give a measure μ_{WP} .

There is a finite measure ν_g in the Lebesgue measure class on $\mathcal{P}^1\mathcal{M}_g$ which is invariant under the earthquake flow. This measure projects to the volume form given by $B(X) \times \mu_{WP}$ on \mathcal{M}_g , where

$$B(X) = \mu_{Th}(\lambda \in \mathcal{ML}, l_\lambda(X) \leq 1)$$

There are two other important flows, the geodesic flow and the horocyclic flow. First there is a natural homeomorphism between $T^1\mathbb{H} \simeq PSL_2(\mathbb{R})$, since $PSL_2(\mathbb{R})$ act simply transitively on it. This morphism can be chosen up to a conjugaison via an other element of $PSL_2(\mathbb{R})$. We will be interested in a special kind of subgroup.

Definition 3.11. A fuchsian group Γ is a finitely generated and discrete subgroup of $PSL_2(\mathbb{R})$. Then Γ act discontinuously on \mathbb{H} .

Then a Hyperbolic surface can be represented as $PSL_2(\mathbb{R})/\Gamma$. If U is a one parameter subgroup of $PSL_2\mathbb{R}$ it act on the quotient.

There are two important exemple:

Definition 3.12. The geodesic flow is a flow on the Teichmüller space given by the action of the diagonal matrices

$$u_t = \begin{pmatrix} e^t & 0 \\ 0 & e^{-t} \end{pmatrix}$$

Definition 3.13. The horocycle flow is a flow on the bundle of nonzero quadratic differential, \mathcal{QD} , of the Teichmüller space given by the unipotent action of

$$u_t = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$$

The geodesic flow is also the flow that we obtain by following geodesic line on \mathbb{H} and the horocycle is the flow we obtain by following curves which are everywhere orthogonal to the geodesic, which is the horizontal line and the circle tangent to the real line.

An important relation is how this two flows interact between each other

$$\begin{pmatrix} e^t & 0 \\ 0 & e^{-t} \end{pmatrix} u_t = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-t} & 0 \\ 0 & e^t \end{pmatrix} = \begin{pmatrix} 1 & se^{2t} \\ 0 & 1 \end{pmatrix}$$

So the conjugaison of the horocyclic flow by the geodesic one is still the horocyclic flow.

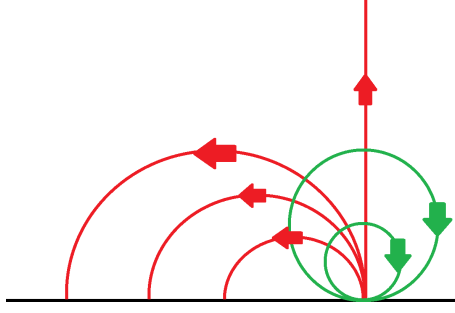


Figure 4: Representation of the horocycle flow, in green, and the geodesic flow, in red

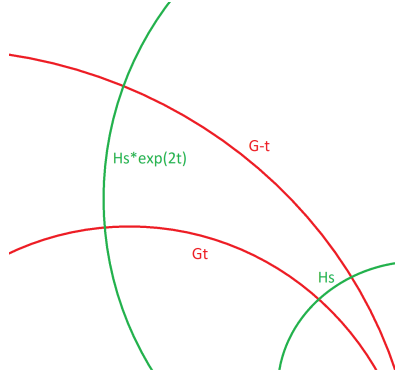


Figure 5: The conjugaison of the horocycle flow by the geodesic one.

3.3 Decomposition of hyperbolic surface

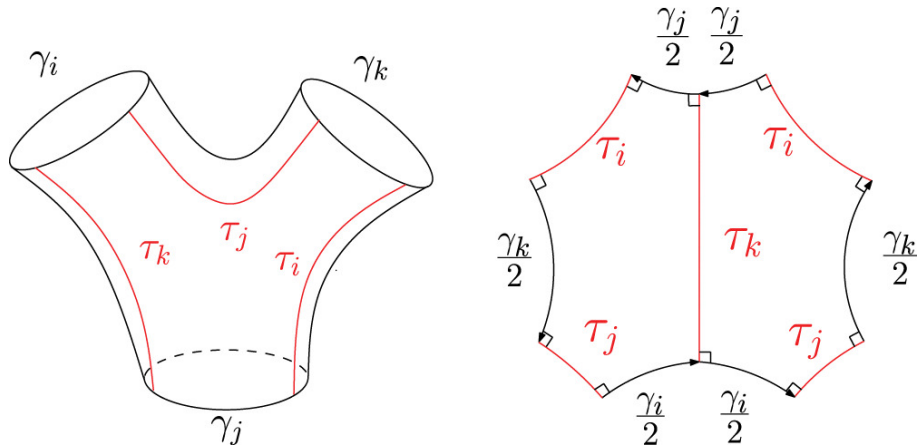
One way to construct all hyperbolic surface is to decompose them in elementary piece, that we will call pair of pant.

