DIVERGENCE OF TEICHMÜLLER GEODESICS

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Abstract. We study the asymptotic geometry of Teichmüller geodesic rays. We show that when the transverse measures to the vertical foliations of the quadratic differentials determining two different rays are topologically equivalent, but are not absolutely continuous with respect to each other, then the rays diverge in Teichmüller space.

1. Introduction

Let $S$ be an oriented surface of genus $g$ with $n$ punctures. We assume $3g - 3 + n \geq 1$. Let $T(S)$ denote the Teichmüller space of $S$ with the Teichmüller metric $d(\cdot, \cdot)$. A basic question in geometry is to study the long term behavior of geodesics. In this paper we study the question of when a pair of geodesic rays $r_1(t), r_2(t)$ stay bounded distance apart, and when they diverge in the sense that $d(r_1(t), r_2(t)) \to \infty$ as $t \to \infty$. Teichmüller’s theorem implies that a Teichmüller geodesic ray is determined by a quadratic differential $q$ at the base point and that the surfaces along the ray are found by stretching along the horizontal trajectories of $q$ and contracting along the vertical trajectories.

Many cases of the question of divergence of rays are already known. It is a general principle that the asymptotic behavior of the ray is determined by the properties of the vertical foliation of $q$. The first instance was if the quadratic differentials $q_1, q_2$ defining $r_1, r_2$ are Strebel differentials. This means that their vertical trajectories are closed and decompose the surface into cylinders. In [5] it was shown that if the homotopy classes of the cylinders for $q_1$ coincide with those of $q_2$, then $r_1, r_2$ stay bounded distance apart. In particular this showed that the Teichmüller metric was not negatively curved in the sense of Busemann. A second known case was if the vertical foliations of $q_1, q_2$ are minimal, topologically equivalent and uniquely ergodic. In that case the rays also stay bounded distance apart (5).

The next possibility is the vertical foliations of $q_1, q_2$ are topologically equivalent, have a minimal component and yet are not uniquely ergodic. In that case in each minimal component there exist a finite number of mutually singular ergodic measures, and any transverse measure is a convex combination of the ergodic measures. Ivanov (3) showed that if the transverse measures of $q_1, q_2$ in these minimal components are absolutely continuous with respect to each other, then the rays stay bounded distance apart. The main result of this paper is the converse. We will prove (Theorem 1) that the rays $r_1, r_2$ diverge if the vertical foliation of $q_1$ is topologically equivalent to the vertical foliation of $q_2$, and there is

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a minimal complimentary component $\Omega$ of the vertical foliations such that the transverse invariant measures are not absolutely continuous with respect to each other. In particular this holds when the transverse measures are distinct ergodic measures.

The last possibility is that the vertical foliations of $q_1, q_2$ are not topologically equivalent. If the geometric intersection of the vertical foliations is nonzero, then the rays diverge (3). We prove (Theorem 2) that the rays $r_1, r_2$ diverge if the vertical foliations are not topologically equivalent and have 0 intersection with each other. These theorems together with the previously known results completely answer the question of divergence of rays.

The outline of the proof of Theorem 1 is as follows. We will find (Proposition 1) for any time $t$, a subsurface $Y(t) \subset \Omega$ with short boundary such that the area of $Y(t)$ is small on the surface on one ray, and bounded away from 0 on the surface along the other. This is where we use the assumption that the measures are not absolutely continuous with respect to each other. We will also find (Lemma 3) a bounded length curve $\gamma(t) \subset Y(t)$ on one surface which is “mostly vertical” with respect to the flat metric of the quadratic differential. Then on the other surface it has comparable length. The fact that the lengths are comparable and the areas have large ratio will allow us (Lemma 4) to show that the ratio of the extremal length of $\gamma(t)$ on a surface along one ray to the extremal length on the other is large. We then apply Kerckhoff’s formula to conclude that the surfaces are far apart in Teichmuller space.

We will also prove (Theorem 3) that given any pair of ergodic measures $\nu_1, \nu_2$ on a minimal nonuniquely ergodic foliation $F$ there is a sequence of multicurves $\{\gamma_i(n)\}_{i=1}^p$ such that for a pair of sequences of weights $\{a_i(n)\}$ and $\{b_i(n)\}$ we have $\sum_{i=1}^p a_i(n)\gamma_i(n) \to \nu_1$ and $\sum_{i=1}^p b_i(n)\gamma_i(n) \to \nu_2$ in the topology of $PMF$, Thurston’s sphere of measured foliations. This problem was suggested to us by Moon Duchin.

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2. Measured foliations

Recall a measured foliation on a surface $S$ consists of a finite set $\Sigma$ of singular points and a covering of $S \setminus \Sigma$ by open sets $\{U_\alpha\}$ with charts $\phi_\alpha : U_\alpha \to \mathbb{R}^2$ such that the overlap maps are of the form

$$(x, y) \to (f(x, y), \pm y + c).$$

The leaves of the foliation are the lines $y = \text{constant}$. The points $\Sigma$ are $p \geq 3$ pronged singularities. One allows single pronged singularities at the punctures. A measured foliation comes equipped with a transverse invariant measure which in the above coordinates is given by $\mu = |dy|$. Henceforth we will denote measured foliations by $[F, \mu]$.

For any homotopy class of simple closed curves $\beta$ let

$$i([F, \mu], \beta) = \inf_{\gamma \sim \beta} \int_{\beta'} d\mu.$$
The intersection with simple closed curves extends to an intersection function
\
i([F_1, \mu_1], [F_2, \mu_2])

on pairs of measured foliations.

Let \( \Gamma_F \) denote the compact leaves of \([F, \mu]\) joining singularities. It is well-known that each component \( \Omega \) of \( S \setminus \Gamma_F \) is either an annulus swept out by closed leaves or a minimal domain in which every leaf is dense.

**Definition 1.** We say that two foliations \([F_1, \mu_1], [F_2, \mu_2]\) are topologically equivalent if there is a homeomorphism of \( S \setminus \Gamma_{F_1} \to S \setminus \Gamma_{F_2} \) isotopic to the identity which takes the leaves of \( F_1 \) to the leaves of \( F_2 \).

