

The complex symplectic geometry of the deformation space of complex projective structures

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This article investigates the complex symplectic geometry of the deformation space of complex projective structures on a closed oriented surface of genus at least 2. The cotangent symplectic structure given by the Schwarzian parametrization is studied carefully and compared to the Goldman symplectic structure on the character variety, clarifying and generalizing a theorem of S. Kawai [Kaw96]. Generalizations of results of C. McMullen are derived, notably quasi-Fuchsian reciprocity [McM00]. The symplectic geometry is also described in a Hamiltonian setting with the complex Fenchel-Nielsen coordinates on quasi-Fuchsian space, recovering results of I. Platis [Pla01].

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1 Introduction

Complex projective structures on surfaces are rich examples of geometric structures. They include in particular the three classical homogeneous Riemannian geometries on surfaces (Euclidean, spherical, hyperbolic) and they extend the theory of complex structures on surfaces, *i.e.* Teichmüller theory. They also have a strong connection to hyperbolic structures on 3-manifolds. Another feature is their analytic description using the Schwarzian derivative, which turns the deformation space of complex projective structures into a holomorphic affine bundle modeled on the cotangent bundle to Teichmüller space. A natural complex symplectic geometry shows through these different perspectives, which has been discussed by various authors, e.g. [Kaw96], [Pla01] and [Gol04]. This article attempts a unifying picture of the complex symplectic geometry of the deformation space of complex projective structures on surfaces, one that carefully relates the different approaches ¹.

Let S be a closed oriented surface of genus $g \geq 2$. A complex projective structure on S is given by an atlas of charts mapping open sets of S into the projective line \mathbb{CP}^1 such that the transition maps are restrictions of projective linear transformations. The deformation space of projective structures $\mathcal{CP}(S)$ is the space of equivalence classes of projective structures on S , where two projective structures are considered equivalent if they are diffeomorphic². Any projective atlas is in particular a holomorphic atlas, therefore a projective structure defines an underlying complex structure. This gives a forgetful projection $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$, where $\mathcal{T}(S)$ is the Teichmüller space of S , defined as the deformation space of complex structures on S .

¹Of course, this has already been done at least partially by authors including the three previously mentioned.

²More precisely, diffeomorphic by a homotopically trivial diffeomorphism, see section 2.1.

The Schwarzian derivative is a differential operator that turns the fibers of p into complex affine spaces. Globally, $\mathcal{CP}(S)$ is a holomorphic affine bundle modeled on the holomorphic cotangent bundle $T^*\mathcal{T}(S)$. This yields an identification $\mathcal{CP}(S) \approx T^*\mathcal{T}(S)$, but it is not canonical: it depends on the choice of the “zero section” $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$. There are at least two natural choices of sections to be considered. The Fuchsian section $\sigma_{\mathcal{F}}$ assigns to a Riemann surface X its Fuchsian projective structure given by the uniformization theorem. However, $\sigma_{\mathcal{F}}$ is not holomorphic. The other natural choice is that of a Bers section, given by Bers’ simultaneous uniformization theorem. Bers sections are a family of holomorphic sections parametrized by Teichmüller space. Like any holomorphic cotangent bundle, $T^*\mathcal{T}(S)$ is equipped with a canonical complex symplectic form ω_{can} . Each choice of a zero section σ thus yields a symplectic structure ω^σ on $\mathcal{CP}(S)$, simply by pulling back the canonical symplectic form of $T^*\mathcal{T}(S)$. A first natural question is: How is ω^σ affected by σ ? A small computation shows:

Proposition 3.3. For any two sections σ_1 and σ_2 to $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$,

$$\omega^{\sigma_2} - \omega^{\sigma_1} = -p^*d(\sigma_2 - \sigma_1) . \quad (1)$$

