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Autor:	Hamenstädt, Ursula
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# NEW EXAMPLES OF MAXIMAL SURFACES

## by Ursula HAMENSTÄDT<sup>\*</sup>)

ABSTRACT. We describe all closed hyperbolic triangle surfaces of a particularly simple type which are maximal, i.e. for which the length of the systole is a local maximum in Teichmüller space. We show that this class of triangle surfaces contains exactly three maximal surfaces. One of these surfaces is the well known Klein surface, the other two examples are new.

### 1. INTRODUCTION

A Riemann surface of finite type is a closed Riemann surface from which a finite number  $m \ge 0$  of points, the so-called *punctures*, have been deleted. Closed Riemann surfaces (with no punctures) are topologically determined by their genus. In this note we only consider surfaces of genus  $g \ge 2$  with  $m \ge 0$ punctures. Such a surface admits a family of complete hyperbolic metrics of finite volume. Each of these metrics corresponds to precisely one complex structure of finite type.

The easiest way to describe all such hyperbolic metrics is to look at the *Teichmüller space*  $\mathcal{T}_{g,m}$  of *marked* hyperbolic metrics of finite volume on a surface  $S_0$  of genus g with m punctures. This Teichmüller space is the set of all pairs (f,h) where h is a hyperbolic metric on a surface S and f is the homotopy class of a homeomorphism  $F: S_0 \to S$  of  $S_0$  onto S. The mapping

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#### U. HAMENSTÄDT

class group Map(g,m) is the group of all isotopy classes of homeomorphisms of  $S_0$  onto itself. It acts on  $\mathcal{T}_{g,m}$  via  $\Psi(f,h) = (f \circ \Psi^{-1}, h)$  and identifies those points in  $\mathcal{T}_{g,m}$  which correspond to isometric surfaces. With respect to a natural topology, the Teichmüller space  $\mathcal{T}_{g,m}$  is homeomorphic to a cell of dimension 6g - 6 + 2m, and the mapping class group Map(g,m) acts properly discontinuously, but not fixed-point free. The quotient of  $\mathcal{T}_{g,m}$  under Map(g,m) is the moduli space of hyperbolic metrics on our surface of genus g with m punctures.

A systole of an oriented hyperbolic surface S of finite volume is a simple closed geodesic on S of minimal length. The length of the systole depends on the choice of the hyperbolic metric and defines a Map(g,m)-invariant continuous function on  $\mathcal{T}_{g,m}$ . This function is bounded from above on  $\mathcal{T}_{g,m}$ by a constant depending on g and m [Bu] (which however tends to infinity as g tends to infinity [BS]), but it is not bounded from below on  $\mathcal{T}_{g,m}$ . We refer to [S3] for other interesting properties of this function.

Following Schmutz [S1] we call a point in  $\mathcal{T}_{g,m}$  a maximal surface if the length of the systole has a local maximum at that point. Maximal surfaces always exist, and Schmutz found in [S1] explicit examples.

The goal of this paper is to look for maximal surfaces among all hyperbolic surfaces which admit a particularly simple combinatorial description. For this recall that every *closed* hyperbolic surface *S* is given by a discrete torsion free subgroup *G* of the isometry group  $PSL(2, \mathbb{R})$  of the hyperbolic plane  $\mathbb{H}^2$ which acts cocompactly on  $\mathbb{H}^2$ . The surface *S* then simply equals  $\mathbb{H}^2/G$ . The *Dirichlet fundamental polygon* for *G* based at a point  $y \in \mathbb{H}^2$  is the set *D* of all points  $z \in \mathbb{H}^2$  with the property that dist  $(z, y) \leq \text{dist}(z, \Psi y)$  for every  $\Psi \in G$ , where dist is the distance function of the hyperbolic metric. This set is a convex hyperbolic polygon.

For a number  $p \ge 5$  define a *fundamental* 2p-gon to be a regular 2p-gon  $\Omega$  in the hyperbolic plane  $\mathbf{H}^2$  with angles  $2\pi/p$  and sides of equal length. Such a 2p-gon admits a cyclic group  $\Gamma$  of order p of isometries whose elements rotate  $\Omega$  about a fixed point, with a multiple of  $2\pi/p$  as rotation angle. We call the fixed point of the elements of  $\Gamma$  the *center* of  $\Omega$ . If we draw 2p geodesic segments from the center 0 to the vertices of the boundary  $\partial\Omega$  of  $\Omega$ , then these segments decompose  $\Omega$  into 2p equilateral triangles with angle  $\pi/p$ .

We call a closed surface  $S = \mathbf{H}^2/G$  a simple triangle surface if G admits a fundamental 2p-gon  $\Omega$  as the Dirichlet fundamental polygon based at the center of  $\Omega$  and if moreover G is normalized by the cyclic group  $\Gamma$ . The action of  $\Gamma$  on  $\mathbf{H}^2$  then descends to an isometric action on  $S = \mathbf{H}^2/G$ . We call this group of isometries the *basic group of isometries* of S. The Gauß-Bonnet formula shows that the genus g of S equals  $\frac{1}{2}(p-1)$ . In particular, the number p is odd.

We number the vertices of  $\partial\Omega$  in counter-clockwise order. These vertices are contained in exactly two vertex cycles under the action of  $\Gamma$ . One of these vertex cycles contains the even vertices, the other contains the odd vertices. The triangulation of  $\Omega$  into 2p equilateral triangles with vertices at 0 and on the boundary  $\partial\Omega$  of  $\Omega$  descends to a triangulation of the quotient surface Swith 3 vertices. We call this triangulation the *canonical triangulation* of S. If we delete the vertices of the canonical triangulation from the surface S then we obtain a surface of genus g with 3 punctures together with a complex structure of finite type which is invariant under the natural action of the basic group of isometries of S. The unique hyperbolic metric of finite volume which defines this complex structure is again invariant under this group of isometries. In other words, to every simple triangle surface S of genus g corresponds a point  $S_{\infty}$  in the Teichmüller space  $\mathcal{T}_{g,3}$  of surfaces of genus g with 3 punctures which we call the *ideal surface*  $S_{\infty}$  associated to S.

The main purpose of this note is to show.

### THEOREM A.

1) Among the simple triangle surfaces there are exactly 3 which are maximal. They are of genus 3, 6 and 10.

2) The ideal surface associated to a simple triangle surface S is maximal if and only if S is maximal.

The maximal surface of genus 3 listed in the above theorem is the well known Klein's surface of genus 3 and appears already in the list of maximal surfaces given by Schmutz in [S1] (compare also the proceedings volume [L] about Klein's surface). The examples of genus 6 and genus 10 are new. We remark that by construction our simple triangle surfaces are indeed triangle surfaces in the usual sense, i.e. their isometry group is a nontrivial finite quotient of a triangle group.

From the proof of Theorem A we obtain additional informations on some of the Teichmüller spaces  $\mathcal{T}_{g,0}$ . To explain this let  $[\gamma]$  be a nontrivial free homotopy class on the closed base surface  $S_0$  of genus g. For every point  $(f,h) \in \mathcal{T}_{g,0}$ , the class  $f[\gamma]$  can be represented by a unique closed geodesic with respect to the hyperbolic metric h. The length of this geodesic defines a continuous function on  $\mathcal{T}_{g,0}$ . We call this function the *length function* of  $[\gamma]$ . We show THEOREM B. For every  $k \ge 2$  and  $g = \frac{k}{2}(k+1)$  the Teichmüller space  $T_{g,0}$  can be parametrized by the length functions of 6g + 3 free homotopy classes contained in the orbit of a fixed class under a maximal finite subgroup G of Map(g,0). The group G is a semidirect product of a cyclic group of order 2g + 1 and a cyclic group of order 3.

We refer to [S2] for a discussion of other interesting parametrizations of  $T_{g,0}$ .

The structure of this note is as follows. In Section 2 we look at simple triangle surfaces with additional symmetries. In Section 3 we give a combinatorial description of a family of curves which contains the systoles of every simple triangle surface. Length estimates in Section 4 lead to a complete description of the systoles of a simple triangle surface. This is used in Section 5 to show our theorems.

As a notational convention, we number the vertices of a fundamental 2p-gon  $\Omega$  counter-clockwise in consecutive order and we number and orient the edges of  $\Omega$  in such a way that the edge i as an oriented arc joins the vertex i-1 to the vertex i. Moreover we write simply  $T_g$  for the Teichmüller space of marked hyperbolic structures on a closed surface of genus g.

# 2. BASIC PROPERTIES OF SIMPLE TRIANGLE SURFACES

Let  $g \ge 2$  and let p = 2g + 1. There is up to isometry a unique 2p-gon  $\Omega$  in the hyperbolic plane  $\mathbf{H}^2$  with geodesic sides of equal length and with angles  $2\pi/p$ . In the introduction we called  $\Omega$  a *fundamental 2p-gon*. The *center* of  $\Omega$  is the unique point  $z \in \Omega$  which has the same distance to each of the vertices. A fundamental 2p-gon admits a cyclic group  $\Gamma$  of isometries whose elements rotate  $\Omega$  about the center with a rotation angle which is a multiple of  $2\pi/p$ . We view  $\Gamma$  as a cyclic group of isometries of the whole hyperbolic plane  $\mathbf{H}^2$ .

We call a closed hyperbolic surface S of genus g a simple triangle surface if  $S = \mathbf{H}^2/G$  where G is a discrete torsion free group  $G \subset PSL(2, \mathbf{R})$  of isometries of  $\mathbf{H}^2$  which is normalized by the group  $\Gamma$  and which admits  $\Omega$ as a fundamental polygon (see [M] for basic informations on fundamental polygons). The group G then acts as a group of side pairing transformations for the polygon  $\Omega$ . This means that for each side a of  $\Omega$  there is an isometry  $\Psi \in G$  which maps a to a second side  $\Psi(a) \neq a$  of  $\Omega$  in such a way that  $\Psi(\Omega) \cap \Omega = \Psi a$ . Our first observation is that simple triangle surfaces exist for every genus  $g \ge 2$ .

# LEMMA 2.1. For every $g \ge 2$ there is a simple triangle surface of genus g.

*Proof.* Let  $p \ge 5$  be an odd number and let  $\Omega$  be a fundamental 2p-gon with center  $0 \in \mathbf{H}^2$ . We have to show that there is a discrete subgroup G of  $PSL(2, \mathbf{R})$  which is normalized by  $\Gamma$  and which admits  $\Omega$  as a fundamental polygon.

Choose a number  $k \in \{2, \ldots, p-1\}$  and define a family  $\{\Psi_1, \ldots, \Psi_p\}$  of isometries of  $\mathbf{H}^2$  by requiring that  $\Psi_j$  maps the (oriented) edge with odd number 2j+1 orientation reversing onto the (oriented) edge 2j+2k in such a way that  $\Psi_j(\Omega) \cap \Omega$  is just the edge 2j+2k. Then necessarily the vertex 2j is mapped to the vertex 2j+2k, and the vertex 2j+1 is mapped to the vertex 2j+2k-1. We claim that these isometries  $\{\Psi_1, \ldots, \Psi_p\}$  generate a discrete subgroup of  $PSL(2, \mathbf{R})$  with fundamental domain  $\Omega$  if and only if k and k-1 are prime to p.



To see this let G be the subgroup of  $PSL(2, \mathbf{R})$  generated by  $\Psi_1, \ldots, \Psi_p$ and assume that G is discrete and torsion free, with fundamental polygon  $\Omega$ . By the choice of  $\Psi_1, \ldots, \Psi_p$ , the G-orbit of an even (or odd) vertex of  $\Omega$ intersects  $\Omega$  only in the set of even (or odd) vertices. Different such vertex cycles project to different points on the surface  $S = \mathbf{H}^2/G$ . If  $m \ge 2$  is the number of points in the vertex cycle of the vertex a, then a neighborhood of the projection  $\bar{a}$  of a to S consists of 2m equilateral hyperbolic triangles with angle  $\pi/p$  which contain  $\bar{a}$  as one of their vertices. Since S is a smooth hyperbolic surface, the angles at  $\bar{a}$  of these triangles must add up to  $2\pi$ . This means that there are precisely 2 vertex cycles for the action of G, each

### U. HAMENSTÄDT

containing only even or only odd vertices. By the definition of G this is the case if and only if the number  $k \in \{2, \ldots, p-1\}$  is prime to p and k-1 is prime to p as well. Such a group G is then normalized by the group  $\Gamma$  of rotations of  $\Omega$  with rotation angle a multiple of  $2\pi$ .

The same argument also shows that for  $k \in \{2, ..., p-1\}$  which is prime to p and such that k-1 is prime to p as well the group G induces a simple triangle surface of genus g. Since p = 2g + 1 is odd we can always choose k = 2 to obtain an example.  $\Box$ 

In the above proof we observed that we obtain a simple triangle surface from a fundamental 2p-gon  $\Omega$  by identifying the edge 1 with the edge 2kfor some  $k \in \{2, \ldots, p-1\}$  if and only if k and k-1 are prime to p. We denote by S(p;k) the surface obtained in this way. For fixed  $p \ge 5$ this defines a finite non-empty collection of simple triangle surfaces of genus  $\frac{1}{2}p-1$  indexed by the set of all numbers  $k \in \{2, \ldots, p-1\}$  which are prime to p and such that k-1 is prime to p as well. However these surfaces are not necessarily distinct as hyperbolic surfaces. For example, via exchanging the roles of the even and odd vertices of our fundamental 2p-gon  $\Omega$  we observe that the surface S(p;k) is isometric to the surface S(p;p-k+1). Thus we may restrict our attention to the case that  $k \le \frac{1}{2}(p+1)$ . In the sequel we sometimes identify the surfaces S(p;k) and S(p;p-k+1) without further comment.