**Definition 2.** A foliation \([F, \mu]\) in a minimal domain \( \Omega \) is said to be uniquely ergodic if the transverse measure \( \mu \) restricted to \( \Omega \) is the unique transverse measure of the foliation \([F, \mu]\) up to scalar multiplication.

More generally suppose \( \Omega \) is a minimal component of \([F, \mu]\). There exist invariant transverse measures \( \nu_1 = \nu_1(\Omega), \ldots, \nu_p = \nu_p(\Omega) \) such that

- \( p \) is bounded in terms of the topology of \( \Omega \).
- \( \nu_i \) is ergodic for each \( 1 \leq i \leq p \).
- any transverse invariant measure \( \nu \) on \( \Omega \) can be written as \( \nu = \sum_{i=1}^{p} a_i \nu_i \) for \( a_i \geq 0 \).

Thus the transverse measures are parametrized by a simplex in \( \mathbb{R}^p \). Two foliations \([F, \mu_1]\) and \([F, \mu_2]\) are absolutely continuous with respect to each other if when the measures are expressed as a convex combination as above, the indices with positive coefficients are identical. Equivalently they are absolutely continuous with respect to each other if they lie in the same open face of the simplex.

### 3. Quadratic differentials and Teichmüller rays

A meromorphic quadratic differential \( q \) on a closed Riemann surface \( X \) with a finite number of punctures removed is a tensor of the form \( q(z)dz^2 \) where \( q \) is a holomorphic function and \( q(z)dz^2 \) is invariant under change of coordinates. We allow \( q \) to have at most simple poles at the punctures.

As such there is a metric defined by \( |q(z)|^{1/2}|dz| \). The length of an arc \( \beta \) with respect to the metric will be denoted by \( |\beta|_q \). There is an area element defined by \( |q(z)||dz|^2 \). We will denote by \( \text{Area}_q\Omega \) the area of a subsurface \( \Omega \subseteq X \).

Away from the zeroes and poles of \( q \) there are natural holomorphic coordinates \( z = x + iy \) such that in these coordinates \( q = dz^2 \). The lines \( x = \text{constant} \) with transverse measure \( |dx| \) define the vertical foliation \([F^v_q, |dx|]\). The lines \( y = \text{constant} \) with transverse measure \( |dy| \) define the horizontal measured foliation \([F^h_q, |dy|]\). The transverse measure of an arc \( \beta \) with respect to \( |dy| \) will be denoted by \( v_q(\beta) \) and called the vertical length of \( \beta \). Similarly we have the horizontal length denoted by \( h_q(\beta) \).

We denote by \( \Gamma_q \) the vertical critical graph of \( q \). This is the union of the vertical leaves joining the zeroes of \( q \).
Definition 3. Suppose there is an embedding of a Euclidean cylinder in $\mathbb{R}^3$ into $X$ which is an isometry with respect to the metric of $q$. The image is called a flat cylinder.

The Teichmüller space of $S$ denoted by $\mathcal{T}(S)$ is the set of equivalence classes of homeomorphisms $f : S \to X$ where $f_i : S \to X_i$, $i = 1, 2$ are equivalent if there is a conformal map $h : X_1 \to X_2$ with $f_2$ homotopic to $h \circ f_1$. The Teichmüller metric on $\mathcal{T}(S)$ is the metric defined by

$$d((X, g), (Y, h)) := \frac{1}{2} \inf \{ \log K(f) : f : X \to Y \text{ is homotopic to } h \circ g^{-1} \}$$

where $f$ is quasiconformal and

$$K(f) := \| K_x(f) \|_\infty \geq 1$$

is the quasiconformal dilatation of $f$, where

$$K_x(f) := \left| \frac{f_z(x)}{|f_z(x)|} \right| + \left| \frac{f_x(x)}{|f_x(x)|} \right|$$

is the pointwise quasiconformal dilatation at $x$.

Teichmüller’s Theorem states that, given any $X, Y \in \mathcal{T}(S)$, there exists a unique (up to translation in the case when $S$ is a torus) quasiconformal map $f$, called the Teichmüller map, realizing $d(X, Y)$. The Beltrami coefficient $\mu := \frac{\partial f}{\partial \bar{f}}$ is of the form $\mu = k \frac{\bar{q}}{|q|}$ for a unique unit area quadratic differential $q$ on $X$ and some $k$ with $0 \leq k < 1$. Define $t$ by

$$e^{2t} = \frac{1 + k}{1 - k}.$$ 

There is a quadratic differential $q(t)$ on $Y$ such that in the natural local coordinates $w = u + iv$ of $q(t)$ and $z = x + iy$ of $q$ the map $f$ is given by

$$u = e^t x, \quad v = e^{-t} y.$$ 

Thus $f$ expands along the horizontal leaves of $q$ by $e^t$, and contracts along the vertical leaves by $e^{-t}$.

Conversely, any unit area $q$ on $X$ determines a 1-parameter family of Teichmüller maps $f_t$ defined on $X$. Namely $f_t$ has Beltrami differential $\mu = k \frac{\bar{q}}{|q|}$ where $e^{2t} = \frac{1 + k}{1 - k}$. The image surface is denoted by $r(t)$ and $\{ r(t) : t \geq 0 \}$ is the Teichmüller ray based at $X$ in the direction of $q$. On each $r(t)$ we have the quadratic differential $q(t)$.

Now let $q_1, q_2$ quadratic differentials on $X_1$ and $X_2$ with vertical foliations $[F_{q_1}^v, |dx_1|]$ and $[F_{q_2}^v, |dx_2|]$ and determining rays $r_1, r_2$. Our main result is then

Theorem 1. Suppose $[F_{q_1}^v, |dx_1|]$ is topologically equivalent to $[F_{q_2}^v, |dx_2|]$. The rays $r_1, r_2$ diverge if there is a minimal complimentary component $\Omega$ of the foliation $F_{q_1}^v$ with ergodic measures $\nu_1, \ldots, \nu_p$ and so that restricted to $\Omega$, $|dx_1| = \sum \nu_i$, $|dx_2| = \sum \nu_i$ and there is some index $i$ so that either $a_i = 0$ and $b_i > 0$, or $a_i > 0$ and $b_i = 0$.