A hyperbolic geometric exercice show that a hexagone which side are geodesics and with right angles is determined by the lenght of three sides which are not consecutifs.

On the image above γ_i , γ_j and γ_k determined the hexagone. Then we can glued them to have a pair of pant.

Definition 3.14. A pair of pant is a hyperbolic surface with three geodesic boundaries and no ponctured.

Remark. The pair of pant is uniquely determined by the lenght of the three boundarie geodesics.



Remark. The lenght of one or more geodesic can go to zero and the boundaries become a punctured.

We can now decompose, with the following theorem, all hyperbolic surfaces in a collection of pair of pants.

Theorem 3.2. *Let S be a surface of genus g and with n punctured. There is a set of $3g - 3 + n$ simple closed curves $(\gamma_1, \dots, \gamma_{3g-3+n})$ such that $S \setminus \gamma_i$ is a disjoint collection of pair of pants.*

Definition 3.15. Given a surface S and a pant decomposition $\gamma_1, \dots, \gamma_{3g-3+n}$, we have a map

$$(S) \rightarrow (\mathbb{R}^{+3g-3+n}, \mathbb{R}^{3g-3+n})X \mapsto (l_{\gamma_1}(X), \dots, l_{\gamma_{3g-3+n}}(X), \tau_{\gamma_1}(X), \dots, \tau_{\gamma_{3g-3+n}}(X))$$

This map is injective and is call the Fenchel-Nielsen coordinates.

Theorem 3.3. *There is a collection $\delta_1, \dots, \delta_{9g-9}$ of simple closed curves such that $\mathcal{T}_g \rightarrow \mathbb{R}^{9g-9}$ is injective.*

Proof. Let take $(\gamma_1, \dots, \gamma_{9g-9})$ a decomposition in pair of pants, $(\alpha_1, \dots, \alpha_{9g-9})$ be a collection of simple closed curves such that $i(\gamma_i, \alpha_i) > 0$ and $i(\gamma_i, \alpha_j) = 0$ for $i \neq j$, finnely we take $\beta_i = D_{\gamma_i}(\alpha_i)$. We want to show that the length of this collection of $9g - 9$ curves determined the hyperbolic structure $X \in \mathcal{T}_g$. X already has the Fenchel-Nielsen coordinate, of the pant decomposition $(\gamma_1, \dots, \gamma_{3g-3}), (l_{\gamma_1}(X), \tau_{\gamma_1}(X), \dots, l_{\gamma_{3g-3}}(X), \tau_{\gamma_{3g-3}}(X))$ so we need only to show that the parameters $\tau_{\gamma_i}(X)$ are determined by the lenght of the collection. Up to a renormalisation we can take $\tau_{\gamma_i}(X) = 0$ for every i . Now let's take $t = (t_1, \dots, t_{3g-3}) \in \mathbb{R}^{3g-3} \setminus 0$. We will note X_t the hyperbolic geometry which has the same length as X and twist parameters t in the Fenchel-Nielsen coordinate of the pair of pants. So $X_0 = X$. We will consider the function $A(t) = l_{\alpha_1}(X_t)$ and $B(t) = l_{\beta_1}(X_t)$. This function depend only of t_1 as $i(\gamma_i, \alpha_j) = 0$ for $i \neq j$. Moreover they are strictly convex and by definition we have $A(t_1 + l_{(\gamma_1)}(X)) = B(t_1)$. We will show that there is no $t_1 \neq 0$ such that $A(t_1) = A(0)$ and $B(t_1) = B(0)$ that is $A(t_1 + l_{(\gamma_1)}(X)) = A(l_{(\gamma_1)}(X))$. We will note $s = t_1$ and $L = l_{(\gamma_1)}(X)$ Suppose there is $s \neq 0$ such that $A(s) = A(0)$, we can take $s > 0$, the other case is symetric. If $s < L$, then by convexity for every $t \in]0; s[$, $A(t) < A(0) = A(s)$ and A is strictly increasing after s so as $s < L < L + s$ we have $A(L) < A(L + s)$. If $s > L$, then $L < s < L + s$ and $A(L) < A(L + s)$. The final case $s = L$ is also impossible since we would have $A(0) = A(L) = A(2L)$. Finally we can make the same argument for the other twist parameters which conclude the proof. \square

3.4 The collaring theorem

We will now give a useful tool to give necessary condition on length of two intersecting geodesics.

The collar function $\eta :]0; \infty[\rightarrow]0; \infty[$ is defined as follow. We draw a segment of lenght $l > 0$ on a geodesic γ , then we project perpendiculary to the geodesic the end of this segment to infinity and draw the geodesic δ which have this endpoint. So we have $\eta(l) = d(\gamma, \delta)$.