Let again  $\Gamma$  be the group of rotations of  $\Omega$  which descends to a group of isometries on a simple triangle surface S of genus g. The natural  $\Gamma$ -invariant triangulation of  $\Omega$  into 2p equilateral triangles with angle  $\pi/p$  projects to the  $\Gamma$ -invariant canonical triangulation whose 3 vertices 0, A, B are just the fixed points for the action of  $\Gamma$ . The quotient  $S/\Gamma$  of S under  $\Gamma$  is a topological 2-sphere. The hyperbolic metric on S projects to a hyperbolic metric on  $S/\Gamma$  with 3 singular points  $\hat{A}, \hat{B}, \hat{0}$  which are the projections of the vertices A, B, 0 of the canonical triangulation of S. With this metric,  $S/\Gamma$  is isometric to two equilateral hyperbolic triangles with angle  $\pi/p$  glued at their boundaries. This observation is used in the proof of the following.

LEMMA 2.2.

1) Let  $p \ge 5$  be an odd number and let  $k, m \in \{2, ..., p-1\}$  be numbers which are prime to p and such that k - 1, m - 1 are prime to p as well. If either  $(k-1)m+1 \equiv 0 \mod p$  or  $(m-1)k+1 \equiv 0 \mod p$  then the surfaces S(p;k) and S(p;m) are isometric. 2) A simple triangle surface S with basic group  $\Gamma$  of isometries admits a nontrivial group  $\Sigma \not\subset \Gamma$  of orientation preserving isometries which normalizes  $\Gamma$  if and only if one of the following holds.

- i) S = S(p;k) for some  $k \ge 2$  and a divisor  $p \ge k+1$  of k(k-1)+1. The group  $\Sigma$  is then cyclic of order 3.
- ii) S = S(p; 2) and the group  $\Sigma$  is cyclic of order 2 and generated by a hyperelliptic involution.

*Proof.* Let  $p \ge 5$  and let  $k \le p-1$  be such that k-1 and k are prime to p. Let  $\Omega$  be a fundamental 2p-gon and let 0, A, B be the vertices of the canonical triangulation of S. We assume that 0 is the projection of the center of  $\Omega$  and A is the projection of the odd vertices of the boundary of  $\Omega$ .

As in the introduction we number the 2p edges of  $\Omega$  in counterclockwise order in such a way that the edge *i* is adjacent to the vertices i-1 and *i*. Let  $T_i \subset S$  be the projection of the triangle in  $\Omega$  with one vertex at the center of  $\Omega$  and with the edge *i* of  $\Omega$  as the opposite side. The triangles  $T_1, \ldots, T_{2p}$ are arranged in counterclockwise order around the vertex 0.

There is a different representation of *S* as a quotient of  $\Omega$  under a group of side pairing transformations in such a way that the center of  $\Omega$  projects to the vertex *A* of the canonical triangulation. Namely, if we cut *S* open along the geodesic arcs connecting the vertices 0 and *B*, then the result is a fundamental 2p-gon which consists again of the triangles  $T_1, \ldots, T_{2p}$ . The arrangement of these triangles around the vertex *A* is given by a permutation  $\sigma$ of  $\{1, \ldots, 2p\}$  with  $\sigma(1) = 1$ , i.e. the counterclockwise order of the triangles around the vertex *A* is  $T_{\sigma(1)}, \ldots, T_{\sigma(2p)}$ . The parity of  $\sigma(i)$  coincides with the parity of *i*. Moreover for every  $i \in \{1, \ldots, p\}$  we have  $\sigma(2i) = \sigma(2i+1)+1$ mod 2p.



The side pairings of  $\Omega$  which define S in such a way that the center of  $\Omega$  projects to 0 glue the edge 2k to the edge 1 and therefore we have

 $\sigma(2) = 2k$  and  $\sigma(3) = 2k - 1$ . The basic group  $\Gamma$  of isometries of *S* permutes the triangles  $T_i$  and fixes the vertex *A*. This implies that  $\sigma$  normalizes the group of permutations of  $\{1, \ldots, 2p\}$  generated by the permutation  $\tau(i) = i+2$ mod 2p and hence necessarily  $\sigma(2i) = 2i(k-1) + 2$ .

To obtain our surface S we have to identify the edge 2i - 1 with the edge 2im for some  $m \in \{2, \ldots, p-1\}$  with an orientation reversing isometry. The number m is uniquely determined if we require in addition that the triangles adjacent to odd edges of  $\Omega$  project once again to the triangles  $T_{2i-1}$   $(i = 1, \ldots, p)$  of the canonical triangulation.

Comparing the arrangement of triangles around 0 and A we conclude that  $\sigma(2m) = 2p$ . Together with the above this shows that  $2m(k-1) + 2 \equiv 0 \mod 2p$  or, equivalently,  $m(k-1)+1 \equiv 0 \mod p$ . In other words, if  $m, k \geq 2$  are such that  $m(k-1)+1 \equiv 0 \mod p$  then the surfaces S(p;k) and S(p;m) are isometric. This shows the first part of the lemma.

To show the second part of our lemma let S be a simple triangle surface which admits a non-trivial group  $\Sigma$  of orientation preserving isometries normalizing the basic group  $\Gamma$ . Then the action of  $\Sigma$  on S descends to an isometric action on the sphere  $S/\Gamma$ . The sphere  $S/\Gamma$  consists of two equilateral triangles with angle  $\pi/p$  glued at their boundaries. One of these triangles is the projection of the odd triangles of the canonical triangulation of S, the other one is the projection of the even triangles.

Every isometry of  $S/\Gamma$  has to preserve the singular set  $\{\widehat{A}, \widehat{B}, \widehat{0}\} \subset S/\Gamma$  of ramification points which consists of the vertices of the two triangles forming  $S/\Gamma$ . The only nontrivial isometry of  $S/\Gamma$  which fixes each of the ramification points  $\widehat{0}, \widehat{A}, \widehat{B}$  is the orientation reversing reflection which exchanges the two triangles forming  $S/\Gamma$ . By assumption the elements of  $\Sigma$  preserve the orientation of S and hence of  $S/\Gamma$ , and therefore there are two possibilities:

- 1)  $\Sigma$  contains an element  $\Psi$  which permutes cyclicly the singular points  $\widehat{A}, \widehat{B}, \widehat{0}$  of  $S/\Gamma$  and preserves each of the two triangles which form  $S/\Gamma$ .
- 2)  $\Sigma$  fixes one singular point of  $S/\Gamma$ , permutes the two other ones and exchanges the two triangles which form  $S/\Gamma$ .

Assume that S = S(p;k) admits an isometry  $\Psi$  as in 1) above. Then  $\Psi$  permutes the triangles of the canonical triangulation, but preserves their parity. If we cut S = S(p;k) open along those edges of the triangles of the canonical triangulation which connect the vertices A and B, then the result is the fundamental 2p-gon  $\Omega$  and we obtain our surface from  $\Omega$  by a side pairing which identifies the edges 1 and 2k. Since  $\Psi$  is an isometry of S

which preserves the canonical triangulation, if we cut S open along the edges connecting the vertices  $\Psi(A)$  and  $\Psi(B)$  then the result is again the polygon  $\Omega$ , and once again we obtain S from  $\Omega$  by identifying the edges 1 and 2k. This together with the above consideration shows that  $k(k-1)+1 \equiv 0 \mod p$  and therefore p divides k(k-1)+1.

Assume now that S admits an isometry  $\Psi$  as in 2) above. Then  $\Psi$  permutes the triangles of the canonical triangulation and changes their parity with respect to a given counter clockwise numbering around a given vertex. Let  $m \le p-1$  be such that  $k(m-1)+1 \equiv 0 \mod p$ . The above considerations imply that necessarily k = p - m + 1 and hence  $(m - 1)^2 \equiv 1 \mod p$  or equivalently  $m(m-2) \equiv 0 \mod p$ . Since  $m \ge 1$  is prime to p we conclude that either m = 2 or that p divides m-2. But  $m \le p-1$  and therefore only the case m = 2 is possible.

We are left with showing that the isometry  $\Psi$  is a hyperelliptic involution. For this notice that every fixed point of  $\Psi$  projects to a fixed point for the induced isometry  $\widehat{\Psi}$  of  $S/\Gamma$ . The map  $\widehat{\Psi}$  has precisely two fixed points: A singular point  $\widehat{0}$  of  $S/\Gamma$  and the midpoint y of the geodesic arc connecting the two other singular points.

There are exactly p = 2g + 1 preimages of y in S. Since  $\Psi^2 = Id$  and since  $\Psi$  normalizes  $\Gamma$ , either every preimage or no preimage is fixed by  $\Psi$ . The Riemann Hurwitz-formula [F] shows that the second case is impossible. Thus  $\Psi$  has exactly p + 1 = 2g + 2 fixed points and is a hyperelliptic involution.  $\Box$ 

COROLLARY 2.3. For every  $g \ge 2$  there is a hyperelliptic surface of genus g whose full automorphism group is the direct product of a cyclic group of order 2g + 1 and a cyclic group of order 2 generated by a hyperelliptic involution.

*Proof.* We showed in Lemma 2.1 that for each  $g \ge 2$  there is a simple triangle surface S(2g + 1; 2). By Lemma 2.2 and its proof, this surface is hyperelliptic and its isometry group is a stated in the corollary.

REMARK. There are surfaces S(p;k) for  $p \notin \{\ell(\ell-1)+1 \mid \ell \geq 2\}$  which admit a cyclic group  $\Sigma$  of isometries of order 3 contained in the normalizer of the basic group  $\Gamma$ . The simplest surface of this kind is the surface S(19;8)of genus g = 9.

#### U. HAMENSTÄDT

# 3. GEOMETRIC PROPERTIES OF SYSTOLES OF SIMPLE TRIANGLE SURFACES

This section is devoted to a description of some geometric properties of the systoles on a simple triangle surface S = S(p; k) and its associated ideal surface  $S_{\infty}$ . We continue to use the notations from Section 2.

The canonical triangulation of the surface S is invariant under the group  $\Gamma$  of isometries of S, and its vertices 0, A, B are fixed points for the action of  $\tilde{\Gamma}$ . The quotient  $S/\Gamma$  is a topological 2-sphere with a singular hyperbolic metric which is isometric to two equilateral hyperbolic triangles with angles  $\pi/p$  glued at their boundaries. Every closed geodesic on S which does not pass through any of the vertices A, B, 0 projects to a closed geodesic on  $S/\Gamma$ . We first observe that this is the case for the projection to  $S/\Gamma$  of a systole on S.

LEMMA 3.1. A systole of S does not pass through a vertex of the canonical triangulation.

*Proof.* Let  $\gamma$  be a geodesic in S which passes through one of the vertices of the canonical triangulation, say through the vertex 0. Assume that we obtain S from side pairing transformations of a fundamental 2p-gon  $\Omega$  in such a way that the center of  $\Omega$  projects to the point 0.

The lift of  $\gamma$  to the polygon  $\Omega$  has to intersect the boundary  $\partial \Omega$  of  $\Omega$  and hence its length is not smaller than twice the distance between the center of  $\Omega$  and  $\partial \Omega$ . In particular, if  $\alpha$  is any geodesic arc in  $\Omega$  of minimal length which connects the edge 1 to an edge  $r \neq p+1$ , then  $\alpha$  is necessarily shorter than  $\gamma$ .

Let k < p be such that the side pairings for  $\Omega$  which define *S* identify the edge 1 with the edge 2k. If  $2k \neq p+1$  then the above shows that the closed geodesic on *S* which is the projection of the arc of minimal length in  $\Omega$  connecting the edges 1 and 2k is shorter than  $\gamma$ .

On the other hand, if 2k = p + 1, then we obtain from Lemma 2.2 that the side pairings which define  $\Omega$  with center at the point A identify the edge 1 with an edge 2m for some  $m \neq (p+1)/2$ . Again we conclude that the arc  $\gamma$  is longer than a systole on S.  $\Box$ 

Let  $\Omega$  be a fundamental 2p-gon and let  $\gamma$  be the geodesic arc through the center 0 of  $\Omega$  which connects the vertex 2p to the vertex p. Let  $\Psi$  be the reflection in  $\mathbf{H}^2$  along  $\gamma$ . Then  $\Psi$  leaves  $\Omega$  invariant and maps a pair of edges of the form  $\{2i+1, 2i+2k\}$  to the pair  $\{2p-2i, 2p-2i-2k+1\}$ of the same form. In other words,  $\Psi$  descends to an orientation reversing isometry of S. The group  $\widetilde{\Gamma}$  of isometries of S generated by  $\Psi$  and the basic group  $\Gamma$  has order p+1 and contains the group  $\Gamma$  as a normal subgroup of index 2. The orientation reversing isometry  $\Psi$  of S descends to an orientation reversing isometry  $\widehat{\Psi}$  of order 2 of  $S/\Gamma$  which exchanges the two triangles.

Let  $\triangle$  be an equilateral hyperbolic triangle with angle  $\pi/p$ . The triangle  $\triangle$  will be viewed as a billiard table. A billiard orbit consists of geodesic arcs inside  $\triangle$  which are joined at points of the boundary  $\partial \triangle$  according to the rule that the angle of incidence equals the angle of reflection. We view a billiard orbit as unparametrized and unoriented.

A closed geodesic on  $S/\Gamma$  not passing through one of the singular points  $\widehat{0}, \widehat{A}, \widehat{B}$  corresponds to a periodic billiard orbit in  $\triangle$  of one of the following three types:

a) A periodic billiard orbit with an odd number of collisions with the boundary of  $\triangle$ , none of them perpendicular.