An equivalent way of formulating the Theorem is that the rays diverge if the measures do not lie in the same open face of the simplex of invariant measures.
3.1. Extremal length. We recall the notion of extremal length. Suppose $X$ is a Riemann surface and $\Gamma$ is a family of arcs on $X$. Suppose $\rho$ is a conformal metric on $X$. For an arc $\gamma$, denote by $\rho(\gamma)$ its length and by $A(\rho)$ the area of $\rho$.

**Definition 4.**

$$Ext_X(\Gamma) = \sup_\rho \inf_{\gamma \in \Gamma} \frac{\rho^2(\gamma)}{A(\rho)},$$

where the sup is over all conformal metrics $\rho$.

We will apply this definition when $\Gamma$ consists of all simple closed curves in a free homotopy class of some $\alpha$. In that case we will write $Ext_X(\alpha)$.

The following formula due to Kerckhoff ([4]) is extremely useful in estimating Teichmüller distances. For $X, Y \in T(S)$

$$d(X, Y) = \frac{1}{2} \log \sup_{\alpha} \frac{Ext_Y(\alpha)}{Ext_X(\alpha)}.$$

**Lemma 1.** Let $X$ be a Riemann surface. Let $q$ be a unit area quadratic differential on $X$. Let $\Omega$ be a subsurface with geodesic boundary $\gamma$. If the length $|\gamma|_q$ is small enough, then for any homotopy class of curves $\alpha \subset \Omega$

$$Ext_X(\alpha) \geq \frac{|\alpha'|^2_q}{Area_q(\Omega) + O(|\gamma|^2)}.$$

where $\alpha'$ is the geodesic in the homotopy class of $\alpha$.

**Proof.** Let $\epsilon = |\gamma|_q$. Define a metric $\rho$ on $X$ as follows. Let $\rho$ coincide with the $q$-metric on $N_\epsilon(\Omega)$, the $\epsilon$-neighborhood of $Y$ and the $q$ metric multiplied by a small $\delta$ on $\Omega' = X \setminus N_\epsilon(\Omega)$. Let $\alpha''$ be any curve in the homotopy class of $\alpha$. If $\alpha''$ is not contained in $\Omega$ then $\alpha''$ and a segment of $\gamma$ bound a disk. The fact that $d_\rho(\Omega', \Omega) = \epsilon$ and $\gamma$ is a geodesic implies that we can replace an arc of $\alpha''$ with an arc of $\gamma$ to produce $\alpha''' \subset \bar{Y}$ with smaller length. We conclude that the infimum of the length in the metric $\rho$ is realized by the geodesic $\alpha'$ in $\Omega$. By definition,

$$Ext_X(\alpha) \geq \frac{\inf_{\alpha'' \sim \alpha} |\alpha''|^2_q}{A(\rho)} \geq \frac{|\alpha'|^2_q}{Area_q(\Omega) + O(\epsilon^2) + \delta Area_q(\Omega')}.$$

Since $\delta$ is arbitrary we have the result.

**Definition 5.** Given a quadratic differential $q$ and $\delta > 0$, a geodesic $\gamma$ in the $q$ metric is called almost $(q, \delta)$-vertical if $v_q(\gamma) \geq \delta h_q(\gamma)$.

**Lemma 2.** Let $q$ be a quadratic differential on $X$ a surface without boundary. For any $\delta > 0$ there is a curve $\beta$ which is almost $(q, \delta)$-vertical.

**Proof.** If $\Gamma_q \neq \emptyset$ there is a vertical saddle connection which is obviously almost $(q, \delta)$-vertical. Thus we can assume that the vertical foliation is minimal. Let $A$ be the area of $q$. The first return map of the foliation to a horizontal transversal $I$ with an endpoint at a
singularity defines a generalized interval exchange transformation. The maximal number of intervals $n_0$ is determined by the genus of the surface and the orders of the singularities of $q$. Choose a horizontal transversal $I$ of length $\lambda$ satisfying

$$\lambda^2 < \frac{A}{2n_0\delta}.$$  

The transversal $I$ determines a decomposition of the surface into rectangles $\{R_i\}$, with heights $h_i$ and widths $\lambda_i$, whose horizontal sides are subsets of $I$. Each rectangle has two horizontal sides on $I$. Consequently, if we count each $\lambda_i$ twice we have

$$\sum_i \lambda_i = 2\lambda.$$  

Since we count each $\lambda_i$ twice we have

$$\sum_i h_i\lambda_i = 2A.$$  

**Figure 1.** $\beta$ is the union of $\beta_1$ and $\beta_2$  

**Figure 2.** $\beta$ is the union of $\beta_1, \beta_2, \beta_3$ and $\beta_4$  

We conclude that

$$\max_i h_i > \frac{A}{\lambda n_0}.$$  

Let $h_i$ realize this maximum. There are two cases. The first case (see Figure 1) is that the top and bottom of $R_i$ are on the opposite sides of $I$. Fix a small neighborhood $\mathcal{N}$ of
I. We form a simple closed curve \( \beta = \beta_1 \ast \beta_2 \). Here \( \beta_1 \) is a vertical segment in \( R_i \) whose endpoints \( p \) and \( q \) are on the boundary of \( N \), and \( \beta_2 \) is an arc transverse to the horizontal foliation in \( N \) joining \( p \) and \( q \). Then \( \beta \) is also transverse to the horizontal foliation. Its geodesic representative has the same vertical length, namely, \( h_i \). The horizontal length of \( \beta \) is at most \( \lambda \). Together with (2) and (3) we have that
\[
\frac{v_q(\beta)}{h_q(\beta)} \geq \delta.
\]

In the second case (Figure 2) the top and the bottom of \( R_i \) are on the same side of \( I \) (call it \( I^+ \)). Then there must also be a rectangle \( R_j \) with top and bottom on \( I_- \). We may form a simple closed \( \beta \) which consists of a vertical segment in \( R_i \), a vertical segment in \( R_j \) and a pair of arcs in \( N \) which are transverse to the horizontal foliation. Similar to the case above, the ratio of vertical and horizontal components of \( \beta \) is at least \( \delta \).

\[\square\]

Definition 6. Given a unit area quadratic differential \( q \) on a surface \( X \) without boundary a subsurface \( \Omega \subset X \) is said to be \((\epsilon, \epsilon_0)\)-thick
- Ext\(_X\)\((\partial\Omega) \leq \epsilon \)
- the shortest non-peripheral curve in \( \Omega \) has \( q \) length at least \( \epsilon_0 \).
- The boundary of \( \Omega \) is a geodesic in the metric of \( q \).