A significantly different description of $\mathcal{CP}(S)$ is given by the holonomy of complex projective structures. Holonomy is a concept defined for any geometric structures, in this situation it gives a local identification $hol : \mathcal{CP}(S) \rightarrow \mathcal{X}(S, PSL_2(\mathbb{C}))$, where the character variety $\mathcal{X}(S, PSL_2(\mathbb{C}))$ is defined as a quotient of the set of representations $\rho : \pi_1(S) \rightarrow PSL_2(\mathbb{C})$. By a general construction of Goldman, $\mathcal{X}(S, PSL_2(\mathbb{C}))$ enjoys a natural complex symplectic structure ω_G . Does this symplectic structure compare to the cotangent symplectic structures ω^σ introduced above? A theorem of Kawai [Kaw96] gives a pleasant answer to that question: If σ is any Bers section, then ω^σ and ω_G^3 agree up to some constant. Kawai’s proof is highly technical and not very insightful though. Also, the conventions chosen in his paper can be misleading⁴. Relying on theorems of other authors, we give a simple alternative proof of Kawai’s result. In fact, we are able to do a little better and completely answer the question raised above. Our argument is based on the observation that there is an intricate circle of related ideas:

- (i) $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$ is a Lagrangian fibration (with respect to ω_G).
- (ii) Bers sections $\mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ are Lagrangian (with respect to ω_G).

³We mean here $hol^* \omega_G$ rather than ω_G , but we abusively use the same notation for the two (as explained in section 4.3).

⁴With the conventions chosen in his paper, Kawai finds $\omega^\sigma = \pi \omega_G$. Compare with our result: $\omega^\sigma = -i \omega_G$. Whether the constant is real or imaginary does matter when taking the real and imaginary parts, obviously, and this can be significant. Kawai’s choices imply that ω_G takes imaginary values in restriction to the Fuchsian slice, which does not seem very relevant. Goldman showed in [Gol84] that (with appropriate conventions) ω_G is just the Weil-Petersson Kähler form on the Fuchsian slice. For the interested reader, we believe that, even after rectifying the conventions, there is a factor 2 missing in Kawai’s result.

- (iii) If M is a 3-manifold diffeomorphic to $S \times \mathbb{R}$, then the Bers simultaneous uniformization map $\beta : \mathcal{T}(\partial_\infty M) \rightarrow \mathcal{CP}(\partial_\infty M)$ is Lagrangian (with respect to ω_G).
- (iv) ω_G restricts to the Weil-Petersson Kähler form ω_{WP} on the Fuchsian slice.
- (v) If σ is any Bers section, then $d(\sigma_{\mathcal{F}} - \sigma) = -i\omega_{WP}$.
- (vi) McMullen's quasi-Fuchsian reciprocity (see [McM00] and Theorem 6.18).
- (vii) For any Bers section σ , $\omega^\sigma = -i\omega_G$.

Let us briefly comment on these. (iv) is a result due to Goldman ([Gol84]). (v) and (vi) are closely related and due to McMullen ([McM00]). Steven Kerckhoff discovered that (iii) easily follows from a standard argument, we include this argument in our presentation (Theorem 4.3) for completeness. (vii) appears to be the strongest result, as it is not too hard to see that it implies all other results⁵. However, using Proposition 3.3 written above and a simple analytic continuation argument (Theorem 6.7), we show that (iv) and (v) imply (vii). In fact, we give a characterization of sections σ such that ω^σ agrees with ω :

Theorem 6.8. Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a section to p . Then ω^σ agrees with the standard complex symplectic structure ω_G on $\mathcal{CP}(S)$ if and only if $\sigma_{\mathcal{F}} - \sigma$ is a primitive for the Weil-Petersson metric on $\mathcal{T}(S)$:

$$\omega^\sigma = \omega_G \Leftrightarrow d(\sigma_{\mathcal{F}} - \sigma) = \omega_{WP} . \quad (2)$$

(vii) then follows from McMullen's theorem (v):

Theorem 6.10. If $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ is any Bers section, then

$$\omega^\sigma = -i\omega_G . \quad (3)$$

We also get the expression of the symplectic structure pulled back by the Fuchsian identification:

Corollary 6.13. Let $\sigma_{\mathcal{F}} : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be the Fuchsian section. Then

$$\omega^{\sigma_{\mathcal{F}}} = -i(\omega_G - p^*\omega_{WP}) . \quad (4)$$

Generalizing these ideas in the setting of convex cocompact 3-manifolds, we prove a generalized version of Theorem 6.10, relying on a result of Takhtajan-Teo[TT03]⁶:

Theorem 6.15. Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a generalized Bers section. Then

$$\omega^\sigma = -i\omega_G . \quad (5)$$

⁵ This is not entirely true *per se*, but we do not want to go into too much detail here.

⁶ However, we stress that the proof also relies indirectly on Theorem 6.10.