In the sequel we call such a billiard orbit an *A*-orbit. An *A*-orbit  $\tilde{\gamma}$  admits a lift to a closed geodesic  $\hat{\gamma}$  on  $S/\Gamma$ , unique up to reparametrization, which is freely homotopic as a curve on the thrice punctured sphere  $S/\Gamma \setminus \{\hat{0}, \hat{A}, \hat{B}\}$ to its image under the isometry  $\hat{\Psi}$ . Its trace is invariant under  $\hat{\Psi}$ . The lift of every collision point of the billiard orbit with  $\partial \Delta$  is a transverse intersection of  $\hat{\gamma}$  with the common boundary of the two triangles forming  $S/\Gamma$ . The length of  $\hat{\gamma}$  is twice the length of  $\tilde{\gamma}$ .

b) A periodic billiard orbit whose trace consists of one piecewise geodesic arc which meets the boundary  $\partial \triangle$  orthogonally at its endpoints.

We call such an orbit a *B*-orbit in the sequel. A *B*-orbit  $\tilde{\gamma}$  admits a lift to  $S/\Gamma$ , unique up to reparametrization, which is freely homotopic to the image  $\widehat{\Psi}(\widehat{\gamma}^{-1})$  under  $\widehat{\Psi}$  of its inverse  $\widehat{\gamma}^{-1}$ . Its trace is invariant under  $\widehat{\Psi}$  and its length is twice the length of  $\widetilde{\gamma}$ .

c) A periodic billiard orbit with an even number of collisions with the boundary of  $\triangle$ , none of them perpendicular.

We call such an orbit a *C-orbit*. A *C*-orbit  $\tilde{\gamma}$  admits two different lifts  $\hat{\gamma}_1, \hat{\gamma}_2$  to closed geodesics on  $S/\Gamma$  whose traces intersect transversely and whose lengths coincide with the length of the billiard orbit. The geodesic  $\hat{\gamma}_2$  is the image of  $\hat{\gamma}_1$  under the isometry  $\hat{\Psi}$  of  $S/\Gamma$ . Neither the geodesic  $\hat{\gamma}_i$  nor its inverse  $\hat{\gamma}_i^{-1}$  is freely homotopic to  $\hat{\Psi}(\hat{\gamma}_i)$ .

Call a periodic billiard orbit  $\tilde{\gamma}$  on  $\Delta$  as above *liftable to* S if there is a closed geodesic  $\gamma$  on S whose projection to  $S/\Gamma$  is a lift  $\hat{\gamma}$  of  $\tilde{\gamma}$  to  $S/\Gamma$ . We then call  $\gamma$  a *lift of*  $\tilde{\gamma}$  *to* S.

The group  $\widetilde{\Gamma}$  also acts as a group of isometries on the ideal surface  $S_{\infty}$  associated to S. The quotient of  $S_{\infty}$  unter the basic group  $\Gamma$  is the thrice punctured sphere  $S_{\infty}/\Gamma$  with the complete hyperbolic metric of finite volume. The orientation reversing involution  $\widehat{\Psi}$  acts on  $S_{\infty}/\Gamma$  as the natural reflection which leaves each of the punctures fixed. Every closed geodesic on  $S_{\infty}$  projects to a closed geodesic on  $S_{\infty}/\Gamma$ .

Let  $\triangle_{\infty}$  be an ideal triangle. Once again we can view  $\triangle_{\infty}$  as a billiard table. The above definition for billiard orbits in  $\triangle$  can also be made for billiard orbits in  $\triangle_{\infty}$ . We call a billiard orbit  $\tilde{\gamma}$  in  $\triangle_{\infty}$  *liftable* to the ideal surface  $S_{\infty}$  if there is a closed geodesic  $\gamma$  on  $S_{\infty}$  which projects to  $\tilde{\gamma}$ . In the remainder of this section the ideal triangle, its billiard orbits and their lifts to the ideal surface  $S_{\infty}$  are always included in our considerations without further comments. More precisely, even though for simplicity we formulate all our statements only for billiard orbits in  $\triangle$  and the surface S it is immediately clear from the proofs that they are equally valid for  $\triangle_{\infty}$  and the ideal surface  $S_{\infty}$ .

A first example of a liftable billiard orbit is given in the next lemma.

LEMMA 3.2. There is a unique A-orbit  $\tilde{\gamma}_1$  in  $\triangle$  with 3 collisions with the boundary, and this orbit is liftable. The length of a lift of  $\tilde{\gamma}_1$  to S is not bigger than 6  $\operatorname{arccosh} \frac{3}{2}$ .



**Proof.** Let S = S(p;k) and let  $\Omega$  be a fundamental 2p-gon. Connect the midpoint of the edge 1 in  $\Omega$  with the midpoint of the edge 3 by a simple arc, and connect the midpoint of the edge 2k with the midpoint of the edge 2k+2 by a simple arc. These two arcs together project to a simple closed curve on S which is freely homotopic to a closed geodesic  $\gamma$  on S. The geodesic  $\gamma$  is necessarily a lift of an A-orbit  $\tilde{\gamma}_1$  in  $\Delta$  of period 3. Notice that there are exactly p lifts of  $\tilde{\gamma}_1$ , and every such lift intersects exactly 6 other lifts, with each of these intersections consisting of a single point. The length  $\ell_1$  of a lift of  $\tilde{\gamma}_1$  to S is twice the length of  $\tilde{\gamma}_1$ .

To give a sharp upper bound for  $\ell_1$  notice that  $\ell_1/2$  is just the smallest circumference of a hyperbolic triangle with vertices on the sides of  $\Delta$  and hence  $\ell_1/2$  is not larger than the smallest circumference of a hyperbolic triangle  $T_{\infty}$  with vertices on the boundary of an ideal triangle. This circumference is the limit as  $k \to \infty$  of the circumferences of hyperbolic triangles  $T_k$  whose vertices are the midpoints of the sides of an equilateral triangle  $\Delta_k$  with angle  $\pi/k$ .

To give a formula for the circumference of  $T_k$  let  $\lambda_k$  be the length of the sides of  $\Delta_k$ , and let  $\ell_k$  be the length of the sides of  $T_k$ .

Hyperbolic trigonometry (see [I]) gives  $\cosh \frac{\lambda_k}{2} = \frac{\cos \pi/2k}{\sin \pi/k}$  and

$$\cosh \ell_k = (\cosh \frac{\lambda_k}{2})^2 - (\sinh \frac{\lambda_k}{2})^2 \cos \frac{\pi}{k} = \frac{(1 - \cos \pi/k)(\cos \pi/2k)^2}{(\sin \pi/k)^2} + \cos \frac{\pi}{k}.$$

This shows that as  $k \to \infty$  we have  $\cosh \ell_k \to \frac{3}{2}$  and  $6\ell_k \to 6 \operatorname{arccosh} \frac{3}{2} \sim 5.775$ . This completes the proof of our lemma.  $\Box$ 

As an immediate consequence of Lemma 3.2, the length of the systole of a simple triangle surface and its associated ideal surface does not exceed 6 arccosh  $\frac{3}{2} < 5.8$ . In particular, for large genus such triangle surfaces are never globally maximal [BS].

LEMMA 3.3. A lift to S of an A-orbit  $\tilde{\gamma}$  which is different from  $\tilde{\gamma}_1$  is not a systole.

*Proof.* By Lemma 3.2 it suffices to show that the length of every A-orbit  $\tilde{\gamma}$  in  $\Delta$  is not smaller than the length of the A-orbit  $\tilde{\gamma}_1$  from Lemma 3.1, with equality if and only if  $\tilde{\gamma} = \tilde{\gamma}_1$ .

For this recall from the definition that an A-orbit  $\tilde{\gamma}$  is a closed curve in  $\Delta$  with an odd number of collisions with the boundary, none of them perpendicular. This implies that for every pair of sides of the boundary of  $\Delta$ there is a geodesic arc of  $\tilde{\gamma}$  with endpoints on these sides.

Thus we can find three points  $E_1, E_2, E_3$  which lie on the three different sides of the boundary of  $\triangle$  and are contained in  $\tilde{\gamma}$  in this order with respect to the choice of some fixed orientation and some fixed initial point. Since  $\tilde{\gamma}$  is closed, its length is not smaller than the circumference of the triangle T inscribed in  $\triangle$  with vertices  $E_1, E_2, E_3$  with equality if and only if  $\tilde{\gamma}$ coincides with the boundary of T. However the length of the orbit  $\tilde{\gamma}_1$  from Lemma 3.2 is the smallest circumference of any triangle with vertices on the three different sides of  $\triangle$ . From this the lemma is immediate.  $\Box$  *B*-orbits and *C*-orbits in  $\triangle$  are more difficult to control. For their investigation let  $S_*$  be a thrice punctured sphere. We equip  $S_*$  with the (noncomplete) hyperbolic metric which we obtain by glueing two equilateral hyperbolic triangles  $T_1, T_2$  with angle  $\pi/p$  along their boundaries. Thus  $S_*$  with this metric is just the space  $S/\Gamma - \{\widehat{0}, \widehat{A}, \widehat{B}\}$ . The sides of  $T_1, T_2$  are geodesics a, b, c in  $S_*$  which connect a pair of punctures of  $S_*$ . We call a, b, c the edges of  $S_*$ . Define a curve  $\alpha$  in  $S_*$  to be admissible if  $\alpha$  is a closed curve with the additional property that every connected component of an intersection of  $\alpha$  with one of the triangles  $T_i$  consists of a single geodesic arc in  $T_i$ . We call these components the segments of  $\alpha$ . Thus  $\alpha$  is composed of a finite number of geodesic arcs with endpoints on the edges of  $S_*$ , and no two consecutive such segments are contained in the same triangle  $T_i$ . In the sequel we identify two such curves if they coincide up to an orientation preserving reparametrization.

An admissible homotopy of an admissible curve  $\alpha$  is a free homotopy of  $\alpha$  through admissible curves. We call the admissible curve  $\alpha$  on  $S_*$  essential if  $\alpha$  can not be homotoped into one of the punctures. An admissible subcurve of  $\alpha$  is a connected subarc  $\beta$  of  $\alpha$  such that there exists an admissible homotopy of  $\alpha$  which deforms  $\beta$  into a closed admissible curve. For every admissible subcurve  $\beta$  of  $\alpha$  we can write  $\alpha = \beta \gamma$  for an admissible subcurve  $\gamma$ . We say that  $\alpha$  is *irreducible* if for every essential admissible subcurve  $\beta$  of  $\alpha$  the curve  $\gamma = \alpha - \beta$  is not essential. A curve which is not irreducible is called *reducible*. An irreducible essential curve  $\alpha$  is called *minimal* if  $\alpha$  does not contain any nontrivial essential closed subcurve.

There are two obvious types of minimal closed curves which can be described as follows. The first type consists of curves which are freely homotopic to a lift of the A-orbit  $\tilde{\gamma}_1$  from Lemma 3.2. We call such a curve a *minimal curve of type A*. The second type consists of curves which are freely homotopic to a curve of the form  $\alpha\beta$  where  $\alpha$  and  $\beta$  are simple closed curves in  $S_*$  which generate the fundamental group of  $S_*$ . Up to orientation there are three different free homotopy classes of such minimal curves which correspond to a choice of two of the three punctures.

LEMMA 3.4. Every minimal admissible closed curve is either a minimal curve of type A or a minimal curve of type B.

*Proof.* Let  $\alpha$  be a minimal admissible closed curve. If  $\alpha$  contains two consecutive geodesic segments with endpoints on the same pair of edges of  $S_*$  then  $\alpha$  contains a nontrivial non-essential admissible subcurve  $\beta$  and

necessarily  $\alpha = \beta \gamma$  where  $\gamma$  is non-essential. Since  $\alpha$  is essential,  $\beta$  and  $\gamma$  are homotopic to different punctures. The same argument can be applied to any subarc of  $\gamma$  which consists of two consecutive geodesic segments and shows that  $\gamma$  has exactly two segments. This means that  $\alpha$  is of type B.

On the other hand, if there are no two consecutive segments of  $\alpha$  hitting the same edges of  $S_*$  then  $\alpha$  is necessarily homotopic to a multiple of the lift of the *A*-orbit  $\tilde{\gamma}_1$  from Lemma 3.2. By minimality,  $\alpha$  is of type *A*. This shows the lemma.

Let now  $\alpha$  be any irreducible closed curve. A *simplification* of  $\alpha$  is an admissible essential subcurve  $\beta$  of  $\alpha$  such that  $\alpha$  can be written in the form  $\alpha = \beta \gamma$  where  $\gamma$  is non-essential. A *minimal model* is a minimal closed curve which can be obtained from  $\alpha$  by finitely many simplifications. Clearly every irreducible closed curve has a minimal model which is not necessarily unique.

Recall that  $S_*$  admits a natural orientation reversing isometry  $\widehat{\Psi}$  which fixes pointwise the edges of  $S_*$ . This isometry acts on the space of admissible curves. We have

LEMMA 3.5. Let  $\alpha$  be an irreducible admissible curve which admits a minimal model of type B. Then  $\alpha$  is freely homotopic to  $\widehat{\Psi}(\alpha^{-1})$ .

*Proof.* Let  $\alpha$  be an irreducible admissible closed curve. Assume that  $\alpha$  admits a minimal model  $\beta$  of type *B*. We have to show that  $\widehat{\Psi}(\alpha^{-1})$  is freely homotopic to  $\alpha$ .

By definition of a minimal model, with respect to a suitable numbering of the edges of  $S_*$  the curve  $\beta$  can be written in the form  $\beta = \beta_1 \beta_2 \beta_3 \beta_4$  where  $\beta_1$  connects the edge *a* to the edge *b*,  $\beta_2$  connects the edge *b* to the edge *a*,  $\beta_3$  connects *a* to *c* and  $\beta_4$  connects *c* to *a*. Notice that  $\beta$  has exactly 4 intersection points with the edges of  $S_*$ .