The surface \( X \) itself is \( \epsilon_0 \)-thick if it satisfies condition (2) above.

Lemma 3. For any \( B > 0, \epsilon_0 > 0 \) there exists \( \epsilon > 0, \delta > 0, D > 0, m_0 \) such that for any \((\epsilon, \epsilon_0)\)-thick surface \( \Omega \subset X \) which does not contain a flat annulus isotopic to a boundary component and such that \( \text{Area}_q(\Omega) \geq B \)
(1) there is an almost \((q, \delta)\)-vertical geodesic \( \gamma \) whose interior lies in \( \Omega \) and such that \( |\gamma|_q < D \).
(2) there is an \( m \leq m_0 \) and a collection \( \omega_1, \ldots, \omega_m \) of disjoint vertical leaves so that for every horizontal leaf \( L \)
\[
|\text{card}(L \cap \gamma) - \sum_{i=1}^{m} \text{card}(L \cap \omega_i)| \leq 2.
\]

Proof. For the proof of the first statement, we argue by contradiction. If it is not true then there is a sequence \( X_n \) of surfaces, and unit area quadratic differentials \( q_n \) on \( X_n \); a sequence of \((1/n, \epsilon_0)\)-thick subsurfaces \( \Omega_n \) with area at least \( B \) such that the shortest almost \((q_n, 1/n)\)-vertical curve on \( \Omega_n \) has length at least \( n \). Passing to subsequences, we can assume (9) that \( \Omega_n \) converges to some punctured surface \( \Omega_\infty \), and that \( q_n \) restricted to \( \Omega_n \) converges to a quadratic differential \( q_\infty \) on \( \Omega_\infty \), uniformly on compact sets. Specifically this means that for any neighborhood \( U \) of the punctures on \( \Omega_\infty \)
(1) for large enough \( t_n \) there is a conformal map \( F_n : \Omega_\infty \setminus U \to \Omega_n \)
(2) \( F_n^* q_n \to q_\infty \) as \( n \to \infty \) uniformly on \( \Omega_\infty \setminus U \).

This implies that the \( q_\infty \) area of \( \Omega_\infty \) is at least \( B \), and \( \Omega_\infty \) is \( \epsilon_0/\sqrt{B} \)-thick,
By Lemma \ref{lemma:vertical- subsequences}, taking $\delta = 1$, there is a curve $\beta$ on $\Omega_\infty$ such that
\[
\frac{v_{q_\infty}(\beta)}{h_{q_\infty}(\beta)} \geq 1.
\]
By uniform convergence, $v_{q_n}(\beta) \to v_{q_\infty}(\beta)$, and $h_{q_n}(\beta) \to h_{q_\infty}(\beta)$ and thus for large enough $n$,
\[
\frac{v_{q_n}(\beta)}{h_{q_n}(\beta)} \geq 1/2
\]
and furthermore, $|\beta|_{q_n} \leq |\beta|_{q_\infty} + 1$. This is a contradiction proving the first statement.

If the second statement is false, then for each $m$ there is an $\Omega_m$ such that there does not exist a sequence $\omega_1, \ldots, \omega_m$ of vertical arcs corresponding to the closed curve $\gamma_m$ found in the first part. Passing to a subsequence we can assume again that $q_m \to q_\infty$, $\Omega_m \to \Omega_\infty$ and $\gamma_m \to \gamma_\infty$, where $\gamma_\infty$ is almost $(q_\infty, \delta_\infty)$-vertical for some $\delta_\infty > 0$. Now $\gamma_\infty$ has the property that there is a fixed collection of vertical leaves $\omega_1, \ldots, \omega_{m_0}$ with the desired property. If $q_\infty$ has the same singularity pattern as $q_m$ for all large $m$, then it is clear that there are corresponding vertical segments $\omega_1^{m}, \ldots, \omega_m^{m_0}$ with the required property for $\gamma_m$, which is a contradiction. If some zeros of $q_m$ have coalesced to a higher order zero of $q_\infty$ the curve $\gamma_m$ may include a bounded number of short segments joining zeroes of $q_m$. In this case we include a bounded number of additional vertical segments. This is again a contradiction proving the lemma. \hfill \Box

The following Lemma allows us to find curves with very different extremal length if there are subsurfaces with very different areas.

**Lemma 4.** For any $B, M > 0$, $\delta > 0$, $\epsilon_0 > 0$ and $C > 0$, there exists an $\epsilon > 0$ so that the following holds. If $q_1$ and $q_2$ are quadratic differentials on $X_1, X_2$ and $\Omega$ is a subsurface with geodesic boundary and which does not contain a flat annulus isotopic to a boundary component such that

(i) \[\text{Area}_{q_1}(\Omega) \geq B, \text{Area}_{q_2}(\Omega) < \epsilon\]

(ii) for any almost $(q_1, \delta)$-vertical curve $\gamma \in \Omega$ the vertical components satisfy \[
\frac{1}{C} \leq \frac{v_{q_1}(\gamma)}{v_{q_2}(\gamma)} \leq C
\]

(iii) $|\delta_{\Omega}|_{q_i} < \epsilon$ for $i = 1, 2$

(iv) $\Omega$ is $(\epsilon, \epsilon_0)$- thick with respect to $q_1$

then there exists a curve $\gamma$ in $\Omega$ so that
\[
\frac{\text{Ext}_{X_2}(\gamma)}{\text{Ext}_{X_1}(\gamma)} \geq M.
\]

**Proof.** By Lemma \ref{lemma:subsequence} for some $\delta$ and $D$ there is an almost $(q_1, \delta)$-vertical curve $\gamma \subset \Omega$ such that

(4) \[\epsilon_0 \leq |\gamma|_{q_1} < D\]
Let $\sigma_i$ be the hyperbolic metric on $X_i$ and $l_{\sigma_i}(\gamma)$ denote the length of the geodesic in the hyperbolic metric. By Theorems 1 and 4 in Rafi [13],

$$(5) \quad l_{\sigma_1}(\gamma) < C_1 \frac{1}{\sqrt{\text{Area}_{q_1}(\Omega)}} |\gamma|_{q_1} = C_1 |\gamma|_{q_1}/\sqrt{A} \leq C_1 D/\sqrt{A},$$

the constant $C_1$ depending only topology of the surface. Also by Maskit’s comparison of hyperbolic and extremal lengths in [10],

$$(6) \quad \text{Ext}_{X_1}(\gamma) \leq \frac{1}{2} l_{\sigma_1}(\gamma)e^{l_{\sigma_1}(\gamma)/2} \leq C_1 D/\sqrt{A} e^{C_1 D/2\sqrt{A}}.$$

Set $C_2 = C_1 D/\sqrt{A} e^{C_1 D/2\sqrt{A}}$.