We derive a generalization of McMullen’s result (v):

Corollary 6.17. Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a generalized Bers section. Then

$$d(\sigma_{\mathcal{F}} - \sigma) = -i\omega_{WP} . \quad (6)$$

and a generalized version of McMullen’s quasi-Fuchsian reciprocity:

Theorem 6.18. Let $f : \mathcal{T}(S_j) \rightarrow \mathcal{CP}(S_k)$ and $g : \mathcal{T}(S_k) \rightarrow \mathcal{CP}(S_j)$ be reciprocal generalized Bers embeddings. Then $D_{X_j}f$ and $D_{X_k}g$ are dual maps. In other words, for any $\mu \in T_{X_j}\mathcal{T}(S_j)$ and $\nu \in T_{X_k}\mathcal{T}(S_k)$,

$$\langle D_{X_j}f(\mu), \nu \rangle = \langle \mu, D_{X_k}g(\nu) \rangle . \quad (7)$$

Finally, we discuss the symplectic geometry of $\mathcal{CP}(S)$ in relation to complex Fenchel-Nielsen coordinates on the quasi-Fuchsian space $\mathcal{QF}(S)$. These are global holomorphic coordinates on $\mathcal{QF}(S)$ introduced by Kourouniotis ([Kou94]) and Tan ([Tan94]) that are the complexification of the classical Fenchel-Nielsen coordinates on Teichmüller space $\mathcal{T}(S)$, or rather the Fuchsian space $\mathcal{F}(S)$. In [Wol82], [Wol83] and [Wol85], Wolpert showed that the Fenchel-Nielsen coordinates on $\mathcal{F}(S)$ encode the symplectic structure. For any simple closed curve γ on the surface S , there is a hyperbolic length function $l_\gamma : \mathcal{F}(S) \rightarrow \mathbb{R}$ and a twist flow $\text{tw}_\gamma : \mathbb{R} \times \mathcal{F}(S) \rightarrow \mathcal{F}(S)$. Given a pants decomposition $\alpha = (\alpha_1, \dots, \alpha_N)^T$ on S , choosing a section to $l_\alpha = (l_{\alpha_1}, \dots, l_{\alpha_N})$ yields the classical Fenchel-Nielsen coordinates on Teichmüller space $(l_\alpha, \tau_\alpha) : \mathcal{F}(S) \rightarrow (\mathbb{R}_{>0})^N \times \mathbb{R}^N$. Wolpert showed that the twist flow associated to a curve γ is the Hamiltonian flow of the length function l_γ . He also gave formulas for the Poisson bracket of two length functions, which show in particular that the length functions l_{α_i} associated to a pants decomposition α define an integrable Hamiltonian system, for which the functions l_{α_i} are the action variables and the twist functions τ_{α_i} are the angle variables. In [Pla01], Platis shows that this very nice “Hamiltonian picture” remains true in its complexified version on the quasi-Fuchsian space for some complex symplectic structure ω_P , giving complex versions of Wolpert’s results. This Hamiltonian picture is also extensively explored on the $SL_2(\mathbb{C})$ -character variety by Goldman in [Gol04]. Independently from Platis’ work, our analytic continuation argument shows that complex Fenchel-Nielsen coordinates are Darboux coordinates for the symplectic structure on $\mathcal{QF}(S)$:

Theorem 6.19. Let α be any pants decomposition of S . Complex Fenchel-Nielsen coordinates $(l_\alpha^{\mathbb{C}}, \beta_\alpha^{\mathbb{C}})$ on the quasi-Fuchsian space $\mathcal{QF}(S)$ are Darboux coordinates for the standard complex symplectic structure:

$$\omega_G = \sum_{i=1}^N dl_{\alpha_i}^{\mathbb{C}} \wedge d\tau_{\alpha_i}^{\mathbb{C}} \quad (8)$$

⁷*i.e.* a maximal collection of nontrivial distinct free homotopy classes of simple closed curves, see section 5.1.

and this shows in particular that

Corollary 6.20. Platis' symplectic structure ω_P is equal to the standard complex symplectic structure ω_G on the quasi-Fuchsian space $\mathcal{QF}(S)$ ⁸.

We thus recover Platis' and some of Goldman's results, in particular that the complex twist flow is the Hamiltonian flow of the associated complex length function. Although in the Fuchsian case it would seem unnecessarily sophisticated to use this as a definition of the twist flow, this approach might be fruitful in the space of projective structures. This transformation relates to what other authors have called *quakebends* or *complex earthquakes* discussed by Epstein-Marden [EM87], McMullen [McM98], Series [Ser01] among others.