Since  $\beta$  is a minimal model for  $\alpha$ , the curve  $\alpha$  can be represented in the form  $\alpha = \beta_1 \alpha_1 \beta_2 \alpha_2 \beta_3 \alpha_3 \beta_4 \alpha_4$  where  $\alpha_i$  is an admissible closed curve. By assumption  $\alpha$  is irreducible and therefore the curves  $\alpha_i$  are non-essential.

We distinguish three cases.

## 1) The curve $\beta_1 \alpha_1 \beta_2$ is essential.

Then  $\alpha_1$  consists of an even number of geodesic arcs which connect the edges *b* and *c*. Moreover the subcurve  $\alpha_2\beta_3\alpha_3\beta_4\alpha_4$  has to be non-essential and therefore  $\alpha = \beta_1\alpha_1\beta_2(\beta_3\beta_4)^m$  for some  $m \ge 1$ . In particular,  $\alpha$  is freely homotopic to  $\widehat{\Psi}(\alpha^{-1})$ .

2) The curve  $\beta_3 \alpha_3 \beta_4$  is essential.

As above we conclude that then  $\alpha = (\beta_1 \beta_2)^m \beta_3 \alpha_3 \beta_4$  and  $\alpha$  is freely homotopic to  $\widehat{\Psi}(\alpha^{-1})$ .

3)  $\beta_1 \alpha_1 \beta_2 = (\beta_1 \beta_2)^{m_1}$  and  $\beta_3 \alpha_3 \beta_4 = (\beta_3 \beta_4)^{m_2}$  for some  $m_1, m_2 \ge 1$ .

Since the curves  $\alpha_2$  and  $\alpha_4$  are non-essential and have their endpoints on the side *a* this implies that  $\alpha$  can be represented in the form  $\alpha = (\beta_1 \beta_2)^{\ell_1} (\beta_3 \beta_4)^{\ell_2}$  for some  $\ell_1, \ell_2 \ge 1$ . Once again we conclude that  $\alpha$  is homotopic to  $\widehat{\Psi}(\alpha^{-1})$ .  $\Box$ 

REMARK. The proof of Lemma 3.5 also shows the following: Let  $\alpha$  be an irreducible admissible essential closed curve on  $S_*$  which admits a minimal model of type *B*. Then with respect to a suitable labeling of the edges of  $S_*$ ,  $\alpha$  is freely homotopic to a curve of the form  $(\beta_1\beta_2)^k\beta_3\zeta^m\beta_4$  where  $k \ge 1$ ,  $m \ge 0$  and  $\beta_1$  is an arc joining the edge *a* to the edge *b*,  $\beta_2$  connects *b* to *a*,  $\beta_3$  joins *b* to *c*,  $\zeta$  is nonessential and  $\beta_4$  connects *c* to *a*.

LEMMA 3.6. The projection to  $S/\Gamma - \{\widehat{0}, \widehat{A}, \widehat{B}\}$  of a systole on a simple triangle surface S = S(p; k) is irreducible.

*Proof.* By Lemma 3.2 it suffices to show that the length of every admissible reducible closed curve  $\alpha$  in  $S_*$  is bigger than twice the length of the A-orbit  $\tilde{\gamma}_1$ . For this let  $\alpha$  be reducible and write  $\alpha = \alpha_1 \alpha_2$  where the curves  $\alpha_1, \alpha_2$  are essential.

Let  $\beta$  be an irreducible admissible essential subcurve of  $\alpha_1$ . If  $\beta$  has a minimal model of type A, then we can cut from  $\beta$  finitely many non-essential closed curves to obtain a shorter curve which is homotopic to two copies of the A-orbit  $\tilde{\gamma}_1$  from Lemma 3.2. Since the lift  $\hat{\gamma}_1$  of  $\tilde{\gamma}_1$  to  $S/\Gamma$  has minimal length in its free homotopy class and since  $\alpha$  is homotopic to  $\beta\gamma$  for some closed curve  $\gamma$ , the length of  $\alpha$  is bigger than the length of the lift  $\hat{\gamma}_1$  of  $\tilde{\gamma}_1$  to  $S_*$ . Thus by Lemma 3.2  $\alpha$  can not lift to a systole on S.

We are left with the case that all minimal models of irreducible subcurves  $\alpha_1, \alpha_2$  of  $\alpha$  are of type *B*. Then we can cut away finitely many closed curves from  $\alpha$  which shortens the length of  $\alpha$  to end up with a closed curve  $\beta$  of the form  $\beta = \beta_1 \gamma \beta_2 \delta$  where  $\beta_1, \beta_2$  are minimal curves of type *B* and  $\gamma, \delta$  are possibly trivial arcs connecting the edges containing the endpoints of  $\beta_1, \beta_2$ . If  $\gamma, \delta$  are not trivial then we can replace  $\gamma \beta_2 \delta$  by a minimal curve  $\gamma \tilde{\beta}_2 \delta$  of type *B* where  $\tilde{\beta}_2$  is an admissible subcurve of  $\beta_2$ . In other words, we may as well assume that  $\beta = \beta_1 \beta_2$ .

Now we distinguish two cases.

# 1) The curves $\beta_1, \beta_2$ are homotopic.

Then there are simple closed generators  $\eta, \zeta$  of the fundamental group of  $S_*$  such that  $\beta$  is freely homotopic to  $\eta \zeta \eta \zeta$ . In particular there is a closed geodesic  $\rho$  on  $S_*$  which is freely homotopic to  $\beta$ , whose length is not bigger than the length of  $\beta$  and which is not a prime geodesic. This geodesic is the double of a minimal curve  $\gamma$  of type B. The length of  $\rho$  equals twice the length of  $\gamma$ . However, since the length  $\ell_1$  of the A-orbit  $\tilde{\gamma}_1$  from Lemma 3.2 is the minimal length of any closed curve in the triangle  $\Delta$  which intersects the three sides of  $\Delta$ , the length of  $\tilde{\gamma}_1$  is strictly smaller than the length of  $\gamma$ . Thus  $\rho$  is longer than a lift of  $\tilde{\gamma}_1$  and  $\alpha$  can not lift to a systole on S.

# 2) The curves $\beta_1, \beta_2$ are not homotopic.

Let  $\tilde{\zeta}$  be the *B*-orbit in  $\triangle$  whose lift to  $S/\Gamma - \{\widehat{A}, \widehat{B}, \widehat{0}\} = S_*$  is freely homotopic to  $\beta_1\beta_2$ . The length of  $\tilde{\zeta}$  is not bigger than half the length of  $\beta_1\beta_2$  and  $\tilde{\zeta}$  consists of four arcs  $\tilde{\zeta}_1, \tilde{\zeta}_2, \tilde{\zeta}_3, \tilde{\zeta}_4$ . The arc  $\tilde{\zeta}_1$  meets one of the sides, say the side *a*, perpendicularly, and  $\tilde{\zeta}_4$  meets a different side, say the side *b*, perpendicularly.

We denote by  $E_1, E_2, E_3$  the endpoints of  $\tilde{\zeta}_2$  and  $\tilde{\zeta}_3$ ; they lie on the three different sides of  $\Delta$ .

Once again we distinguish two cases:

a) The arcs  $\tilde{\zeta}_1$  and  $\tilde{\zeta}_4$  intersect.



Then the length of  $\tilde{\zeta}$  is bigger than the length of the triangle inscribed in  $\Delta$  with vertices  $E_1, E_2, E_3$ . In particular, the length of  $\tilde{\zeta}$  is bigger than the length of the A-orbit  $\tilde{\gamma}_1$  from Lemma 3.2.

b) The arcs  $\tilde{\zeta}_1$  and  $\tilde{\zeta}_4$  do not intersect.



In this case either the arc  $\tilde{\zeta}_1$  intersects the arc  $\tilde{\zeta}_3$  or the arc  $\tilde{\zeta}_4$  intersects the arc  $\tilde{\zeta}_2$ . Assume that the second case holds.

Let again  $E_1, E_2$  be the endpoints of  $\tilde{\zeta}_2$  where  $E_1$  lies on the edge band let  $E_4$  be the endpoint of the arc  $\tilde{\zeta}_4$  on the edge b. Since  $\tilde{\zeta}_4$  meets borthogonally at  $E_4$  and has its second endpoint  $E_3$  on the side a, the angle at  $E_4$  of the triangle with vertices  $E_1, E_4, E_2$  is strictly bigger than  $\frac{\pi}{2}$ . This means that the distance between  $E_2$  and  $E_4$  is smaller than the length of the arc  $\tilde{\zeta}_2$  and therefore the length of  $\tilde{\zeta}$  is bigger than the circumference of the triangle with vertices  $E_2, E_3, E_4$ . In particular, this length is bigger than the length of the A-orbit  $\tilde{\gamma}_1$ .

This completes the proof of our lemma.

As an immediate corollary of Lemma 3.6 and Lemma 3.5 we obtain

COROLLARY 3.7. A C-orbit in  $\triangle$  does not lift to a systole on S.

## 4. LENGTH ESTIMATES FOR SYSTOLES

In this section we complete the geometric description of the systoles of a simple triangle surface and its associated ideal surface. As a consequence we obtain that a simple triangle surface which is different from one of the three surfaces listed in the introduction is not maximal.

We resume the assumptions and notations from Section 3. Our goal is to describe all *B*-orbits in the equilateral triangle  $\triangle$  with angle  $\pi/p$  or in an ideal triangle  $\triangle_{\infty}$  which lift to a systole on a simple triangle surface *S* or its associated ideal surface  $S_{\infty}$ . For this it is convenient to consider any piecewise geodesic  $\alpha$  in  $\triangle$  with the following properties:

- a) There is a pair  $e_1, e_2$  of sides of  $\triangle$  which is connected by at most one subarc of  $\alpha$ .
- b) If  $e_3$  is the third side of  $\triangle$  then the subcurves  $\alpha_1, \alpha_2$  of  $\alpha$  which contain all arcs of  $\alpha$  joining  $e_1, e_2$  to  $e_3$  are connected and either  $\alpha = \alpha_1 \alpha_2$  or  $\alpha_1 \alpha_2$  is not connected.

We call such a curve *irreducible*. A *B*-orbit  $\tilde{\gamma}$  which is irreducible in this sense and with the additional property that there is a pair of sides of  $\Delta$  which is not connected by any geodesic segment of  $\tilde{\gamma}$  will be called a  $B_0$ -orbit. An irreducible *B*-orbit which is not a  $B_0$ -orbit will be called a  $B_1$ -orbit. In the same way we define irreducible  $B_0$ -orbits and  $B_1$ -orbits in the ideal triangle  $\Delta_{\infty}$ .

A lift to  $S/\Gamma$  of an irreducible curve  $\alpha$  in  $\triangle$  is an admissible closed piecewise geodesic in  $S/\Gamma \setminus \{\widehat{A}, \widehat{B}, \widehat{0}\}$  whose trace is invariant under the natural isometry  $\widehat{\Psi}$  of order 2 of  $S/\Gamma$  exchanging the two triangles and which projects to  $\alpha$ . Call two irreducible curves  $\alpha, \beta$  in  $\triangle$  homotopic if there are lifts of  $\beta$  and  $\alpha$  to  $S/\Gamma$  which are freely homotopic in  $S/\Gamma - \{\widehat{A}, \widehat{B}, \widehat{0}\}$ .

The remark after Lemma 3.5 shows that a *B*-orbit in  $\triangle$  is irreducible in the above sense if and only if its lift to  $S/\Gamma - \{\widehat{0}, \widehat{A}, \widehat{B}\}$  is irreducible in the sense of Section 3. Thus we obtain from the results in Section 3.

COROLLARY 4.1. A B-orbit in  $\triangle$  or  $\triangle_{\infty}$  which lifts to a systole on S or  $S_{\infty}$  is irreducible.

For the description of all *B*-orbits in  $\triangle$  which lift to a systole of a simple triangle surface we use a length comparison argument. Namely, observe that we can talk about homotopic irreducible arcs in nonisometric hyperbolic triangles in an obvious way. We have.

LEMMA 4.2. Let  $q > p \ge 5$  and let  $\triangle, \triangle'$  be equilateral triangles with angles  $\pi/p, \pi/q$  respectively. Let  $\gamma, \gamma'$  be two homotopic *B*-orbits in  $\triangle, \triangle'$ . Then the length of  $\gamma$  is smaller than the length of  $\gamma'$ .

*Proof.* For  $t < \pi/3$  denote by  $T_t$  the equilateral hyperbolic triangle with angle t. Since a *B*-orbit is the shortest curve in its homotopy class it suffices to show the following: If  $t < t_0 < \pi/3$  and if  $\gamma \subset T_{t_0}$  is any *B*-orbit, then every admissible curve in  $T_t$  which is homotopic to  $\gamma$  is longer than  $\gamma$ .

But this follows simply from the fact that for  $t < t_0$  the triangle  $T_{t_0}$  can be isometrically embedded into the triangle  $T_t$  (see [I]). More precisely, the center of the triangle  $T_t$  is the unique point in  $T_t$  which has the same

distance to each of the vertices of  $T_t$ . There is an (essentially unique) isometric embedding of  $T_{t_0}$  into  $T_t$  which maps the center of  $T_{t_0}$  to the center of  $T_t$ and such that each geodesic in  $T_t$  which connects the center to one of the vertices passes through a vertex of  $T_{t_0}$ . Map  $T_{t_0}$  onto  $T_t$  by a diffeomorphism which maps each geodesic  $\gamma$  through the center to itself and scales the parametrization by the proportionality factor length  $(\gamma \cap T_t)/\text{length} (\gamma \cap T_{t_0})$ . This map strictly increases the length of nontrivial curves in  $T_{t_0}$ . From this the lemma is immediate.