It is an exercice to show that:

$$\eta(l) = \frac{1}{2} \ln \left(\frac{\cosh(l/2) + 1}{\cosh(l/2) - 1} \right)$$

This quantity will code a long in the "tube" generate by a simple closed geodesic. We give a definition to make this a little more precise.

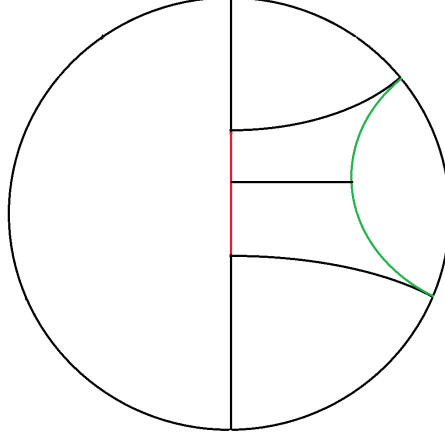


Figure 6: In red the segment on γ , in green δ . $\eta(l)$ is the length of the black segment between them.

Definition 3.16. Let γ be a simple closed geodesic of length l on a hyperbolic surface X . If the δ -neighborhood

$$A_\delta(\gamma) := \{x \in X | d(x, \gamma) < \delta\}$$

is isometric to the δ -neighborhood of the unique simple closed geodesic on the cylinder of modulus $\frac{\pi}{l}$, we say that γ admit a δ -collar, or that $A_\delta(\gamma)$ is the δ -collar of γ .

We can now state a useful theorem.

Theorem 3.4. Let X be a complete hyperbolic surface, and let $\Gamma := \gamma_1, \dots$ be a collection of disjoint simple closed geodesic, each γ_i of length l_i . Then $A_{\eta(l_i)}(\gamma_i)$ are collars around the γ_i , and they are disjoint.

Proof. Choose γ_1 and γ_2 and add other simple closed curve to have a maximal multicurve that includes both. Now cutting along this curve we have a set of pair of pant so we only have to show that the $\eta(l_i)$ neighborhood of γ_i the boundaries of the pair of pant do not intersect each other. We cut the pair of pant along geodesics comming from a boundary C and meeting the two other boundaries A and B . We unfold this figure in the hyperbolic plane and name the side of the octogone following the figure below.

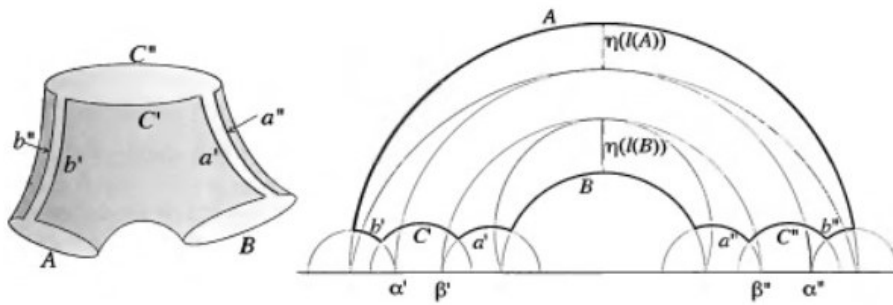


Figure 7: image from [2]

Since a' and b' have the common perpendicular C' , they do not intersect and similarly for a'' and b'' . The theorem follow easily by the definition of the function η .

□

There are some corollaries which follow from this theorem and are ready to use in many occasions.

Corollaire. *Let X be a hyperbolic surface, and γ_1, γ_2 two simple closed geodesics on X of lengths l_1 and l_2 . If $l_2 < 2\eta(l_1)$, then either $\gamma_1 = \gamma_2$ or $\gamma_1 \cap \gamma_2 = \emptyset$*

Proof. If $\gamma_1 \neq \gamma_2$ and $\gamma_1 \cap \gamma_2 \neq \emptyset$ then γ_2 must cross the collar neighborhood of γ_1 from one boundary to the other and so have length strictly superior than $2\eta(l_1)$. \square

Corollaire. *Let X be a hyperbolic surface, and let γ_1, γ_2 be two simple closed geodesics with lengths $< \ln(3 + 2\sqrt{2})$. Then either $\gamma_1 = \gamma_2$ or $\gamma_1 \cap \gamma_2 = \emptyset$.*

Corollaire. *Let X be a complete hyperbolic surface, γ a simple closed geodesic on X of length l , and A_γ the collar around γ . Then any simple geodesic δ on X that enter A_γ either intersect γ or spirals towards γ .*