On the other hand, by (1), assumption (i) and the fact that $\gamma$ is almost $(q_1, \delta)$-vertical

$$(7) \quad |\gamma|_{q_2} \geq v_{q_2}(\gamma) > \frac{1}{C} v_{q_1}(\gamma) > \frac{\delta}{C(1+\delta)} |\gamma|_{q_1} \geq \frac{\epsilon_0 \delta}{C(1+\delta)}.$$

and by Lemma 1

$$(8) \quad \text{Ext}_{X_2}(\gamma) \geq \frac{|\gamma|_{q_2}^2}{\text{Area}_{q_2}(\Omega) + O(\delta \Omega_{q_2}^2)}.$$

Putting the inequalities (7), (8) together and using assumptions (i) and (iii), we obtain

$$(9) \quad \frac{\text{Ext}_{X_2}(\gamma)}{\text{Ext}_{X_1}(\gamma)} \geq \frac{\epsilon_0^2 \delta^2}{C_2 C^2(1+\delta)^2(\text{Area}_{q_2}(\Omega) + O(\delta \Omega_{q_2}^2))} \geq \frac{C_4}{\epsilon}$$

where $C_4$ does not depend on $\epsilon$ if $\epsilon$ is small enough. Now setting $\epsilon < \frac{C_4}{\epsilon}$ guarantees that the Lemma holds.

4. Areas of subsurfaces along rays

The proof of the theorem is now based on

**Proposition 1.** Suppose $q_1, q_2$ are quadratic differentials on $X_1, X_2$ such that the vertical foliations $[F_{q_1}^v, |dx_1|], [F_{q_2}^v, |dx_2|]$ are topologically equivalent and have a minimal nonuniquely ergodic component $\Omega$. Suppose with respect to the invariant ergodic measures $\nu_1, \ldots, \nu_p$ on $\Omega$, $|dx_1| = \sum_{k=1}^p a_k \nu_k$, with $a_1 > 0$, while $|dx_2| = \sum_{k=1}^p b_k \nu_k$ with $b_1 = 0$. Let $r_1(t), r_2(t)$ be the corresponding rays and let $q_1(t), q_2(t)$ be the quadratic differentials on $r_1(t), r_2(t)$ respectively. Then there exists $\epsilon_0 > 0, M_0 > 0$ so that for small enough $\epsilon$, there is $t_0$ such that for $t \geq t_0$, there is a subsurface $Y(t) \subset \Omega$ satisfying

(i) $Y(t)$ is $(\epsilon, \epsilon_0)$ thick with respect to $q_1(t)$.

(ii) $\text{Area}_{q_1(t)}(Y(t)) \geq a_1(1 - M_0 \epsilon)$.

(iii) $\text{Area}_{q_2(t)}(Y(t)) < \epsilon$.

**Proof.** For $i = 1, 2$ let $|dy_i|$ denote the transverse measure to the horizontal foliation of $q_i$. We normalize the measures $\nu_k$ so that

$$(10) \quad \int_\Omega d\nu_k |dy_1| = 1.$$
This implies $\sum_k a_k = \text{Area}_{q_1}(\Omega)$. The measures $|dy_1|, |dy_2|$ are uniformly comparable. This implies that there is a constant $C$ such that for any subsurface $Z$ and each $k$.

\[(11) \quad \frac{1}{C} \int_Z dv_k |dy_1| \leq \int_Z dv_k |dy_2| \leq C \int_Z dv_k |dy_1|.\]

Applying the left hand inequality to $Z = \Omega$ and using the fact that $\text{Area}_{q_2}(\Omega) = \sum_k \int_{\Omega} b_k dv_k |dy_2|$ we find there is a bound $C'$ such that $\sum_{k=1}^{\nu} b_k \leq C'$.

We can find a finite set of horizontal transversals $I$ to the vertical foliation in $\Omega$ such that for any $\nu_i, \nu_j, i \neq j$ there is a transversal $I$ from this set and $\delta > 0$ such that

\[(12) \quad |\frac{\nu_i(I)}{\nu_j(I)} - 1| > \delta.\]

Let $\Lambda_i$ be the set of generic points for $\nu_i$ and the transversals $I$ in the set; that is, if $x \in \Lambda_i$ and $l(x)$ is the vertical leaf of $q_1$ through $x$ of length $T$, then

\[(13) \quad \lim_{T \to \infty} \frac{1}{T}|l(x) \cap I| \to \nu_i(I).\]

The sets $\Lambda_i$ are pairwise disjoint; $\nu_i$ almost every point belongs to $\Lambda_i$ and almost every point in $\Omega$ belongs to $\bigcup \Lambda_i$ with respect to the area element defined by $q_1$.

By [7], as $t \to \infty$ there is a maximal collection of disjoint curves $\gamma_1(t), \ldots, \gamma_m(t) \subset \Omega$ such that

\[\text{Ext}_{r_1(t)}(\gamma_i(t)) \to 0.\]

Consequently we can find $\epsilon_0 > 0$, such that given any $\epsilon > 0$, for $t$ sufficiently large $\Omega$ can be decomposed into a collection \{Y(t)\} of $(\epsilon, \epsilon_0)$ thick subsurfaces. We can assume that $Y(t)$ is either a flat annulus or it does not contain a flat annulus isotopic to a boundary component. There is a uniform bound $N$ for the number of these surfaces.