Note: The study of Taubes' symplectic structure on the deformation space of *minimal hyperbolic germs*⁹ (in restriction to *almost-Fuchsian space*, which embeds as an open subspace of quasi-Fuchsian space $\mathcal{QF}(S)$) is addressed in a forthcoming paper ([Lou14]). Both articles are based on the author's PhD thesis ([Lou11]).

Structure of the paper: Section 2 reviews complex projective structures, Fuchsian and quasi-Fuchsian projective structures, the relation between complex projective structures and hyperbolic 3-manifolds, (generalized) Bers sections and embeddings. Section 3 introduces the affine cotangent symplectic structures given by the Schwarzian parametrization of $\mathcal{CP}(S)$. Section 4 reviews the character variety, holonomy of projective structures, Goldman's symplectic structure and some of its properties. In section 5, we briefly review Wolpert's "Hamiltonian picture" of Teichmüller space, then describe the complex Fenchel-Nielsen coordinates in quasi-Fuchsian space and Platis' symplectic structure. In section 6, we describe an analytic continuation argument then discuss and compare the different symplectic structures previously introduced. Our results are essentially contained in that last section.

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⁸This fact is mentioned as "apparent" in [Pla01] and is implied in [Gol04], but it would seem that it was not "formally proved".

⁹We refer to [Tau04] and [Lou14] for the interested reader.

2 Teichmüller space and the deformation space of complex projective structures

2.1 $\mathcal{T}(S)$ and $\mathcal{CP}(S)$

Let S be a surface. Unless otherwise stated, we will assume that S is connected¹⁰, oriented, smooth, closed and with genus $g \geq 2$.

A complex structure on S is a maximal atlas of charts mapping open sets of S into the complex line \mathbb{C} such that the transition maps are holomorphic. The atlas is required to be compatible with the orientation and smooth structure on S . A Riemann surface X is a surface S equipped with a complex structure.

The group $\text{Diff}^+(S)$ of orientation preserving diffeomorphisms of S acts on the set of all complex structures on S in a natural way: a compatible complex atlas on S is pulled back to another one by such diffeomorphisms. Denote by $\text{Diff}_0^+(S)$ the identity component of $\text{Diff}^+(S)$, its elements are the orientation preserving diffeomorphisms of S that are homotopic to the identity. The quotient $\mathcal{T}(S)$ of the set of all complex structures on S by $\text{Diff}_0^+(S)$ is called the *Teichmüller space* of S , its elements are called *marked Riemann surfaces*.

In a similar fashion, define a *complex projective structure* on S as a maximal atlas of charts mapping open sets of S into the complex projective line \mathbb{CP}^1 such that the transition maps are (restrictions of) projective linear transformations (*i.e.* Möbius transformations of the Riemann sphere). The atlas is also required to be compatible with the orientation and smooth structure on S . A complex projective surface Z is a surface S equipped with a complex projective structure. In terms of geometric structures (see e.g. [Thu97]), a complex projective structure is a $(\mathbb{CP}^1, \text{PSL}_2(\mathbb{C}))$ -structure.

Again, $\text{Diff}^+(S)$ naturally acts on the set of all complex projective structures on S . The quotient $\mathcal{CP}(S)$ by the subgroup $\text{Diff}_0^+(S)$ is called the *deformation space of complex projective structures* on S , its elements are *marked complex projective surfaces*.

$\mathcal{T}(S)$ and $\mathcal{CP}(S)$ are complex manifolds

Kodaira-Spencer deformation theory (see [KS58], also [EE69]) applies and it shows that $\mathcal{T}(S)$ is naturally a complex manifold with holomorphic tangent space given by $T_X^{1,0}\mathcal{T}(S) = \check{H}^1(X, \Theta_X)$, where Θ_X is the sheaf of holomorphic vector fields on X . Denote by K the canonical bundle over X (the holomorphic cotangent bundle of X). By Dolbeault's theorem, $\check{H}^1(X, \Theta_X)$ is isomorphic to the Dolbeault cohomology space $H^{-1,1}(X)$. Elements of $H^{-1,1}(X)$ are Dolbeault classes of smooth sections of $K^{-1} \otimes \bar{K}$, which are called *Beltrami differentials*. In a complex chart $z : U \subset S \rightarrow \mathbb{C}$, a Beltrami differential μ has an expression of the form $\mu = u(z) \frac{d\bar{z}}{dz}$ where u is a smooth