Proof. Suppose the geodesic δ enters A_γ . We can lift the situation in the universal cover of the hyperbolic disc, where $\tilde{\gamma}$ is a lift of γ can be a diameter of the circle. Then if $\tilde{\delta}$ do not intersect $\tilde{\gamma}$ and do not have the same point at infinity, then its two endpoint are on the same side of $\tilde{\gamma}$ in the disc. Now the translation along $\tilde{\gamma}$ of length $l_\gamma(X)$ is in the representation of $\pi_1(X)$. If $\tilde{\delta}$ intersect A_γ then by the definition of δ it will intersect with its image by the translation cited before and hence is not simple in X . \square

4 Isomorphisme of Mirzhakani

The aim of this part is to demonstrate the following statement

Theorem 4.1. *There is a measurable conjugacy F between the earthquake flow $(\lambda, X) \mapsto (\lambda, E_{t\lambda}(X))$ on $\mathcal{ML} \times \mathcal{T}_g$ and the Teichmüller unipotent flow action of*

$$u_t = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$$

on the bundle \mathcal{QD} of nonzero quadratic differentials over Teichmüller space \mathcal{T}_g .

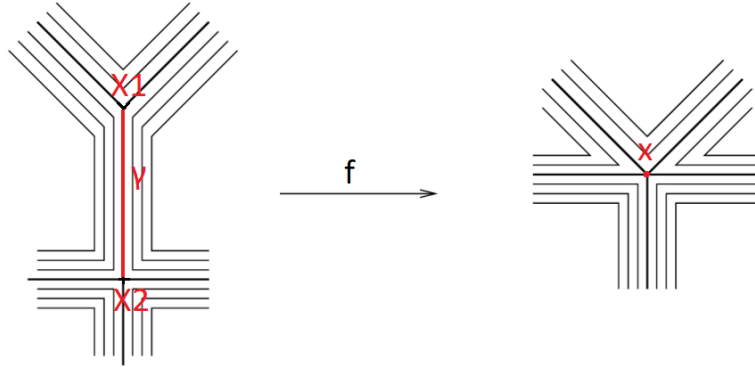
$$\begin{array}{ccc} \mathcal{ML} \times \mathcal{T}_g & \xrightarrow{E_t} & \mathcal{ML} \times \mathcal{T}_g \\ F \downarrow & & \downarrow F \\ \mathcal{QD} & \xrightarrow{u_t} & \mathcal{QD} \end{array}$$

4.1 Tightening map

A first correspondence, found by Thurston, exist between measured foliation and measured lamination. We will mostly follow the paper of Levitt [4].

Definition 4.1. We say that two foliations are equivalent if we can pass from one to the other by Whithead (see definition below) moves or isotopy (homeomorphism isotopic to the identity).

Definition 4.2. Given a measure foliation, an critical segment γ is an arc between two singularities along a leaf which is not a simple closed curve. There is a map f homotopic to the identity that collapse γ to a point x and is identity outside a neighborhood of γ which contain no other singularity. Doing so we reduce the number of singularities of the foliation and if the extremities of γ are singularities of order k_1 and k_2 , x is now a singularity of the new foliation of order $k_1 + k_2 - 2$.



Theorem 4.2. *Let X be a closed orientable hyperbolic surface and \mathcal{F} a foliation. There is a canonical geodesic lamination $\gamma(\mathcal{F})$ associated to \mathcal{F} . If \mathcal{F} and \mathcal{F}' are associated foliation then $\gamma(\mathcal{F}) = \gamma(\mathcal{F}')$. In the opposite direction given a geodesic lamination γ , one can find a foliation \mathcal{F} such that $\gamma(\mathcal{F}) = \gamma$ and it's unique up to equivalence.*

Definition 4.3. A *transverse curve* is a simple closed curve C which is never tangent to \mathcal{F} and contain no singularity of \mathcal{F} .

Remark. Since \mathcal{F} contain only saddle singularities, C cannot be contractible, therefor C is isotopic to a simple closed geodesic.

We will work on the universal cover of X , which is the Poincaré disc \mathbb{D} with circle "at infinity" \mathbb{S} . We call $p : X \rightarrow \mathbb{D}$ the universal projection. $\tilde{\mathcal{F}}$ is $p^{-1}(\mathcal{F})$.

We will say that a foliation follow the (*) condition if the following is true:

If f_1 and f_2 are two compact homotopic leaves then all leaf in the open annulus between them is also compact.

Lemma 4.3. *Let h be a leaf of $\tilde{\mathcal{F}}$. Each end of h converge to a point of \mathbb{S} ; the two point at infinity cannot be the same*

Proof. First, we should notice that the behavior of leaf at infinity do not change if we take an equivalent foliation. Indeed a homeomorphism ϕ on a compact fundamental domain isotopic to the identity can be extend to an homeomorphism $\tilde{\phi}$ on \mathbb{D} such that $dist(x, \tilde{\phi}(x)) \leq K$. This implie that $\tilde{\phi}$ extend es the identity on the boundary \mathbb{S} .