Let $f_t : X_0 \to r_1(t)$ denote the corresponding Teichmuller map. Let $\Lambda_i(t) = f_t(\Lambda_i)$. We now claim that for $t$ big enough, for each subsurface $Y(t)$ in this collection there is an $i$ such that

\[(14) \quad \bigcup_{j \neq i} \text{Area}_{q_1}(Y(t) \cap \Lambda_j(t)) \leq \epsilon/CC'.\]

We argue by contradiction. If the claim is not true, there exists $\epsilon_1 > 0$, a sequence $t_n \to \infty$, and disjoint subsurfaces $Y(t_n) \subset \Omega$ such that for at least two distinct values of $j$,

\[(15) \quad \text{Area}_{q_1(t_n)}(Y(t_n) \cap \Lambda_k(t_n)) > \epsilon_1.\]

Assume first that $Y(t_n)$ is not a flat cylinder. By passing to a subsequence we can assume that the surfaces $Y(t_n)$ converge to a limiting punctured surface $Y(\infty)$ and the corresponding $q_1(t_n)$ converges to a limiting $q_1(\infty)$ on $Y(\infty)$. Again this means that for any neighborhood $U$ of the punctures on $Y(\infty)$

1. for large enough $t_n$ there is a conformal map $h_n : Y(\infty) \setminus U \to Y(t_n)$
2. $h_nq_1(t_n) \to q_1(\infty)$ as $t_n \to \infty$ uniformly on $Y(\infty) \setminus U$.
Now from condition (2) above it follows that for each such $U$, for $t_n$ large enough,

$$\gamma_i(t_n) \cap h_n(Y(\infty) \setminus U) = \emptyset.$$  

Since $Y(t_n)$ does not contain a flat cylinder in the homotopy class of a component of $\partial Y(t_n)$ we may find $U$ so that

(16) \quad \text{Area}_{q_1(t_n)}(Y(t_n) \setminus (h_n(Y(\infty) \setminus U))) \leq \epsilon_1/2.

Now consider the collection of rectangles $R$ with respect to the flat structure of $q_1(\infty)$ that are contained in $K := Y(\infty) \setminus U$. We now follow an argument in [7]. For any such rectangle $R$ we argue that there cannot be points $x_i, x_j \in \Lambda_i, \Lambda_j; i \neq j$ such that

$$y_i = \lim f_{t_n}(x_i) \in R.$$

For suppose there were $x_i, x_j$ with this property. There is a rectangle $R' \subset R$ whose vertical sides $L_i, L_j$ have endpoints at $y_i, y_j$. For every horizontal segment $H$,

$$|\text{card}(H \cap L_i) - \text{card}(H \cap L_j)| \leq 2.$$  

Let $y_{i,n} = f_{t_n}(x_i), y_{j,n} = f_{t_n}(x_j)$ and let $L_{i,n}, L_{j,n}$ the vertical segments of $q_1(t_n)$ that converge to $L_i, L_j$. For $t_n$ large enough, for any horizontal segment $H_n$ of $q(t_n)$

$$\left| \frac{\text{card}(L_{i,n} \cap H_n)}{\text{card}(L_{j,n} \cap H_n)} - 1 \right| \leq \delta/2.$$

Mapping $L_{i,n}$ back to $X_0$ by $f_{t_n}^{-1}$ and applying the above to the transversal $H_n = f_{t_n}(I)$, we have a contradiction to (12) and (13).

Thus for each rectangle $R$ there is some $i = i(R)$ such that for all $j \neq i$ and for all $x$ we have

$$\chi_R(f_{t_n}(x))\chi_{\Lambda_j}(x) \to 0.$$  

Then by the Lebesgue dominated convergence theorem and the fact that the map $f_{t_n}$ is area preserving,

$$\text{Area}_{q_1(t_n)}(\Lambda_j(t_n) \cap R) = \int_{X_1} \chi_R(f_{t_n}(x))\chi_{\Lambda_j}(x)|dx||dy_1| \to 0.$$  

Now we take a covering of $K$ by such rectangles. If any two rectangles $R, R'$ overlap then $i(R) = i(R')$. It follows from the connectedness of $K$, that there is a single $i$ such that for all $R, i(R) = i$. Thus for $t_n$ large enough, for all $j \neq i$,

$$\text{Area}_{q_1(t_n)}(\Lambda_j(t_n) \cap Y(t_n)) \leq \epsilon_1/2.$$

Combining with (16) we have contradicted our hypothesis (15) and proven the claim (14) in this case.

Now suppose $Y(t_n)$ is a flat cylinder with core curve $\beta_n$. Then $v_q(\beta_n) \to \infty$ as $n \to \infty$. Again we cannot have images of points of $\Lambda_i, \Lambda_j$ in $Y(t_n)$; otherwise again every horizontal intersecting a vertical segment through one will intersect the vertical segment through the other one, and again we have a contradiction. We have proved the claim (14).
Thus for each $Y(t)$, for all but at most one index $k$ we have

$$\int_{Y(t)} dv_k |dy_1| \leq \epsilon/CC'. \tag{17}$$

Let $Z_k(t)$ be the union of those $Y(t)$ such that the above inequality holds for that index. Then $Z_k(t) \subset \Omega$ for otherwise we would have

$$\int_{\Omega} dv_k |dy_1| < N\epsilon/C'C,$$

contradicting (10), for $\epsilon$ sufficiently small. Let $Y_1(t) = \Omega \setminus Z_1(t)$, and so we have

$$\text{Area}_{q_1(t)}(Y_1(t)) \geq a_1 \int_{Y_1(t)} dv_1 |dy_1| \geq a_1 (1 - N\epsilon/C'C'),$$

proving (ii) with $M_0 = N/CC'$. Now conclusion (iii) follows from (17) applied to $k = 1$, the right hand inequality in (11), the fact that $b_1 = 0$, and the sum of $b_k$ is at most $C'$. \hfill \Box

**Proof of Theorem** Without loss of generality we can assume that for some minimal component $\Omega$ we have $a_1 > 0$ and $b_1 = 0$. Fix $M > 0$. It suffices to show that there exists $t_0$ such that for $t \geq t_0$ there is a simple closed curve $\gamma(t)$ with

$$\frac{\text{Ext}_{r_2}(\gamma(t))}{\text{Ext}_{r_1}(\gamma(t))} > M. \tag{18}$$