Let again  $\Omega$  be a fundamental 2p-gon, let  $k \in [2, (p+1)/2]$  and let S = S(p;k) be a simple triangle surface. The side pairings for  $\Omega$  which induce the surface S define a collection of p simple closed geodesics on S which are invariant under the action of the basic group  $\Gamma$ . Each of these geodesics is freely homotopic to the projection to S of a geodesic arc in  $\Omega$  connecting the midpoint of the side 2i+1 to the midpoint of the side 2i+2k. Their projection to  $S/\Gamma$  is the lift of an irreducible  $B_0$ -orbit  $\tilde{\gamma}_0$  which can be described as follows.

- a)  $\tilde{\gamma}_0$  has one endpoint on the edge opposite to a vertex  $\tilde{0}$  which is the only collision point with this edge.
- b) There are k collisions with the edge joining 0 to a second vertex  $\tilde{A}$  and k-1 collisions with the edge joining 0 to the third vertex  $\tilde{B}$  for some  $k \in [2, p/2]$ .

We call a  $B_0$ -orbit  $\tilde{\gamma}$  with properties a) and b) for an arbitrary  $k \leq p/2$ a *side pairing orbit*. With this notation, every minimal  $B_0$ -orbit is a side pairing orbit. Moreover a side pairing orbit is determined up to isometries of  $\Delta$  by the number of its geodesic segments, or, equivalently, by the number of its collision points with the boundary of  $\Delta$ . For a simple triangle surface S there are at most three different liftable side pairing orbits (compare Section 2).

Using Lemma 4.2 and a comparison argument we can now estimate the length of a large family of irreducible B-orbits.

LEMMA 4.3. Let  $\tilde{\eta}$  be an irreducible B-orbit. Assume that either

- 1.  $\widetilde{\eta}$  is a  $B_1$ -orbit with at least 5 collisions with the boundary or
- 2.  $\tilde{\eta}$  is a  $B_0$ -orbit which is not a side pairing orbit and has at least 6 collisions with the boundary.

Then a lift of  $\tilde{\eta}$  to  $S/\Gamma - \{\widehat{A}, \widehat{B}, \widehat{0}\}$  is longer than a systole on S.

*Proof.* By definition, a  $B_1$ -orbit contains at least 3 geodesic arcs. Up to isometries of  $\triangle$  there is a unique  $B_1$ -orbit  $\tilde{\gamma}$  consisting of exactly 4 arcs.



This orbit admits a subarc which is homotopic to a side pairing orbit with 3 segments. In particular, if S = S(p; k) admits a liftable side pairing orbit which consists of at most three segments, then this side pairing orbit is homotopic to a proper subarc of  $\tilde{\gamma}$  and therefore a lift of  $\tilde{\gamma}$  to  $S/\Gamma$  is longer than a systole on S.

Lemma 2.2 shows that for  $p \le 9$  every simple triangle surface of genus  $\frac{p-1}{2}$  is isometric to a surface S(p;m) for m = 2 or m = 3 and hence admits a liftable side pairing orbit which consists of at most 3 segments.

On the other hand, an explicit computation (using Maple or Mathematica) shows that for p = 11 the length of  $\tilde{\gamma}$  is bigger than 3 arccosh  $\frac{3}{2}$ . Thus by Lemma 3.2, Lemma 4.2 and the above, a lift of  $\tilde{\gamma}$  to  $S/\Gamma - \{\hat{A}, \hat{B}, \hat{0}\}$  is longer than a systole on S(p; k).

Since every  $B_1$ -orbit  $\tilde{\eta}$  with at least 5 collisions with the boundary admits a subarc which is homotopic to  $\tilde{\gamma}$ , our statement for  $B_1$ -orbits follows.

Let  $\tilde{\eta}$  be a  $B_0$ -orbit which is not a side pairing orbit and has at least 6 collisions with the boundary. Denote by C the vertex of  $\Delta$  whose adjacent sides are not connected by any subarc of  $\tilde{\gamma}$ . Then  $\tilde{\gamma}$  contains a subarc which consists of two segments and connects the sides adjacent to C. If we replace this arc by a single geodesic segment, then we obtain a shorter curve which contains a subcurve homotopic to the  $B_1$ -orbit  $\tilde{\gamma}$  above. Thus the statement for  $B_0$ -orbits follows once again from the length estimate for  $\tilde{\gamma}$ .

COROLLARY 4.4. Every systole on a simple triangle surface is either a lift of the A-orbit  $\tilde{\gamma}_1$  in  $\triangle$  or a lift of a side pairing orbit on  $\triangle$ .

*Proof.* By Lemma 4.3, a *B*-orbit  $\tilde{\eta}$  which is not a side pairing orbit can only lift to a systole if either

1)  $\tilde{\eta}$  is a  $\mathcal{B}_0$ -orbit with exactly 5 collisions with the boundary



or

2)  $\tilde{\eta}$  is a  $B_1$ -orbit with exactly 4 collisions with the boundary.



Consider first an orbit  $\tilde{\eta}$  as in 1) above. Assume that  $\tilde{\eta}$  lifts to a closed geodesic on the surface S(p;k). The lifts of  $\tilde{\eta}$  then define piecewise geodesics in the fundamental 2p-gon  $\Omega$ .

Choose such a piecewise geodesic  $\eta$  with the property that the center of  $\Omega$  corresponds to a vertex of  $\Delta$  whose adjacent sides are connected by an arc of  $\tilde{\eta}$ . Then  $\eta$  consists of two components  $\eta_1$ ,  $\eta_2$ . After a suitable numbering of the edges of  $\Omega$  we may assume that  $\eta_1$  connects the edge 1 to the edge 6 and that  $\eta_2$  connects the edge 6 - 2k + 1 to the edge 6 - 2k + 2 where  $k \geq 2$  is such that S = S(p; k).

Since  $\eta$  projects to a closed geodesic on S(p;k) we have  $6 - 4k + 3 \equiv 1 \mod 2p$  and therefore  $4 - 2k \equiv 0 \mod p$ . Since p is odd and  $k \leq p - 1$  this is only possible if k = 2. But then there is a liftable side pairing orbit of S(p;k) which consists of 2 segments and is shorter than  $\tilde{\eta}$ .

A similar purely combinatorial argument shows that an orbit  $\tilde{\eta}$  as in 2) above is not liftable to any simple triangle surface. This shows the lemma.  $\Box$ 

86

### **PROPOSITION 4.5.**

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1) For  $3 \le k \le 5$  the surface S(k(k-1) + 1;k) and its associated ideal surface has 3k(k-1) + 3 systoles. These systoles are the images of a single simple closed geodesic under the action of the isometry group of S(k(k-1) + 1;k).

2) A simple triangle surface S which is not isometric to one of the surfaces  $S(k(k-1)+1;k)(3 \le k \le 5)$  is not maximal, neither is the ideal surface associated to S.

*Proof.* Let p = 2g + 1 for an arbitrary  $g \ge 2$  and let S be a simple triangle surface of genus g.

Recall that there are numbers  $k(0), k(A), k(B) \ge 2$  such that the sidepairings of the 2p-gon  $\Omega$  defining S with base-point 0, A, B identify the edge 1 with the edge 2k(0), 2k(A), 2k(B).

Let  $k_0 = \min\{k(0), k(A), k(B)\}$  and assume (via renaming) that  $k_0 = k(0)$ . The projection to *S* of the geodesic arc  $\tilde{\gamma}_0$  in  $\Omega$  which connects the edge 1 to the edge  $2k_0$  and is orthogonal to both edges is then a simple closed geodesic  $\gamma_0$  in *S* whose length we denote by  $\ell_0$ .

Corollary 4.4 shows that there are only two possibilities for a systole  $\gamma$  on S.

- 1)  $\gamma$  is a lift  $\gamma_1$  of length  $\ell_1$  of the A-orbit  $\widetilde{\gamma}_1$  on  $\triangle$  of period 3.
- 2)  $\gamma$  is the image under an isometry of S of the geodesic  $\gamma_0$  of length  $\ell_0$ .

Consider a surface S = S(p; k) as in Lemma 2.2 which admits a cyclic group  $\Sigma$  of order 3 of isometries normalizing the basic group  $\Gamma$ . If  $\ell_0$  is smaller than  $\ell_1$  then S admits 3p = 6g + 3 systoles which are just the lifts of the unique liftable side pairing orbit for S. We claim that this is the case if and only if S = S(7; 3) or S = S(13; 4) or S = S(21; 5).

To see this, recall from Lemma 2.2 that each such surface with these additional symmetries is of the form S = S(p;k) for some  $k \ge 3$  and a divisor p > k of k(k-1) + 1. The unique liftable side pairing orbit for S(p;k) consists of min $\{k, p-k+1\}$  segments. However, explicit computation shows that a side pairing orbit with 6 segments in an equilateral triangle with angle  $\pi/15$  is longer than the upper bound 3 arccosh  $\frac{3}{2}$  for  $\ell_1$ . Together with Lemma 4.2 this shows that if S(p;k) is such that  $\ell_0 \le \ell_1$  then either  $p \le 13$  or min $\{k, p-k+1\} \le 5$ .

The surfaces S(7;3) and S(13;4) are such surfaces S(p;k) with  $p \le 13$ . Any further example corresponds to a pair of numbers (p,k) such that k and that moreover p is a proper divisor of <math>k(k-1) + 1. However the only pairs of this kind are (13, 10) and (7, 5) and we find once again our surfaces S(13; 10) = S(13; 4) and S(7; 5) = S(7; 3).

Next we look for surfaces S(p;k) as above with  $\min\{k, p - k + 1\} \le 5$ and such that  $p > \min\{k, 14\}$  is a divisor of k(k-1) + 1. Write m = p - kand assume that  $m \le 4$  and that p = k + m divides k(k-1) + 1 = (p - m)(p - m - 1) + 1 = p(p - 2m - 1) + m(m + 1) + 1. Then p also divides m(m + 1) + 1, and since we assumed that  $p \ge 15$  we just obtain the surface S(21; 17) = S(21; 5) as a solution.

In other words, if  $\ell_0 \leq \ell_1$  and if S(p;k) admits a cyclic group of order 3 of isometries normalizing the basic group  $\Gamma$  then S is one of the surfaces S(7;3), S(13;4) and S(21;5). Explicit computation now shows that for these surfaces we indeed have  $\ell_0 < \ell_1$ .

Schmutz observed in [S1] that a closed hyperbolic surface S of genus g can only be maximal if S has at least 6g-5 systoles. Using this fundamental fact, the proof of our proposition can now be reduced to the above discussion by distinguishing the following 4 cases.

i)  $\ell_1 < \ell_0$ .

Then only lifts of the A-orbit  $\tilde{\gamma}_1$  can be systoles of S. If g is the genus of S then there are p = 2g + 1 systoles, and S is not maximal.

ii) S = S(p; 2) for some  $p \ge 5$ .

The surface S(p; 2) admits a liftable side pairing orbit  $\tilde{\gamma}_0$  which consists of 2 segments and hence is shorter than the orbit  $\tilde{\gamma}_1$  from Lemma 3.2. Moreover it admits a cyclic group  $\Sigma$  of order 2 of isometries which commutes with the basic group  $\Gamma$ . The action of  $\Sigma$  on the sphere  $S/\Gamma$  does not leave the trace of a lift of the side pairing orbit  $\tilde{\gamma}_0$  invariant. Thus S(p; 2) has exactly 2p = 4g + 2 systoles and can only be maximal if either g = 2 or g = 3. However an explicit analysis of the surfaces S(5; 2) and S(7; 2) shows that these surfaces are not maximal (this fact was already established by Schmutz [S1]).

iii)  $S \notin \{S(k(k-1)+1;k) \mid k \ge 2\} \cup \{S(p;2) \mid p \ge 5\}$  and  $\ell_0 \le \ell_1$ .

Then if  $k_0 = k(0)$  we have  $k(A) > k_0, k(B) > k_0$  and therefore there are at most p = 2g + 1 systoles which are lifts of a side pairing orbit in  $\triangle$ . If  $\ell_0 < \ell_1$  then these are the only systoles. In the case  $\ell_1 = \ell_0$  (which does not occur if the genus g of S is 2 or 3) there are 4g + 2 systoles. The surface S is not maximal.

iv)  $k \in \{3, 4, 5\}$  and S = S(k(k-1) + 1; k).

Then the length  $\ell_0$  of  $\gamma_0$  is smaller than  $\ell_1$  and there are 3p = 6g + 3 systoles which are the images of the geodesic  $\gamma_0$  under the isometry group

of S. In particular, the cardinality of the quotient of the isometry group of S under the subgroup fixing a given systole equals 6g + 3.

To complete the proof of our proposition we have to investigate the ideal surfaces  $S_{\infty}$  associated to simple triangle surfaces S(p;k). The above considerations are equally valid for these surfaces and show that  $S_{\infty}$  has more than 4g + 4 systoles if and only if p divides k(k-1) + 1 and if the length  $\ell_0$  of a lift of a side pairing orbit for  $S_{\infty}$  is not bigger than 6 arccosh  $\frac{3}{2}$ . An explicit computation shows as before that this is the case if and only if  $S_{\infty}$  is associated to one of the surfaces S(7; 3), S(13; 4), S(21; 5).