¹⁰In some sections (e.g. 2.3), we will allow S to be disconnected in order to be able to consider the case where S is the boundary of a compact 3-manifold. This does not cause any issue in the exposition above.

function. The fact that we only consider (Dolbeault) classes of Beltrami differentials can be expressed as follows : if V is a vector field on X of type $(1,0)$, then the Beltrami differential $\bar{\partial}V$ induces a trivial (infinitesimal) deformation of the complex structure X . Recall that X carries a unique hyperbolic metric within its conformal class (called the Poincaré metric) by the uniformization theorem. By Hodge theory, every Dolbeault cohomology class has a unique harmonic representative μ . The tangent space $T_X\mathcal{T}(S)$ is thus also identified with the space $HB(X)$ of harmonic Beltrami differentials.

We can also derive a nice description of the Teichmüller cotangent space using cohomology machinery. $\check{H}^1(X, \Theta_X) = H^1(X, K^{-1})$ because $\dim_{\mathbb{C}}X = 1$ and this space is dual to $H^0(X, K^2)$ by Serre duality. An element $\varphi \in Q(X) := H^0(X, K^2)$ is called a *holomorphic quadratic differential*. In a complex chart $z : U \subset S \rightarrow \mathbb{C}$, φ has an expression of the form $\varphi = \phi(z)dz^2$, where ϕ is a holomorphic function. The holomorphic cotangent space $T_X^*\mathcal{T}(S)$ is thus identified with the space $Q(X)$ of holomorphic quadratic differentials. The duality pairing $Q(X) \times H^{-1,1}(X) \rightarrow \mathbb{C}$ is just given by $(\varphi, \mu) \mapsto \int_S \varphi \cdot \mu$. Note that we systematically use tensor contraction (when dealing with line bundles over X) : $\varphi \cdot \mu$ is a section of $K \otimes \bar{K} \approx |K|^2$, so it defines a conformal density and can be integrated over S . With the notations above, $\varphi \cdot \mu$ has local expression $\phi(z)u(z)|dz|^2$.

An easy consequence of the Riemann-Roch theorem is that $\dim_{\mathbb{C}}Q(X) = 3g - 3$, so that $\mathcal{T}(S)$ is a complex manifold of dimension $3g - 3$.

Similarly, Kodaira-Spencer deformation theory applies to show that $\mathcal{CP}(S)$ is naturally a complex manifold with tangent space $T_Z\mathcal{CP}(S) = \check{H}^1(Z, \Xi_Z)$, where Ξ_Z is the sheaf of projective vector fields on Z (see also [Hub81]). It follows that $\mathcal{CP}(S)$ is a complex manifold of dimension $6g - 6$.

Unlike Teichmüller tangent vectors, there is no immediate way to describe tangent vectors to $\mathcal{CP}(S)$ in a more tangible way. However, note that a complex projective atlas is in particular a holomorphic atlas, so that a complex projective surface Z has an underlying structure of a Riemann surface X . This yields a forgetful map

$$p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S) \tag{9}$$

which is easily seen to be holomorphic. We will see in section 3.1 that the fiber $p^{-1}(X)$ is naturally a complex affine space whose underlying vector space is $Q(X)$. In particular $\dim_{\mathbb{C}}\mathcal{CP}(S) = \dim_{\mathbb{C}}\mathcal{T}(S) \times \dim_{\mathbb{C}}Q(X) = 6g - 6$ as expected.

The Weil-Petersson Kähler metric on $\mathcal{T}(S)$

The *Weil-Petersson product* of two holomorphic quadratic differentials Φ and Ψ is given by

$$\langle \varphi, \psi \rangle_{WP} = -\frac{1}{4} \int_X \varphi \cdot \sigma^{-1} \cdot \bar{\psi} \tag{10}$$

where σ^{-1} is the dual current of the area form σ for the Poincaré metric¹¹. It is a Hermitian inner product on the complex vector space $Q(X)$.