Choose $\epsilon > 0$ small. Since the measures $|dy_1|$ and $|dy_2|$ are uniformly comparable, the vertical lengths $v_{q_1(t)}(\gamma)$ and $v_{q_2(t)}(\gamma)$ of any curve $\gamma$ are uniformly comparable. Thus given $\delta > 0$, there is a fixed constant $C$ such that condition (ii) of Lemma 4 holds. We may also choose a fixed constant $B$ such that for $t > t_0$, the subsurface $Y(t)$ given by Proposition 1 satisfies

$$\text{Area}_{q_1(t)}(Y(t)) > B$$

$$\text{Area}_{q_2(t)}(Y(t)) < \epsilon$$

and

$$\text{Ext}_{r_1(t)}(\partial Y(t)) \leq \epsilon/M.$$  

If $|\partial Y(t)|_{q_2(t)} \geq \epsilon^2$, then $\text{Ext}_{r_2(t)}(\partial Y(t)) \geq \epsilon$, and we are done; we may choose $\gamma = \partial Y(t)$. Thus assume

$$|\partial Y(t)|_{q_2(t)} \leq \epsilon^2 \leq \epsilon.$$  

If $Y(t)$ is not a flat cylinder, for $\epsilon$ small enough, we can apply Lemma 3 and Lemma 4, which provide a curve $\gamma \subset Y(t)$ with the desired property (18).

Thus assume $Y(t)$ is a flat cylinder. Let $\alpha$ be a core curve of $Y(t)$. Then $|\alpha|_{q_1(t)} < \epsilon$. Suppose first that $\alpha$ is $(q_1(t), \delta)$-almost vertical. The reciprocal of the modulus of the cylinder is an upper bound for $\text{Ext}_{r_1(t)}(\alpha)$, and we have

$$\text{Ext}_{r_1(t)}(\alpha) \leq \frac{|\alpha|^2_{q_1(t)}}{\text{Area}_{q_1}(Y(t))} \leq \frac{|\alpha|^2_{q_1(t)}}{B} \leq \frac{\epsilon^2}{B} \tag{19}$$
We now want to estimate $\text{Ext}_{r_2(t)}(\alpha)$. By (19), the flat length

$$|\alpha|_{q_2(t)} > \frac{\delta |\alpha|_{q_1(t)}}{C(1 + \delta)}.$$  

We can assume

$$\text{Ext}_{r_2(t)} \leq \frac{Me^2}{B},$$

for otherwise we are done. As a consequence of Theorem 5.1 in Minsky([11]), there is an annulus $A(t)$ which is a union of $Y(t)$ and an expanding annulus $Y'(t)$, and a universal constant $c > 0$ such that

$$\text{Ext}_{r_2(t)}(\alpha) \geq \frac{c}{\text{mod}(A(t))} \geq \frac{c}{\text{mod}(Y(t)) + \text{mod}(Y'(t))} \geq \frac{c}{-\log |\alpha|_{q_2(t)} + \frac{\text{Area}_{q_2}(Y(t))}{|\alpha|_{q_2(t)}}} \geq \frac{c'}{\frac{\log |\alpha|_{q_1(t)}}{c} + \frac{\text{Area}_{q_1}(Y(t))}{|\alpha|_{q_1(t)}} + \frac{t}{\text{Area}_{q_1}(Y(t))}}.$$

Comparing with (19) we see that for $\epsilon$ small enough, $\alpha$ is a curve that satisfies (18).

Suppose now the core curve $\alpha$ of $Y(t)$ is not $(q_1(t), \delta)$ almost vertical. If $Y(t)$ is nonseparating, choose a nontrivial isotopy class of arcs in the complement of $Y(t)$ joining the top and bottom of $Y(t)$. If $Y(t)$ is separating choose two nontrivial isotopy classes, one that joins the top of $Y(t)$ to itself and the other which joins the bottom to itself. These families can be chosen to lie in the thick part of the surface $r_1(t)$ and as such have extremal length bounded independently of $t$. In the first case we also take a families of arcs $\beta$ crossing $Y(t)$ that intersect a fixed perpendicular at most once. The arcs $\beta$ are $(q_1(t), \frac{1}{2\delta})$ almost vertical. In the second case we take a pair of arcs crossing $Y(t)$ which are $(q_1(t), \frac{1}{2\delta})$ almost vertical. Let $\delta' = \frac{1}{2\delta}$. Now we can form a closed curve $\gamma$ as a concatenation of an arc outside $Y(t)$ and an arc $\beta$. or in the separating case, a pair of arcs outside and a pair of arcs crossing. For some constant $c$, again by Theorem 5.1 in Minsky([11]).

$$\text{Ext}_{r_1(t)}(\gamma) \leq c\text{Ext}_{r_1(t)}(\beta) \leq c\frac{|\beta|_{q_1(t)}^2}{\text{Area}_{q_1}(Y(t))} \leq c\frac{|\beta|_{q_1(t)}^2}{B}.$$  

On the other hand the curves $\gamma$ formed this way are longer and fewer than the arcs $\beta$ crossing the cylinder. Since the arcs $\beta$ are $(q_1(t), \delta')$ almost vertical, we have

$$\text{Ext}_{r_2(t)}(\gamma) \geq \text{Ext}_{r_2(t)}(\beta) = \frac{|\beta|_{q_2(t)}^2}{\text{Area}_{q_2}(Y(t))} \geq \frac{\delta' |\beta|_{q_1(t)}^2}{\epsilon C(1 + \delta')}.$$

and we are done for $\epsilon$ small enough. \hfill \square

**Theorem 2.** Suppose $q_1, q_2$ are quadratic differentials such that the vertical foliations $[F_{q_1}^v, dx_1]$ and $[F_{q_2}^v, dx_2]$ are not topologically equivalent, but $i([F_{q_1}^v, dx_1], [F_{q_2}^v, dx_2]) = 0$. Then the rays $r_1$ and $r_2$ diverge.

Before beginning the proof we need a definition and estimates found in [13] and [12]. First one defines an expanding annulus $A$ as an annulus where the curvature of each boundary component has constant sign, either positive or negative at each point, the boundary curves
are equidistant and there are no zeroes inside \( A \). Let \( d(A) \) be the distance between the boundary components. The first statement in the following is Lemma 3.6 of [14] and the second is Theorem 4.6 of Minsky ([12]). We assume \( q \) is a quadratic differential of area 1 on a surface \( X \).