Then given a leaf h of $\tilde{\mathcal{F}}$, we take a half leah h_0 . If $p(h_0)$ is compact or spiral toward a compact leaf of \mathcal{F} then the first part of the lemme is imediate.

Otherwise, $p(h)$ meet a transverse curve C infinitely often. With an isotopie we can take C to be a geodesic. Now h_0 can meet a connect component of $\tilde{C} = p^{-1}(C)$ only one time. Otherwise there will be a disk bound by an arc of \tilde{C} and an arc of h_0 , which is impossible considering the transversity of C and that \mathcal{F} have no 1-type singularities.

Now every compact of \mathbb{D} meet a finite number of connected components of \tilde{C} so the limit set of h_0 must be on \mathbb{S} . This limit set is connected and non empty. Moreover it should not contains any end of a connected component of \tilde{C} . But the ends of connected components of \tilde{C} are dense in \mathbb{S} as \tilde{C} is the image of a geodesic by $\pi_1(X)$. This show the first point of the lemma.

The second assertion is clear if $p(h)$ is compact or if it meet a transverse curve C at least twice since then every connected components of \tilde{C} separate the end of h .

Otherwise $p(h)$ spiral toward two compact leaf f_1 and f_2 . If $f_1 = f_2$ and the two end point of h are the same then there will be a singularity that would not be a saddle. $f_1 \neq f_2$ is impossible since \mathcal{F} follow the condition (*). \square

We can now associate to every leaf h a geodesic $\gamma(h)$ by joining the endpoint. Then $\gamma(\tilde{\mathcal{F}}) = \cup_{h \in \tilde{\mathcal{F}}} \gamma(h)$ is a disjoint union of geodesic invariant by $\pi_1(X)$. We have to show that this set is closed to concluded that we have a lamination.

Lemma 4.4. *$\gamma(\tilde{\mathcal{F}})$ is closed in $\bar{\mathbb{D}}$*

Proof. Let $g_n = \gamma(h_n)$ be a sequence of geodesics in $\gamma(\tilde{\mathcal{F}})$ converging to a geodesic g . We want to show $g \in \gamma(\tilde{\mathcal{F}})$. We can suppose that all the g_n are distinct of g and are all on the same side.

Let L be the limit set in $\bar{\mathbb{D}}$. For all leaf m in $\tilde{\mathcal{F}}$, we call \bar{m} the closure of m by adding the two end point in \mathbb{S} . Then L meet at least one connected component of $\bar{\mathbb{D}}$ \bar{m} . As the end points of all leaf of $\tilde{\mathcal{F}}$ is a dense subset of \mathbb{S} , L contain a leaf h . Taking a half-leaf h_0 , we want to show that the end point is the same as one of g .

A first case is if there is a simple closed curve C transverse to \mathcal{F} which meet $p(h_0)$ infinitely often. If h_0 does not converge to the corresponding point at infinity then there would be a connected component of $p^{-1}(C)$ that contains the point of infinity of h_0 but does not contain the point of infiny of h_n which is impossible for large n .

A second case is if $p(h_0)$ spirals toward a compact leaf, then closed leaf close to $p(h_0)$ also spirals toward the same compact leaf. Then h_0 converges to one of the points at infinity of g which is a point at infinity of h_n fot n large.

Finally if $p(h)$ is compact then $p(h_n)$ spirals toward it for large n , therefore $\gamma(h)$ and g have one point in common at infinity. If the second was different, by applying a transformation leaving $\gamma(h)$ invariant (but not g), we would separate h from the leaves h_n , and it is a contradiction. \square

Now we want to exhibit an inverse construction which take a lamination λ and give a foliation μ . To do this we still consider $\tilde{\lambda}$ in the universal cover. We will suppose that every complementary region is a ideal polygon.

We can build a skeleton that it compose of edge between vertex and a choosen point in the center. After building the skeleton for every polygon we fill the complementary region which will be between four edge by line between the two vertex.

This map is often called the "collapsing" map and its inverse the "tightening" map.

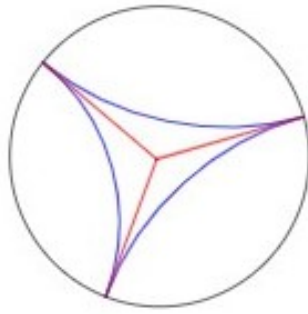


Figure 8: In red the skeleton of the ideal triangle in blue, Image from [7]

The measure we put on this foliation is uniform on every region between four edges of the skeleton.