### 5. PROOF OF THE THEOREM

Using the notation of Lemma 2.2, our goal is to show that the triangle surfaces S(7;3), S(13;4), S(21;5) and their associated ideal surfaces are maximal. Following Schmutz [S1], for this it is enough to show that for each of these surfaces S the Teichmüller space is parametrized in a neighborhood of S by the lengths of those closed geodesics which are freely homotopic to a systole on S.

Let for the moment  $p \ge 5$  be an arbitrary odd number and let  $k \in \{2, \ldots, p-1\}$  be such that k and k-1 are prime to p. Write g = (p-1)/2. As in the introduction let  $T_{g,3}$  be the Teichmüller space of surfaces of genus g with 3 punctures. Let S = S(p;k) and let  $S_{\infty}$  be the ideal surface associated to S. The basic group  $\Gamma$  of orientation preserving isometries of S acts as a group of isometries on the surface  $S_{\infty}$ .

It will be useful to give a geometric description of  $S_{\infty}$ . For this let  $\Delta_{\infty}$  be an ideal triangle in  $\mathbf{H}^2$  and let  $T \subset \Delta_{\infty}$  be the finite equilateral triangle inscribed in  $\Delta_{\infty}$  which is invariant under all isometries of  $\Delta_{\infty}$ . The vertices of T determine a distinguished point on each side of  $\Delta_{\infty}$ .

There is a unique way to glue 2p copies of  $\Delta_{\infty}$  to a disc A with one puncture in its interior and 2p punctures on the boundary in such a way that the glueing maps identify the distinguished points on the sides of  $\Delta_{\infty}$ . The boundary of A then consists of 2p geodesic lines. Each of the triangles which makes up A contains exactly one of these boundary geodesics. We number the boundary geodesics in counter clockwise order and glue the 2i+1-th geodesic to the 2i+2k-th geodesic by an orientation reversing isometry which identifies the distinguished points on these geodesics. The resulting surface is the ideal surface  $S_{\infty}$  associated to S. Notice that  $S_{\infty}$  admits a canonical triangulation into ideal triangles which corresponds to the canonical triangulation of S. Denote by 0,1,2 the cusps of  $S_{\infty}$ . There are p edges of the canonical triangulation which connect the cusp 0 to the cusp 1. There is a natural counter clockwise ordering of these edges which is induced by the ordering of the ideal triangles around the cusp 0. We denote by  $\alpha_i^0$  the *i*-th edge with respect to this ordering and orient it in such a way that it goes from 0 to 1. Similarly we define  $\alpha_i^1$  to be the *i*-th edge of our triangulation with respect to the counter-clockwise ordering around the cusp 1 which goes from the cusp 1 to the cusp 2. Let also  $\alpha_i^2$  be the *i*-th edge ordered around the cusp 2 which goes from the cusp 2 to the cusp 0.

Each marked surface of genus g = (p-1)/2 with three punctures can be triangulated by 2p ideal triangles. If we cut the surface open along the edges of this triangulation, then we obtain 2p ideal triangles. To get the surface back we glue the triangles along their boundary geodesics in the fixed combinatorial pattern as above. The different points in  $T_{g,3}$  then differ by the way this glueing is arranged.

Namely, for each glueing we have one degree of freedom which corresponds to a left earthquake path along one of the geodesic arcs  $\alpha_i^j$ . Using the marking given by the distinguished points on the boundary of an ideal triangle and the induced boundary orientation, the glueings of an ordered pair  $(T_1, T_2)$  of (oriented) ideal triangles along a boundary geodesic can be parametrized by a real (left) sliding parameter. The glueing which identifies the distinguished points corresponds to the parameter 0. A glueing where the distinguished point on the boundary geodesic of the triangle  $T_1$  is mapped to the right of the distinguished point on the boundary geodesic of the triangle  $T_2$  corresponds to a positive sliding parameter.

Following Thurston [T], in order to obtain a complete hyperbolic surface from the 3p glueings of 2p ideal triangles in the above combinatorial way, it is necessary and sufficient that at each of the three punctures of the resulting surface the sum of all the sliding parameters for all geodesics which go to this puncture vanishes. Thus if we denote by  $V \subset \mathbf{R}^p$  the linear subspace of all vectors which are orthogonal to the vector  $(1, \ldots, 1)$ , then there is a natural bijection of  $\mathcal{T}_{g,3}$  onto  $V^3 = V \times V \times V$  which maps a surface  $M \in \mathcal{T}_{g,3}$  to its 3p-tuple of sliding parameters.

Let now  $\gamma_i^0$  be the piecewise geodesic in  $S_\infty$  which consists of the arc  $\alpha_i^0$  with the orientation reversed and the arc  $\alpha_{i+k}^0$ . If we compactify the surface  $S_\infty$  by adding a point at each puncture, then the compactification of  $\gamma_i^0$  is a simple closed curve on S = S(p;k) which is freely homotopic to the closed geodesic  $\psi_i^0$  on S obtained by projecting a geodesic in a fundamental 2p-gon  $\Omega$  which connects the midpoints of the edges 2i + 1 and 2i + 2k. Similarly,

let  $k(1), k(2) \in \{2, ..., p-1\}$  be such that  $k(1)(k-1) + 1 \equiv 0 \mod p$  and  $k(k(2) - 1) + 1 \equiv 0 \mod p$  and denote for j = 1, 2 by  $\gamma_i^j$  the piecewise geodesic which consists of the geodesic  $\alpha_i^j$  with the reversed orientation and the geodesic  $\alpha_{i+k(j)}^j$ . Write also k(0) = k.

An earthquake path through  $S_{\infty}$  induced by the curve  $\gamma_i^j$  deforms the surface  $S_{\infty}$  by a family of glueings with sliding parameter -t along  $\alpha_i^j$ , sliding parameter t along  $\alpha_{i+k(j)}^j$  ( $t \in \mathbf{R}$ ) and sliding parameter 0 otherwise and hence this earthquake path gives rise to a smooth (in fact real analytic) curve in  $\mathcal{T}_{g,3}$ . From this observation the following is immediate.

LEMMA 5.1. For every surface  $M \in T_{g,3}$  the tangents of the earthquake paths along the curves  $\gamma_i^j$  span the tangent space of  $T_{g,3}$  at M.

*Proof.* Let  $M \in \mathcal{T}_{g,3}$  and denote by  $\xi_i^j$  the tangent at M of the earthquake path along  $\alpha_i^j$ . We observed above that there is a linear isomorphism of the vector space  $V^3$  onto the tangent space of  $\mathcal{T}_{g,3}$  at M which maps the point  $(0_1, \ldots, 0_p, a_1, \ldots, a_p, b_1, \ldots, b_p) \in V^3$  to the tangent vector  $\sum_{i,j} j_i \xi_i^j$ . Since the tangent at M of the earthquake path induced by  $\gamma_i^j$  is just  $\xi_{i+k(j)}^j - \xi_i^j$  the lemma follows.  $\Box$ 

There is a natural real analytic submersion P of  $\mathcal{T}_{g,3}$  onto  $\mathcal{T}_g$  which is equivariant under the action of the basic group  $\Gamma$ . This submersion simply maps a surface of genus g with 3 punctures to the surface obtained by compactifying each puncture with a single point. For every  $S \in \mathcal{T}_g$  the fibre of P over S consists of all surfaces in  $\mathcal{T}_{g,3}$  which we obtain from S by removing an ordered triple of pairwise distinct points. In particular, the fibre is a real analytic submanifold of  $\mathcal{T}_{g,3}$  of dimension 6. We denote by Wthe 6-dimensional subbundle of the tangent bundle of  $\mathcal{T}_{g,3}$  which is the kernel of the differential of P. This bundle has a natural direct decomposition  $W = W_0 \oplus W_1 \oplus W_2$  into two-dimensional subbundles  $W_j$ . Here the bundle  $W_j$  is the tangent bundle of the fibres of the fibration  $\mathcal{T}_{g,3} \to \mathcal{T}_{g,2}$  which we obtain by adding for every surface  $M \in \mathcal{T}_{g,3}$  a single point at the punture jof M.

For  $M \in \mathcal{T}_{g,3}$  the compactifications of the curves  $P\gamma_i^j$  are homotopically nontrivial simple closed curves on PM. There is a unique free homotopy class on M which can be represented by a closed curve which does not intersect  $\gamma_i^j$  and whose projection to PM is freely homotopic to the compactification of  $P\gamma_i^j$ . We denote by  $\tilde{\psi}_i^j$  the unique geodesic on M representing this class. We have. LEMMA 5.2. Let  $\xi_i^j, \zeta_i^j$  be the tangent of the earthquake path along  $\widetilde{\psi}_i^j, \gamma_i^j$ . Then there are functions  $a_i^j: \mathcal{T}_{g,3} \to \mathbf{R}$  such that  $\zeta_i^j - a_i^j \xi_i^j \in W_j \oplus W_{j+1}$ .

*Proof.* Let  $M \in \mathcal{T}_{g,3}$  and for  $i \in \{1, \ldots, p\}, j = 0, 1, 2$  consider the piecewise geodesic  $\gamma_i^j$  and the geodesic  $\widetilde{\psi}_i^j$  on M. Since the number of intersections between  $\gamma_i^j$  and  $\widetilde{\psi}_i^j$  is the minimum of the number of intersections between  $\gamma_i^j$  and any curve which is freely homotopic to  $\widetilde{\psi}_i^j$ , the geodesics  $\widetilde{\psi}_i^j$  and  $\gamma_i^j$  on M do not intersect. If we cut the surface M open along the curves  $\gamma_i^j$  and  $\widetilde{\psi}_i^j$  then the interior of one of the connected surfaces with boundary which we obtain in this way, say the surface C, is homeomorphic to an open annulus. One boundary component of C is the curve  $\widetilde{\psi}_i^j$ , the second boundary component has two punctures and consists of the curve  $\gamma_i^j$ .

By construction, the curve  $\tilde{\psi}_i^j$  is non-separating and therefore there is a simple closed geodesic  $\eta$  on M which neither intersects  $\gamma_i^j$  nor  $\tilde{\psi}_i^j$  and such that after cutting M along  $\eta$  we obtain two bordered surfaces  $S_1, S_2$ . The surface  $S_1$  is a surface of genus 1 with one geodesic boundary circle and two punctures in its interior and contains the annulus C bounded by the curves  $\gamma_i^j$  and  $\tilde{\psi}_i^j$ . The earthquake paths along the piecewise geodesic  $\gamma_i^j$  and the geodesic  $\tilde{\psi}_i^j$  leave the hyperbolic length of a closed geodesic  $\sigma$  on M fixed if and only if  $\sigma$  does not have a transverse intersection with  $\gamma_i^j, \tilde{\psi}_i^j$ . Thus these earthquake paths define deformations of the hyperbolic structure on  $S_1$  leaving the length of the boundary fixed.

The Teichmüller space of marked hyperbolic structures on the bordered torus  $S_1$  with two punctures and a boundary geodesic of fixed length is 6-dimensional. Its tangent bundle contains a 5-dimensional subbundle V which consists of all infinitesimal deformations preserving the modulus of a maximal (twice punctured) ring domain with core curve homotopic to  $\tilde{\psi}_i^j$ .

We claim that this 5-dimensional subbundle V contains the tangents of the earthquake paths along the geodesic  $\tilde{\psi}_i^j$  and along the piecewise geodesic  $\gamma_i^j$ .

To see this let  $\zeta$  be the unique simple geodesic arc in  $S_1$  which meets the boundary geodesic  $\eta$  perpendicularly and which neither intersects  $\tilde{\psi}_i^j$  nor  $\gamma_i^j$ . Let  $\bar{S}_1$  be the compactification of  $S_1$  which we obtain by simply adding one point at each puncture. If we cut  $\bar{S}_1$  open along  $\zeta$ , then we obtain a standard ring domain A normalized by the fixed choice of a height, say the height 1, with core curve homotopic to  $\tilde{\psi}_i^j$  and whose modulus is maximal among all ring domains with this property [St]. The boundary of A consists of two circles which contain each a copy of the arc  $\zeta$  as well as a nontrivial component of the boundary geodesic  $\eta$ . We mark the arc on each boundary component which corresponds to the arc  $\zeta$ . The surface  $\bar{S}_1$  is obtained by glueing the two marked arcs on the two boundary components with the restriction of a complex linear map of the complex plane.

The compactification of  $\gamma_i^j$  is a closed curve in the ring domain A which is freely homotopic to the core curve. If we cut A open along this curve then by uniformization we obtain two standard ring domains  $A_1, A_2$  with one common boundary circle. The earthquake path induced by  $\gamma_i^j$  consists in cutting A along the common boundary circle of  $A_1, A_2$  and glueing the ring domains  $A_1, A_2$  back with a new boundary identification. This procedure does not change the lengths of the arcs  $\eta$  or  $\zeta$  nor the modulus of the annulus A. In other words, the tangent of this earthquake path is contained in V. The same argument applies to the earthquake path induced by the geodesic  $\tilde{\psi}_i^j$ . We conclude that this earthquake path induces a nontrivial infinitesimal deformation of the conformal structure on the compactification of our bordered punctured torus which leaves the modulus of a maximal ring domain with core curve homotopic to  $\widetilde{\psi}_i^j$  fixed. In particular, the tangent of this earthquake path is contained in V but not in the kernel of the differential of the natural map which assigns to a twice punctured bordered torus its compactification.

As a conclusion, the tangent at M of the earthquake path induced by  $\gamma_i^j$  can be written in the form  $a_i^j \xi_i^j + \eta_i^j$  where  $\xi_i^j$  is the tangent of the earthquake path along  $\tilde{\psi}_i^j$ ,  $a_i^j \in \mathbf{R}$  and  $\eta_i^j$  is contained in the bundle  $W_j \oplus W_{j+1}$ . This shows the lemma.