By duality, this gives a Hermitian product also denoted by $\langle \cdot, \cdot \rangle_{WP}$ on $H^{-1,1}(X)$ and globally a Hermitian metric $\langle \cdot, \cdot \rangle_{WP}$ on the manifold $\mathcal{T}(S)$. It was first shown to be Kähler by Ahlfors [Ahl61] and Weil.

The Kähler form of the Weil-Petersson metric on $\mathcal{T}(S)$ is the real symplectic form

$$\omega_{WP} = -\text{Im} \langle \cdot, \cdot \rangle_{WP} . \quad (11)$$

2.2 Fuchsian and quasi-Fuchsian projective structures

Note that whenever a Kleinian group Γ (*i.e.* a discrete subgroup of $PSL_2(\mathbb{C})$) acts freely and properly on some open subset U of the complex projective line \mathbb{CP}^1 , the quotient surface U/Γ inherits a complex projective structure. This gives a variety (but not all) of complex projective surfaces, called embedded projective structures.

Fuchsian projective structures are a fundamental example of embedded projective structures. Given a marked complex structure X , the uniformization theorem provides a representation $\rho : \pi_1(S) \rightarrow PSL_2(\mathbb{R})$ such that X is isomorphic to $\mathbb{H}^2/\rho(\pi_1(S))$ as a Riemann surface (where \mathbb{H}^2 is the upper half-plane). \mathbb{H}^2 can be seen as an open set (a disk) in \mathbb{CP}^1 and the Fuchsian group $\rho(\pi_1(S)) \subset PSL_2(\mathbb{R})$ is in particular a Kleinian group, so the quotient $X \approx \mathbb{H}^2/\rho(\pi_1(S))$ inherits a complex projective structure Z . This defines a section

$$\sigma_{\mathcal{F}} : \mathcal{T}(S) \rightarrow \mathcal{CP}(S) \quad (12)$$

to p , called the *Fuchsian section*. It shows in particular that the projection p is surjective. We call $\mathcal{F}(S) := \sigma_{\mathcal{F}}(\mathcal{T}(S))$ the (deformation) space of (standard) Fuchsian (projective) structures on S , it is an embedded copy of $\mathcal{T}(S)$ in $\mathcal{CP}(S)$.

Quasi-Fuchsian structures are another important class of embedded projective structures. Given two marked complex structures $(X^+, X^-) \in \mathcal{T}(S) \times \mathcal{T}(\bar{S})$ ¹² (where \bar{S} is the surface S with reversed orientation), Bers' simultaneous uniformization theorem states that there exists a unique representation $\rho : \pi_1(S) \xrightarrow{\sim} \Gamma \subset PSL_2(\mathbb{C})$ up to conjugation such that:

- The limit set¹³ Λ is a Jordan curve. The domain of discontinuity Ω is then the disjoint union of two simply connected domains Ω^+ and Ω^- . A such Γ is called a quasi-Fuchsian group.
- As marked Riemann surfaces, $X^+ \approx \Omega^+/\Gamma$ and $X^- \approx \Omega^-/\Gamma$.

¹¹In a complex chart with values in the upper half-plane $z = x + iy : U \subset X \rightarrow \mathbb{H}^2$, the tensor product $-\frac{1}{4}\varphi \cdot \sigma^{-1} \cdot \bar{\psi}$ reduces to the classical expression $y^2\varphi(z)\bar{\psi}(z)dx \wedge dy$.

¹²Note that $\mathcal{T}(\bar{S})$ is canonically identified with $\overline{\mathcal{T}(S)}$, which denotes the manifold $\mathcal{T}(S)$ equipped with the opposite complex structure. The same remark holds for $\mathcal{CP}(\bar{S})$ and $\overline{\mathcal{CP}(S)}$.

¹³The *limit set* $\Lambda = \Lambda(\Gamma)$ is defined as the complement in \mathbb{CP}^1 of the domain of discontinuity Ω , which is the maximal open set on which Γ acts freely and properly. Alternatively, Λ is described as the closure in \mathbb{CP}^1 of the set of fixed points of elements of Γ .

Again, both Riemann surfaces X^+ and X^- inherit embedded complex projective structures Z^+ and Z^- by this construction. This defines a map $\beta = (\beta^+, \beta^-) : \mathcal{T}(S) \times \mathcal{T}(\bar{S}) \rightarrow \mathcal{CP}(S) \times \mathcal{CP}(\bar{S})$ which is a holomorphic section to $p \times p : \mathcal{CP}(S) \times \mathcal{CP}(\bar{S}) \rightarrow \mathcal{T}(S) \times \mathcal{T}(\bar{S})$ by Bers' theorem. The map β has the obvious symmetry property: $\beta^-(X^+, X^-) = \beta^+(\bar{X}^-, \bar{X}^+)$.