4.2 Correspondance between foliations and quadratic differentials

For a quadratic differential q , one can define two measured foliations, the horizontal $h(q)$ and the vertical $v(q)$ corresponding in locate coordinate to $Re(z)$ and $Im(z)$. This give a map two the pair of foliation but it is not the subjectif, we should restrict ro the image. Define $\Delta = (\alpha, \beta) : i(\alpha, \gamma) = i(\beta, \gamma) = 0$, for some $\gamma \in \mathcal{MF}$. Δ contain the diagonal (α, α) and is kind of "fat" diagonal.

Lemma 4.5. *For any $q \in \mathcal{QD}$, $(h(q), v(q)) \notin \Delta$*

Theorem 4.6. *The map $q \mapsto (h(q), v(q))$ define a homeomorphism $\mathcal{QD} \rightarrow \mathcal{MF} \times \mathcal{MF} \setminus \Delta$*

4.3 Shear Cordinate

Finally there is a map that, given a hyperbolic structure X and a lamination λ create a measured foliation which is transverse to λ .

For simplicity we will ask that λ is a maximal lamination i.e. if $\tilde{\lambda}$ is the pre-image of λ in the universal cover \mathbb{D} , $\mathbb{D} \setminus \tilde{\lambda}$ is made of ideal triangle. We will first work in this triangles minus a region on the center, then give a measure in this foliation, and finnally show that ot is a homeomorphism.

So in one the ideal triangle, given two side we can draw an arc perpendicular with the this two sides, which is the intersection of the ideal triangle with the circle tangent to the boundary

of \mathbb{D} in the common extremity the two arc chosen. Then by rescaling by a factor $r \in [0; 1]$ and doing the same procedure for the two other pair we get a foliation in the ideal triangle minus a locus in the center.

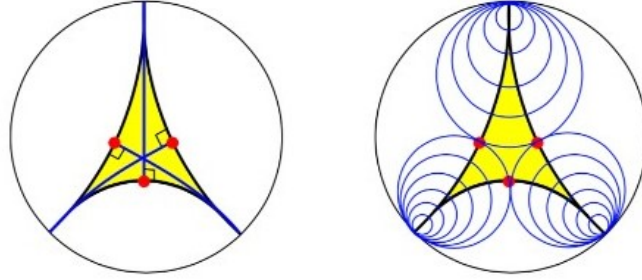


Figure 9: Image from [6]

Then we can find a full foliation by pitching the resulting.

We have a natural transverse measure to this foliation. For an arc in one ideal triangle of the lamination we can project it along the leaf of the foliation to a segment in the edge of the ideal triangle, the length of the arc will be the length of the segment. As the leaf are horocycle circle based on the same point, it will not depend of which side we choose to project. Then given an arbitrarily arc we decompose it along the ideal triangle it meet.

We want to show that this construction is reversible, that is given $\mu \in \mathcal{MF}_\lambda$, the set of foliation transverse to the lamination, we can construct $X \in \mathcal{T}_g$ whose horocycle foliation is μ .

The idea is that, if we already know X , the lamination λ can be lift to $\tilde{\lambda}$ which is invariant of Γ the fushian group of X . But we can built $\tilde{\lambda}$ only with the information given by μ .

We will note $\tilde{\mu}$ the preimage of μ in \mathbb{D} . If we consider two triangles T_1 and T_2 that are complementary region of $\tilde{\lambda}$ and we suppose we take a segment A in a leaf of $\tilde{\mu}$ that goes to an edge of T_1 to T_2 . We name v_1 and v_2 the two vectors with footprint in the edge and tangent to them. Then there is a Moebuis transformation S which take one to the other. With one more information, the "shear", we can place T_2 on \mathbb{D} , according to the position of T_1

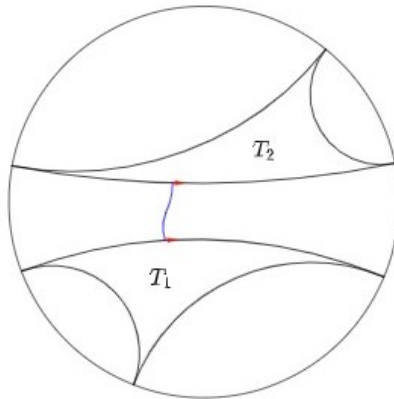


Figure 10: Image from [7]

Indeed given only a Moebuis transformation we still have a one parameter families of triangle T_2 with an edge generated by v_2 . To fix this we trace two orthogeodesic coming from the vertex of the ideal triangles facing the considered edges and from the point of intersection in

T_1 we follow a leaf of the foliation, then when we meet T_2 we have to move along the geodesic edge to find the other point of intersection. This lenght is the shear between T_1 and T_2