Let now  $k \ge 3$  and consider again the ideal surface  $S_{\infty}$  associated to the simple triangle surface S = S(k(k-1) + 1; k). Using the above notation, for m = jp + i  $(j \in \{0, 1, 2\}, i < p)$  write  $\widetilde{\psi}_m = \widetilde{\psi}_i^j$ . For  $M \in \mathcal{T}_{g,3}$  and  $m \in \{1, \ldots, 3p\}$  denote by  $\ell_M(\widetilde{\psi}_m)$  the length of the closed geodesic  $\widetilde{\psi}_m$  on M. The functions  $M \in \mathcal{T}_{g,3} \to \ell_M(\widetilde{\psi}_m)$  are real analytic [K]. This means that we obtain a real analytic map  $\Psi_{\infty}$  of  $\mathcal{T}_{g,3}$  into  $\mathbb{R}^{3p}$  by mapping a surface M to  $\Psi_{\infty}(M) = (\ell_M(\widetilde{\psi}_1), \ldots, \ell_M(\widetilde{\psi}_{3p}))$ . From Lemma 5.1 and Lemma 5.2 we conclude.

COROLLARY 5.3. The map  $\Psi_{\infty}$  is of maximal rank differentiable at  $S_{\infty}$ .

*Proof.* Following Wolpert [W], the tangent of the earthquake path along  $\tilde{\psi}_i^j$  is dual with respect to the Weil Petersen Kähler form to the differential of the length function of  $\tilde{\psi}_i^j$  on  $\mathcal{T}_{g,3}$ . Thus to show the corollary it is enough to show that the tangent space of  $\mathcal{T}_{g,3}$  at  $S_{\infty}$  is spanned by the tangents  $\xi_i^j$  of the earthquake paths along the curves  $\tilde{\psi}_i^j$ .

Let G be the group of isometries of  $S_{\infty}$  which is generated by the basic group  $\Gamma$  and the group  $\Sigma$  of order 3 contained in the normalizer of  $\Gamma$ . The group G acts on the Teichmüller space  $\mathcal{T}_{g,3}$  as a group of automorphism which fixes the surface  $S_{\infty}$ .

Let  $\Lambda$  be the linear isometry of  $\mathbf{R}^p$  defined in canonical coordinates by  $\Lambda(x_1, \ldots, x_p) = (x_2, \ldots, x_p, x_1)$ ; then  $\Lambda \times \Lambda \times \Lambda = \Lambda_3$  is a linear isometry of  $\mathbf{R}^{3p}$ . If  $J_1$  is the canonical generator of the normal cyclic subgroup  $\Gamma$  of G then we have  $\Psi_{\infty}(J_1M) = \Lambda_3 \Psi_{\infty}(M)$ .

Let  $\tau$  be the linear isometry of  $\mathbf{R}^{3p} = \mathbf{R}^p \times \mathbf{R}^p \times \mathbf{R}^p$  which cyclicly permutes the factors  $\mathbf{R}^p$  in the direct decomposition of  $\mathbf{R}^{3p}$ . There is a permutation  $\sigma$  of  $\{1, \ldots, p\}$  of order p-1 with diagonal extension  $\sigma_3$  to  $\mathbf{R}^{3p}$  such that the canonical generator  $J_2$  of the cyclic subgroup  $\Sigma$  acts by  $\Psi_{\infty}J_2(M) = \sigma_3 \circ \tau(\Psi_{\infty}M)$ .

The eigenvalues of the linear isometry  $\Lambda$  are the *p*-th roots of unity. The eigenspace for the eigenvalue 1 is spanned by  $(1, \ldots, 1)$  and the other generalized eigenspaces are of dimension 2. The map  $\sigma_3 \circ \tau$  permutes the generalized eigenspaces of the diagonal extension  $\Lambda_3$  which correspond to eigenvalues different from 1 and acts as a cyclic group of permutations on the eigenspace Z of  $\Lambda^3$  with respect to the eigenvalue 1. The orthogonal complement  $Z^{\perp}$  of Z in  $\mathbf{R}^{3p}$  decomposes into g irreducible invariant subspaces of dimension 6 each.

The surface  $S_{\infty}$  is a fixed point for the action of G. By Lemma 5.1, the tangent space of  $\mathcal{T}_{g,3}$  at  $S_{\infty}$  as a G-space is isomorphic to  $Z^{\perp}$ , where the differential of  $J_1$  acts as the map  $\Lambda_3$  and the differential of  $J_2$  as  $\sigma_3 \circ \tau$ . The 6-dimensional tangent space W at  $S_{\infty}$  of the fibre of the fibration  $P: \mathcal{T}_{g,3} \to \mathcal{T}_g$  is invariant under the action of G and for reasons of dimension necessarily irreducible.

Let as before  $\xi_i^j, \zeta_i^j$  be the tangent at  $S_{\infty}$  of the earthquake path along  $\widetilde{\psi}_i^j, \gamma_i^j$ .

Denote by L the linear map which maps  $\zeta_i^j$  to  $\xi_i^j$ . Then L is G-equivariant and by Lemma 5.2 its kernel is contained in the G-invariant space W. Since W is irreducible under G the kernel of L is either trivial or coincides with W.

We have to show that the latter does not hold. For this we have to find a tangent vector  $X \in W$  such that  $LX \neq 0$ .

Consider the unit disc D in the complex plane with boundary circle  $S^1$  and hyperbolic metric. Let  $D_{\infty}$  be the disc with the point 0 deleted. It carries a unique complete hyperbolic metric for which the puncture is a standard cusp. This metric admits an isometric circle action which induces the standard parametrization of the boundary circle  $S^1 = [0, 2\pi)$ .

Let  $\Omega_0, \Omega$  be the regular ideal hyperbolic 2p-gon in  $D_{\infty}, D$  whose set  $\mathcal{P}$  of vertices consists of the points  $j\pi/p$   $(j = 1, \ldots, 2p)$ . These 2p-gons admit a cyclic group of order 2p of isometries, and  $\Omega_0$  hence is isometric to the once punctured polygon which we obtain by cutting  $S_{\infty}$  along the geodesics of the canonical triangulation joining the cusps 1 and 2.

For an interior point x of  $\tilde{\Omega}$  consider the polygon  $\Omega_x = \tilde{\Omega} \setminus \{x\}$  with one puncture at x. The punctured polygon  $\Omega_x$  carries a hyperbolic metric of finite volume such that the boundary consists of 2p geodesic lines, and it is naturally triangulated into 2p ideal triangles.

Let  $\gamma$  be a hyperbolic geodesic in D through  $\gamma(0) = 0$ . For every  $t \in \mathbf{R}$  there is a unique hyperbolic isometry  $\Psi_t$  of D which fixes the endpoints of  $\gamma$  and maps  $\gamma(t)$  to 0. The image under  $\Psi_t$  of the punctured polygon  $\Omega_{\gamma(t)}$  is an ideal hyperbolic polygon with puncture at 0 and whose vertices on  $S^1$  are the points in  $\Psi_t \mathcal{P}$ . The punctured polygon  $\Psi_t \Omega_{\gamma(t)}$  can be obtained from  $\Omega_0$  by an earthquake deformation along the geodesics which joins 0 to the vertices of  $\Omega_0$  as follows.

Consider an ordered triple (a, b, c) of 3 pairwise distinct points on the boundary circle  $S^1$  of  $D_{\infty}$  arranged in counter clockwise order. These points determine an ideal quadrangle Q which decomposes Q into 2 ideal hyperbolic triangles embedded in  $D_{\infty}$  which have one vertex at 0. Let  $T_1$  be the triangle with vertices a, b, and let  $T_2$  be the triangle with vertices b, c. If the euclidean distance between a and b is smaller than the distance between b and c then the glueing map which gives the quadrangle Q back from the triangles  $T_1$ and  $T_2$  maps the distinguished point of the boundary geodesic of  $T_1$  to the right of the distinguished point on the boundary geodesic of  $T_2$  with respect to the boundary orientation of  $T_2$ . In other words, with our above notation the glueing corresponds to a positive sliding parameter.

The derivative of the restriction of  $\Psi_t$  to  $S^1$  has a maximum at its repelling fix point  $z_1$  and a minimum at its attracting fix point  $z_2$ . It is strictly monotonous on each of the two components of  $S^1 - \{z_1, z_2\}$ . Let  $(z_1, z_2)$  be the component which corresponds to an open interval in  $[0, 2\pi)$ with left endpoint  $z_1$ . The above analysis shows that the deformation of the polygon  $\Omega_0$  which defines  $\Psi_t \Omega_{\gamma(t)}$  has a negative sliding parameter for every geodesic which joins 0 to a point in  $\mathcal{P} \cap (z_1, z_2)$ . The sliding parameter is positive for all geodesics which join 0 to a point in  $\mathcal{P} \cap (z_2, z_1)$ .

Choose now  $\gamma$  in such a way that its forward endpoint equals  $k\pi/2p$ and that its backward endpoint equals  $k\pi/2p + \pi$ . Let  $\rho$  be the reflection of  $\tilde{\Omega}$  along  $\gamma$ . This reflection induces an orientation reversing isometry of  $D_{\infty}$  which commutes with the above deformation of  $\Omega_0$  along  $\gamma$ . Denote by  $\beta_i$ 

#### U. HAMENSTÄDT

the geodesic which connects the center 0 to  $(k+i)\pi/2p$   $(1 \le i \le 2p)$  and let  $\nu_i$  be the tangent of the earthquake path along  $\beta_i$ . By symmetry, the tangent at t = 0 of our deformation of  $\Omega_0$  along  $\gamma$  can be written in the form  $\sum a_i\nu_i$  where  $a_i < 0$  and  $a_{i-p} = -a_i$  for  $i = 1, \ldots, p-1$ .

Consider now the geodesic  $\widetilde{\psi}_1^0$ . It intersects  $\gamma$  perpendicularly and has  $2k-2 \ge 2$  additional intersections with the geodesics  $\beta_i$ . For  $i \in \{1, \ldots, k-1\}$  denote by  $\delta_i$  the oriented angle of the intersection of  $\widetilde{\psi}_1^0$  with the geodesic  $\beta_i$ , where we write  $\delta_i = \pi/2$  if the geodesics  $\beta_i$  and  $\gamma$  do not intersect. By invariance under  $\rho$  we have  $\delta_{2p-i} - \pi/2 = -(\delta_i - \pi/2)$ .

Following Kerckhoff (see [K]), the derivative at t = 0 of the length of  $\widetilde{\psi}_1^0$  under our deformation of  $\Omega_0$  equals up to a positive constant the sum  $\sum a_i \cos \delta_i$ . But  $0 > \cos \delta_i = -\cos \delta_{2p-i}$  for  $1 \le i \le k-1$  and  $\cos \delta_i = 0$  otherwise and therefore the derivative of the length of  $\widetilde{\psi}_1^0$  under our above deformation of  $\Omega_0$  does not vanish. In other words, the map L does not vanish on W. This completes the proof of the corollary.

Let now again  $p \ge 5$  be arbitrary and write g = (p-1)/2. Using the above notation, for  $M \in \mathcal{T}_{g,3}$  let  $\psi_i^j$  be the closed geodesic on the surface PM which is freely homotopic to the compactification of the curve  $\gamma_i^j$ . For  $S \in \mathcal{T}_g$  let  $\ell_S(\psi_i^j)$  be the length of  $\psi_i^j$ . We then obtain a real analytic map  $\Psi$  of  $\mathcal{T}_g$  into  $\mathbf{R}^{3p}$  by mapping S to  $\Psi(S) = (\ell_S(\psi_1^0), \dots, \ell_S(\psi_p^2))$ .

Theorem B from the introduction is an immediate consequence of the following.

# LEMMA 5.4. The map $\Psi$ is of maximal rank differentiable and injective.

*Proof.* Let again  $\xi_i^j$  be the tangent of the earthquake path along the closed geodesic  $\psi_i^j$ . By the results of Wolpert [W] it suffices to show that the tangent space of  $\mathcal{T}_g$  at any point S is spanned by the vectors  $\xi_i^j$ .

An arbitrary choice of three points in the complement of the curves  $\psi_i^j$ on S defines a surface  $M \in \mathcal{T}_{g,3}$ . The earthquake path in  $\mathcal{T}_g$  induced by  $\psi_i^j$ naturally lifts to a path in  $\mathcal{T}_{g,3}$ . The consideration in the proof of Lemma 5.2 shows that this lift is (up to parametrization and up to possibly moving the punctures) just the earthquake path in  $S_\infty$  along  $\widetilde{\psi}_i^j \in M$ . This implies by Lemma 5.2 and Lemma 5.1 that the tangent space of  $\mathcal{T}_g$  at M is spanned by the vectors  $\xi_i^j$  and shows that  $\Psi$  is of maximal rank differentiable. Since the earthquake paths along the curves  $\gamma_i^j$  parametrize  $\mathcal{T}_{g,3}$  the map  $\Psi$  is moreover injective.  $\Box$  The next corollary is an immediate consequence of Lemma 5.3, Lemma 5.4, Proposition 4.8 and the results of Schmutz in [S1].

COROLLARY 5.5. The surfaces S(7;3), S(13;4), S(21;5) and their associated ideal surfaces are maximal.

We conclude the paper with some remarks about the relation between our triangulation and the structure of the Thurston boundary of Teichmüller space.

Consider for the moment an arbitrary closed surface *S*. A geodesic current for *S* is a locally finite Borel-measure on the space of unoriented geodesics in the hyperbolic plane  $\mathbf{H}^2$  which is invariant under the action of the fundamental group  $\pi_1(S)$  of *S*. The space *C* of geodesic currents for *S* only depends on the topological type of *S*. There is a bilinear form *i* on *C*, the so called *intersection form*, which is continuous with respect to the weak\*-topology on *C*. The subset *L* of *C* of all geodesic currents  $\mu$  with vanishing selfintersection  $i(\mu, \mu) = 0$  is the space of *measured geodesic laminations* and is homeomorphic to  $\mathbf{R}^{6g-6}$  [B].