**Lemma 5.** 

1. If \( A \) is an expanding annulus with one boundary component \( \beta \), then
\[
\text{Mod}(A) \asymp \log \frac{d(A)}{|\beta|_q},
\]
where \( \asymp \) means the two quantities are bounded in terms of each other by fixed multiplicative constants.

2. Further suppose there is no flat annulus in the class of \( \beta \). Then
\[
\text{Ext}_X(\beta) \asymp \frac{1}{\text{Mod}(A)}.
\]

**Proof of Theorem 2.** Denote the foliations simply by \( F_1, F_2 \). The first case is if the minimal components, if any coincide. Since the foliations do not coincide, there must be some curve \( \beta \) which is a core curve of a flat cylinder with respect to one quadratic differential, say \( q_1 \), but is not the core curve of a flat cylinder of \( q_2 \). Since \( \beta \) is isotopic to the core curve of a flat annulus of \( q_1 \) we have
\[
\text{Ext}_{r_1(t)}(\beta) \leq ce^{-2t},
\]
for some \( c \). Since \( \beta \) is not a subset of a minimal component of \( F_2 \), we must have \( \beta \subset \Gamma_{q_2} \), the critical graph of \( q_2 \). Now the length of \( \beta \) in the metric of \( q_2(t) \) satisfies \( |\beta|_{q_2(t)} = |\beta|_{q_2}e^{-t} \).

We apply the lower bound given in Lemma 5 to say that
\[
\frac{\text{Ext}_{r_1(t)}(\beta)}{\text{Ext}_{r_1(t)}(\beta)} \rightarrow \infty.
\]

The second case is if one of the foliations, say \( F_1 \) has a minimal component \( \Omega_1 \) which is not a minimal component of \( F_2 \). Since \( i(F_1, F_2) = 0 \), every curve \( \beta \subset \Omega_1 \) satisfies \( i(F_2, \beta) = 0 \), so that \( \beta \subset \Gamma_{q_2} \), the critical graph of \( q_2 \). Since \( \beta \subset \Omega_1 \), we have \( h_{q_1}(\beta) > 0 \) and so the flat length of \( \beta \) with respect to \( q_1 \) satisfies
\[
|\beta|_{q_1(t)} \geq h_{q_1}(\beta)e^t.
\]

This gives
\[
\text{Ext}_{r_1(t)}(\beta) \geq h_{q_1}(\beta)e^{2t}.
\]
It suffices to find an upper bound for \( \text{Ext}_{r_2(t)}(\beta) \). Since \( i(F_1, F_2) = 0 \), \( \beta \) is not isotopic to a flat cylinder and so \( \beta \) is either on the boundary of a minimal component \( \Omega_2 \) of \( F_2 \) or is on the boundary of a flat cylinder.

Suppose we are in the first case. Now we note that since \( \Omega_2 \cap \Gamma_{q_2} = \emptyset \) the shortest saddle connection \( \gamma(t) \) with respect to \( q_2(t) \) has length going to \( \infty \) with respect to \( q_2 \) as \( t \rightarrow \infty \). Thus
\[
e^t|\gamma|_{q_2(t)} \rightarrow \infty.
\]
Since the segments $\alpha \subset \Gamma_{q_2(t)}$ satisfy $|\alpha|_{q_2(t)} = e^{-t}|\alpha|_{q_2}$, we can find an expanding annulus $A$ with $d(A) \asymp e^{-t}$ and boundary component $\beta$ of length $|\beta|_{q_2} e^{-t}$. By Lemma 5 we have shown the extremal length of $\beta$ is bounded above.

The case that $\beta$ is on the boundary of a flat cylinder is similar. Since the distance across the cylinder goes to $\infty$, we can again find an annulus in the class of $\beta$ with modulus bounded below and thus extremal length bounded above. 

\[ \Box \]

**Theorem 3.** Let $\nu_1, \ldots, \nu_k$ be maximal collection of ergodic measures for a minimal foliation $[F, \mu]$. Then there is a sequence of multicurves $\gamma_n = \{\gamma^1_n, \ldots, \gamma^k_n\}$ such that $\gamma^j_n \to [F, \nu_j]$ in $PMF$.

We note that each $\gamma^j_n$ may itself be a multicurve.

**Proof.** Choose corresponding unit area quadratic differentials $q_i$ on some surface $X_0$ whose vertical foliations are $[F, \nu_i]$. Let $r_i(t)$ the corresponding ray. For any sequence of times $t_n \to \infty$ by Proposition 4 there is a collection of disjoint domains $Y_1(t_n), \ldots, Y_p(t_n)$ such that

\[
\text{Area}_{q_i(t_n)}(Y_i(t_n)) \geq B > 0.
\]

Suppose first that $Y_i(t_n)$ is not a cylinder. By the first part of Lemma 3 we may pick a $(q_i(t_n), \delta)$ almost vertical curve $\gamma_i(t_n) \subset Y_i(t_n)$ of length at most $D$. We claim that $\gamma_i(t_n) \to [F, \nu_i]$. As before, let $\Lambda_i(n)$ be the image of the generic points inside $Y_i(t_n)$; generic say with respect to the transversal for the set of all simple closed curves $\alpha$. The generic points are dense, hence we can find a collection $\{\omega_j(n)\}_{j=1}^k$ of vertical segments beginning at generic points satisfying the second conclusion of Lemma 3. By construction of the $\omega_j(n)$, for any fixed $\alpha$,

\[
\frac{i(\gamma_i(t_n), \alpha)}{\sum_{j=1}^k i(\omega_j(n), \alpha)} \to 1.
\]

Since $\omega_j(n)$ is a vertical segment through a generic point,

\[
\frac{i(\omega_j(n), \alpha)}{|\omega_j(n)|_{q_i}} \to \nu_i(\alpha).
\]

Summing over all $1 \leq j \leq k$ we have

\[
\frac{i(\gamma_i(t_n), \alpha)}{\sum_{j=1}^k |\omega_j(n)|_{q_i}} \to \nu_i(\alpha).
\]

However the sum in the denominator is exactly $v_{q_i}(\gamma_i(t_n))$ and so if we let $s_n = \frac{1}{v_{q_i}(\gamma_i(t_n))}$ then we have

\[
\lim_{n \to \infty} s_n i(\gamma_i(t_n), \alpha) \to \nu_i(\alpha)
\]

and we are done. \[ \Box \]
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