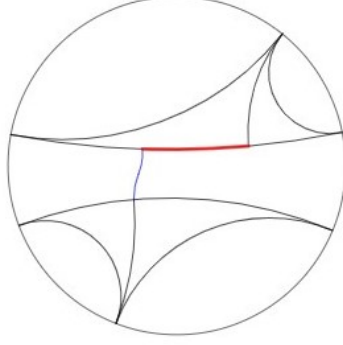


Figure 11: Image from [7]

Let I be the set of all triangles in \mathbb{D} that A meet. For each $i \in I$ we can define v_i^+ and v_i^- the vectors tangent to the edge of the corresponding triangle at the intersection of the edges and A . Note that I is a countable totally ordered but non well ordered set. So if we take S_i the Moebuis transformation which take v_i^- to v_i^+ , we have to give a meaning of the expression

$$\prod_{i \in I} S_i$$

Definition 4.4. Given a countable totally ordered set of indice I and element S_i in a Banach algebra, we say that $\prod_i S_i$ is well defined and equal to S if for any increasing chain

$$I_0 \subset I_1 \subset \dots \subset I$$

with $\cup_k I_k = I$ we have $\lim_{k \rightarrow \infty} \prod_{i \in I_k} S_i = S$.

Lemma 4.7. For element s_i in a Banach algebra index by a countable totallyordered set, if $\sum \|s_i\| < \infty$, then $\prod(1 + s_i)$ is well-defined.

Proof. For $1 \leq m \leq n$, we have

$$\left\| \prod_{i=1}^n (1 + s_i) - \prod_{i=1, i \neq m}^n (1 + s_i) \right\| \leq \|s_m\| \left\| \prod_{i=1, i \neq m}^n (1 + s_i) \right\| \leq \|s_m\| \prod_{i=1}^n (1 + \|s_i\|)$$

Or with the assumption $\sum \|s_i\| < \infty$ we have that $\prod(1 + \|s_i\|) \leq C < \infty$, so removing or adding $1 + s_m$ produce a change bound by $\|s_m\|C$. \square

Now we want to apply this lemma to $S_i - Id$, with Id the identity matrice.

Lemma 4.8. For the previous S_i , if we note $s_i = S_i - Id$ we have $\sum \|s_i\| < \infty$.

Proof. Each S_i is conjugate to a horocycle transformation of time one. The conjugacy is made by a geodesic flow along the edges of the triangle. We can compute

$$\begin{pmatrix} e^{-t/2} & 0 \\ 0 & e^{t/2} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} e^{t/2} & 0 \\ 0 & e^{-t/2} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & e^{-t} \\ 0 & 0 \end{pmatrix}$$

So the norm of s_i is inversally corrolated to the amount of geodesic flow used in the conjugaision. Now we can parttion the indice set I into finely many subset (I_k) according to to which spike

of the lamination the arc of A cross. Then for a spike the sum of $\|s_i\|$ where $i \in I_k$ is finite, indeed the distance between two neighboring crossing is bound below by a constant and so the amount of time we should do the geodesic flow increase at most linearly and finally the norm of the s_i should decrease geometrically. \square

So we can conclude that there is a unique Moebius transformation S equal to the meaningful expression $\prod_i S_i$.

Now we can conclude the proof. There exist, without any hyperbolic structure X topological classes for $\tilde{\mu}$ and $\tilde{\lambda}$. We choose one arbitrary ideal triangle T_1 in the lamination. For every other triangle T_2 , the Moebius transformation and the shear are data that can be computed only using the transverse measure of $\tilde{\mu}$. So we can place T_2 , and the other triangle. The closure of this set gives the lamination $\tilde{\lambda}$. $\tilde{\lambda}$ will be preserved by a Fuchsian group Γ and we will have $X = \mathbb{D}/\Gamma$.

5 Mixing rate

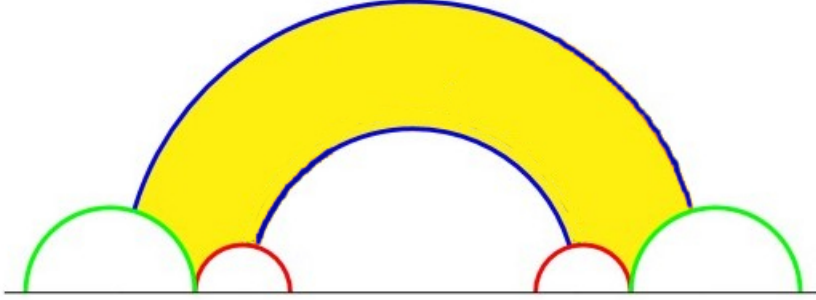
6 Example of the once punctured torus

A torus can not have a hyperbolic structure, it has naturally a flat structure as the quotient $\mathbb{R}^2/\mathbb{Z}^2$. This changes when one study the one punctured torus. It is a torus S where we choose a point p and remove it (or just marked it).