Let  $\mathcal{PC}$  and  $\mathcal{PL}$  be the projectivization of the space of nonzero geodesic currents and laminations. There is a natural continuous embedding J of the Teichmüller space  $\mathcal{T}_g$  into  $\mathcal{PC}$  by mapping  $M \in \mathcal{T}_g$  to the projectivization  $[\lambda_M]$  of its Lebesgue-Liouville current  $\lambda_M$ . The closure of  $J(\mathcal{T}_g)$  in  $\mathcal{PC}$  is just  $J(\mathcal{T}_g) \cup \mathcal{PL}$  [B].

Every simple closed geodesic  $\psi$  on S can naturally be viewed as a measured geodesic lamination and hence induces a linear functional on C via  $\mu \to i(\psi, \mu)$ . If  $\lambda_M$  is the Lebesgue-Liouville current of a point  $M \in \mathcal{T}_g$  in Teichmüller space then  $i(\lambda_M, \psi) = \ell_M(\psi)$  is just the M-length of  $\psi$  [B]. In particular, the map  $M \in \mathcal{T}_g \to i(\lambda_M, \psi)$  is real analytic.

Recall that a collection  $\psi_1, \ldots, \psi_k$  of simple closed curves on *S* fills up if every geodesic on *S* intersects one of the curves  $\psi_i$  transversely. This is equivalent to saying that the complement of  $\{\psi_1, \ldots, \psi_k\}$  in *S* consists of a finite collection of connected simply connected regions. If  $\psi_1, \ldots, \psi_k$ fills up then for every measured geodesic lamination  $\mu \in \mathcal{L}$  the vector  $(i(\psi_1, \mu), \ldots, i(\psi_k, \mu)) \in \mathbf{R}^k$  does not vanish. Thus if we denote by  $P\mathbf{R}^k$  the real projective space of all lines in  $\mathbf{R}^k$  and for  $0 \neq x \in \mathbf{R}^k$  by  $[x] \in P\mathbf{R}^k$  the line in  $\mathbf{R}^k$  through x then the map  $A: M \in \mathcal{T}_g \to [\ell_M(\psi_1), \ldots, \ell_M(\psi_k)] \in P\mathbf{R}^k$ extends continuously to the Thurston compactification  $\mathcal{PL}$  of  $\mathcal{T}_g$  by mapping the projective class  $[\mu]$  of  $\mu \in \mathcal{L}$  to  $A([\mu]) = [i(\psi_1, \mu), \ldots, i(\psi_k, \mu)]$ . A family  $(\psi_1, \ldots, \psi_k)$  of simple closed curves on *S* is called *parametrizing* for

#### U. HAMENSTÄDT

 $\mathcal{PL}$  if the map  $[\mu] \in \mathcal{PL} \to A([\mu]) = [i(\psi_1, \mu), \dots, i(\psi_k, \mu)] \in P\mathbf{R}^k$  is an embedding.

It is also possible to define geodesic currents and measured geodesic laminations for hyperbolic surfaces with cusps. By definition, a measured geodesic lamination of such a surface M with cusps is a compact subset of M which is foliated by geodesics and equipped with a transverse invariant measure.

Let now  $p \ge 5$  and let  $k \in \{2, \ldots, p-1\}$  be such that k and k-1 are prime to p. Denote by  $S_{\infty}$  the ideal surface associated to the triangle surface S(k;p) and let  $\gamma_i^j$  the piecewise geodesics as in Lemma 5.1. If  $\psi$  is any closed geodesic in  $S_{\infty}$  then  $\psi$  does not disappear in the cusps of  $S_{\infty}$  and hence  $\psi$  intersects each of the geodesics  $\gamma_i^j$  transversely in a finite number of points. We denote by  $i(\psi, \gamma_i^j)$  the number of intersections of  $\psi$  with  $\gamma_i^j$ . Since measured laminations on  $S_{\infty}$  have compact support, intersection of closed geodesics with one of the curves  $\gamma_i^j$  extends to a continuous convexlinear functional  $i(\gamma_i^j, \cdot)$  on the space  $\mathcal{L}_{\infty}$  of measured geodesic laminations on  $S_{\infty}$ .

We have:

LEMMA 5.6. The map 
$$\mu \in \mathcal{L}_{\infty} \to A(\mu) =$$
  
 $(i(\gamma_1^0, \mu), \dots, i(\gamma_p^0, \mu), i(\gamma_1^1, \mu), \dots, i(\gamma_p^1, \mu), i(\gamma_q^2, \mu), \dots, i(\gamma_p^2, \mu))$ 

## is an embedding.

*Proof.* It suffices to show that every closed geodesic  $\psi$  is determined by  $A(\psi)$ . For this consider again the edges  $\alpha_i^j$  of the canonical triangulation of  $S_{\infty}$ . It follows immediately from our construction that  $A(\psi)$  determines uniquely the tuple

$$C(\psi) = (i(\alpha_1^0, \psi), \dots, i(\alpha_p^0, \psi), i(\alpha_1^1, \psi), \dots, i(\alpha_p^1, \psi), i(\alpha_1^2, \psi), \dots, i(\alpha_p^2, \psi))$$

(compare the proof of Lemma 5.1). Thus it is enough to show that we can reconstruct  $\psi$  from  $C(\psi)$ .

The arcs  $\alpha_j^i$  define a triangulation of  $S_\infty$  into 2p triangles with vertices at the cusps and such that each arc is the side of exactly two triangles. Let  $\psi$ be any closed geodesic on  $S_\infty$  and let T be a triangle from the triangulation with sides  $\beta_1, \beta_2, \beta_3$ . Write  $j_i = i(\beta_i, \psi)$  and assume that  $j_1 \ge j_2 \ge j_3$ . Since T is contractible in the compactification of  $S_\infty$ , the total intersection number  $j_1 + j_2 + j_3$  of  $\psi$  with the boundary of T is even and hence  $j_2 + j_3 - j_1$  is even as well. Moreover we have  $j_1 \le j_2 + j_3$ . Draw  $\frac{1}{2}(j_2 + j_3 - j_1)$  simple arcs connecting the sides  $\beta_2$  and  $\beta_3, j_2 - \frac{1}{2}(j_2 + j_3 - j_1)$  simple arcs connecting the sides  $\beta_1$  and  $\beta_2, j_3 - \frac{1}{2}(j_2 + j_3 - j_1)$  simple arcs connecting the sides  $\beta_1$  and  $\beta_3$  in such a way that all these arcs are disjoint. The configuration of these arcs in *T* is determined up to isotopy by  $j_1 \ge j_2 \ge j_3$ . But this means that  $\psi$  is uniquely determined by  $C(\psi)$  (compare the discussion in [FLP]) and hence the lemma follows.  $\Box$ 

Recall that a closed curve  $\psi$  on  $S_{\infty}$  is *cusp-parallel* if  $\psi$  is homotopic to a multiple of a circle surrounding one of the cusps of  $S_{\infty}$ . This is equivalent to saying that the infimum of the lengths of all curves in  $S_{\infty}$  which are freely homotopic to  $\psi$  is zero (notice that by abuse of notation we call a contractible curve cusp-parallel as well). A closed curve  $\psi$  on  $S_{\infty}$  is freely homotopic to a closed geodesic if and only if  $\psi$  is not cusp-parallel.

We define now an equivalence relation on the set of all closed curves on  $S_{\infty}$  as follows: Let  $\psi, \eta: [0, 1] \to S_{\infty}$  be parametrized closed curves. Call  $\psi, \eta$  equivalent if there is a subdivision  $0 < t_1 < \cdots < t_k < 1$  of [0, 1] and for each *i* there is a cusp-parallel loop  $\gamma_i$  through  $\psi(t_i)$  such that  $\eta$  is freely homotopic to  $\psi|_{[0,t_1]} \cup \gamma_1 \cdots \cup \gamma_k \cup \psi|_{[t_k,1]}$ .

This is easily seen to be an equivalence relation. The equivalence classes of this relation are in 1 - 1-correspondence to the free homotopy classes of closed curves on the surface S. We denote the class of  $\psi$  by  $[\psi]$ . For a closed curve  $\psi$  on  $S_{\infty}$  and for  $i \in \{1, \ldots, p\}$ , j = 0, 1, 2 define  $\mathcal{J}(\psi, \gamma_i^j)$ to be the infimum of the number of intersections with  $\gamma_i^j$  of all curves  $\eta$ equivalent to  $\psi$ .

Let  $\psi_i^j$  be the closed geodesic on the surface *S* which is freely homotopic to the compactification of  $\gamma_i^j$  viewed as a curve on *S*. For every closed geodesic  $\eta$  on *S* which is different from a multiple of  $\psi_i^j$  the number of intersection points between  $\eta$  and  $\psi_i^j$  is the infimum  $i(\eta, \psi_i^j)$  of the number of intersection points between all curves freely homotopic to  $\eta, \psi_i^j$ .

We have:

LEMMA 5.7. 
$$\mathcal{J}(\zeta, \gamma_i^J) = i([\zeta], \psi_i^J)$$
 for every closed curve  $\zeta$  on  $S_{\infty}$ .

*Proof.* For every closed curve  $\zeta$  on  $S_{\infty}$  there is an equivalent curve  $\eta$  such that  $\mathcal{J}(\zeta, \gamma_i^j)$  equals the number of intersection points of  $\eta$  with  $\gamma_i^j$ . Now if we compactify  $S_{\infty}$  by adding a point at each cusp, then we obtain a surface M of genus g and  $\eta$  and  $\zeta$  are freely homotopic on  $M, \gamma_i^j$  is freely homotopic to the curve  $\psi_i^j$ . But this means that  $\mathcal{J}(\zeta, \gamma_i^j) \geq i([\zeta], \psi_i^j)$ . On the other hand, if  $\zeta$  is any closed curve on S with a minimal number of intersections with  $\psi_i^j$  in its free homotopy class, then we can remove from S three points which do not lie on  $\zeta$  and such that two of these points lie on  $\psi_i^j$ . If we call the resulting surface  $S_{\infty}$  then  $\zeta$  defines a closed curve  $\zeta_{\infty}$  on  $S_{\infty}$ , and  $i(\zeta, \psi_i^j)$  equals the number of intersection points between  $\zeta_{\infty}$  and  $\gamma_i^j$  (where  $\gamma_i^j$  is given as before). This then shows that  $\mathcal{J}(\zeta_{\infty}, \gamma_i^j) \leq i(\zeta, \psi_i^j) = i([\zeta_{\infty}], \psi_i^j)$ 

As an immediate consequence of Lemma 5.6 and Lemma 5.7 we obtain

COROLLARY 5.8. The curves  $\psi_i^j$  on S are parametrizing for  $\mathcal{PL}$ . In particular, for every  $g \ge 2$  there is a family of 6g + 3 free homotopy classes on a closed surface of genus g which is parametrizing for  $\mathcal{PL}$ .

REMARK. From [FLP] one immediately obtains a family of 9g-9 closed curves on a closed surface of genus g which is parametrizing for  $\mathcal{PL}$ . To my knowledge, the minimal number of simple closed curves with this property is not known.

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### REFERENCES

[B]	BONAHON, F. The geometry of Teichmüller space via geodesic currents. Invent. Math. 92 (1988), 139–162.
[Bu]	BUSER, P. Geometry and Spectra of Compact Riemann Surfaces. Birkhäuser, Boston 1992.
[BS]	BUSER, P. and P. SARNAK. On the period matrix of a Riemann surface of large genus. <i>Invent. Math.</i> 117 (1994), 27-56.
[FLP]	FATHI, A., LAUDENBACH, F. and V. POÉNARU. Travaux de Thurston sur les surfaces. Astérisque 66-67 (1979).
[F]	FORSTER, O. Lectures on Riemann Surfaces. Springer Graduate Texts in Math. 81, New York, 1981.
[G]	GARDINER, F. Teichmüller Theory and Quadratic Differentials. Wiley, New York, 1987.
[I]	IVERSEN, B. Hyperbolic Geometry. Cambridge University Press, 1992.
[K]	KERCKHOFF, S. Lines of minima in Teichmüller space. Duke Math. J. 65

(1992), 182-213.

[L]	LEVY, S. (editor) The 8-Fold Way. MSRI Publications 35, Cambridge Univ.
	Press, 1999.
[M]	MASKIT, B. On Poincaré's theorem for fundamental polygons. Advances in
	Math. 7 (1971), 219–230.
[S1]	SCHMUTZ, P. Riemann surfaces with shortest geodesic of maximal length.
	Geom. Funct. Anal. 3 (1993), 564–631.

- [S2] SCHMUTZ SCHALLER, P. Teichmüller space and fundamental domains of Fuchsian groups. L'Enseignement Math. (2) 45 (1999), 169–187.
- [S3] —— Systoles and topological Morse functions for Riemann surfaces. Preprint.
- [St] STREBEL, K. Quadratic Differentials. Ergebnisse der Mathematik 5 (III), Springer, Berlin, 1984.
- [T] THURSTON, W. *Three-Dimensional Topology and Geometry*. Bound notes, Princeton University.
- [W] WOLPERT, S. The Fenchel-Nielsen deformation. Ann. of Math. (2) 115 (1982), 501–528.

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### U. Hamenstädt

Mathematisches Institut der Universität Bonn Beringstrasse 1 D-53115 Bonn Germany *e-mail*: ursula@math.uni-bonn.de