The construction of this object can be done in two manier at least. For the first construction, one have to choose a hyperbolic octogone where one side have length 0 and the two other one l , then we sew the border of two of this octogone which give a pair of pant. Finally we can glued with a twist τ to have the one punctured torus.

A second construction is given by the representation. Given two hyperbolic isomorphism of \mathbb{H} A and B with different fixed point on $\partial\mathbb{H}$ and with $H := ABA^{-1}B^{-1}$ the commutator should be a parabolic element.

A fundamenteal domaine is given by the following image:



Given two generators α and β of $\pi_1(S)$, two closed curves non homotopically trivial which intersect one, one can parametrize all other lamination. Indeed a given lamination $\lambda \in \mathcal{ML}$ is determined by the couple $(i(\alpha, \lambda), i(\beta, \lambda))$ where $i(., .)$ is the geometric intersection number.

We have this useful lemma to estimate the length of the systole function in the Teichmuller space.

Lemma 6.1. *Pick γ a simple closed geodesic, and $X \in \mathcal{T}(S_{1,1})$, if X has Fenchel-Nielsen coordinate $(L, \frac{p}{q})$ with respect to γ , where $\gcd(p, q) = 1$ and $\frac{p}{q} \in]0; 1[$, then*

$$C_1(L)e^{\frac{-L}{2q}} < l_{sys}(X) < C_2(L)e^{\frac{-L}{2q}}$$

where $C_1(L)$, $C_2(L)$ both limits to 4 when p, q are fixed and L goes to ∞

Proof. Let $R(L)$ be the length of the shortest geodesic arc with endpoints on γ . We have

$$R(L) = 2\log(\coth(L/4)) = 2\log\left(\frac{e^{L/2} + 1}{e^{L/2} - 1}\right)$$

By the collar lemma. Then if we take α a simple closed curve that intersect γ , q times exactly, we obtain the following inequality with $a = l_\alpha(X)$

$$qR(a) < L < qR(a) + \frac{qa}{2}$$

Reorganizing the termes we have

$$e^{-a/4}\tanh(a/4) < e^{-L/2q} < \tanh(a/4)$$

As $a \rightarrow 0$ then $L \rightarrow \infty$

$$C_1(L)e^{\frac{-L}{2q}} < a < C_2(L)e^{\frac{-L}{2q}}$$

To complete the proof, we need to show that the length of α is shorter than any other géodesic closed curves, but with the collar lemma there is only one systole whose length goes to 0 and this is the case for α as $L \rightarrow \infty$.

If we don't do any approximation we have

$$2\ln\left(\frac{1 + e^{-L/2q}}{1 - e^{-L/2q}}\right) < a$$

□

Theorem 6.2. *Let $\nu(S_{1,1})$ be the finite measure on $\mathcal{P}^1\mathcal{M}(S_{1,1})$. Then*

$$\nu(S_{1,1})\{(X, \lambda) \in \mathcal{P}^1\mathcal{M}(S_{1,1}) | l_{sys}(X, \lambda) < \epsilon\} = O\left(\frac{\epsilon}{\log \epsilon}\right)$$

as $\epsilon \rightarrow 0$

Let fix $\epsilon = l_{sys}(X)$, and $T > 0$, then $\exists N = N(\epsilon, T)$ such that $\forall n \geq N$

$$|l_{sys}E_t(X, \lambda) - l_{sys}E_t(X, \frac{\gamma_n}{l_{\gamma_n}(X)})| < \epsilon$$

So we calculate T_n such that $\forall |t| < T_n$, $l_{sys}E_t(X, \frac{\gamma_n}{l_{\gamma_n}(X)}) < 2\epsilon$ and $T = \liminf T_n$. If $T > 0$, $\exists N_1$ such that $\forall n \geq N_1$, $T_n \geq \frac{T}{2}$.

Then we set $N_2 = N(\epsilon, T/2)$ and we have $l_{sys}E_t(x, \lambda) \leq 2.5\epsilon$, $\forall 0 \leq t \leq T/2$

We have two useful tools to understand the length function along a earthquake path.

Lemma 6.3. *Let $X \in \mathcal{T}(S_g)$, and γ a curve which is part of a pant decomposition. χ_s is the twist of length s around γ , and b a closed curve with $i(b, \gamma) > 0$ then $s \mapsto l_{\chi_s}(b)$ is strictly convex.*

[1] proposition 10.8

Lemma 6.4. *If α is a closed curve, γ an other closed curve and λ a lamination.*

$$\begin{aligned} \frac{dl_\alpha}{dt}(0) &= \sum_{p_i \in \alpha \cap \gamma} \cos(\theta_{p_i}) \\ \frac{dl_\alpha}{dt}(0) &= \int_\alpha \cos(\theta) d\theta \end{aligned}$$

[3] Corollary 3.3 and 3.4

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