In particular, when $X^- \in \mathcal{T}(\bar{S})$ is fixed, the map $\sigma_{X^-} := \beta^+(\cdot, X^-) : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ is a holomorphic section to p , called a *Bers section*, and its image $\sigma_{X^-}(\mathcal{T}(S))$ in $\mathcal{CP}(S)$ is called a *Bers slice*. On the other hand, when $X^+ \in \mathcal{T}(S)$ is fixed, the map $f_{X^+} = \beta^+(X^+, \cdot)$ is an embedding of $\mathcal{T}(\bar{S})$ in the fiber $P(X^+) := p^{-1}(X^+) \subset \mathcal{CP}(S)$ ¹⁴, f_{X^+} is called a *Bers embedding*. Also, note that $\sigma_{\mathcal{F}}(X) = \beta^+(X, \bar{X}) = \beta^-(X, \bar{X}) = \sigma_{\bar{X}}(X)$. This shows that the Fuchsian section $\sigma_{\mathcal{F}}$ is real analytic but not holomorphic, in fact it is a maximal totally real analytic embedding, see section 6.1.

$\mathcal{QF}(S) := \beta^+(\mathcal{T}(S) \times \mathcal{T}(\bar{S})) \subset \mathcal{CP}(S)$ is called the (deformation) space of (standard) quasi-Fuchsian (projective) structures on S . It is an open neighborhood of $\mathcal{F}(S)$ in $\mathcal{CP}(S)$ (this is a consequence of general arguments mentioned in the next paragraph), and it follows from the discussion above that Bers slices and Bers embeddings define two transverse foliations of $\mathcal{QF}(S)$ by holomorphic copies of $\mathcal{T}(S)$.

2.3 Complex projective structures and hyperbolic 3-manifolds

In this paragraph, we briefly review the relation between complex projective structures on the boundary of a compact 3-manifold \hat{M} and hyperbolic structures on its interior. The quasi-Fuchsian projective structures presented in the previous section occur as a particular case of this discussion. We then define *generalized Bers sections* and *generalized Bers embeddings*, and fix a few notations for later sections.

Let M be a connected complete hyperbolic 3-manifold. The universal cover of M is isometric to hyperbolic 3-space \mathbb{H}^3 , this defines a unique faithful representation $\rho : \pi_1(M) \rightarrow \text{Isom}^+(\mathbb{H}^3) \approx PSL_2(\mathbb{C})$ up to conjugation such that $\Gamma := \rho(\pi_1(M))$ acts freely and properly on \mathbb{H}^3 and $M \approx \mathbb{H}^3/\Gamma$. Let $\Omega \subset \mathbb{CP}^1$ be the domain of discontinuity of the Kleinian group Γ , it is the maximal open set on which Γ acts freely and properly. Here \mathbb{CP}^1 is seen as the ‘‘ideal boundary’’ of \mathbb{H}^3 , also denoted $\partial_\infty \mathbb{H}^3$. The possibly disconnected surface $\partial_\infty M := \Omega/\Gamma$ is called the *ideal boundary* of M and it inherits an embedded complex projective structure as the quotient of $\Omega \subset \mathbb{CP}^1$ by the Kleinian group Γ . Conversely, any torsion-free Kleinian group Γ acts freely and properly on $\mathbb{H}^3 \sqcup \Omega$ (where Ω is the domain of discontinuity of Γ), and the quotient consists of a 3-manifold $\hat{M} = M \sqcup \partial_\infty M$, where $M = \mathbb{H}^3/\Gamma$ is a complete hyperbolic 3-manifold and $\partial_\infty M = \Omega/\Gamma$ is its ideal boundary. In general, the manifold \hat{M} is not compact, if it is then \hat{M} is topologically the end compactification of M . In that case we say that the hyperbolic structure on M is *convex cocompact*. The *convex core* of M is the quotient of the convex hull of the

¹⁴which has the structure of a complex affine space as we will see in section 3.1.

limit set Λ in \mathbb{H}^3 by Γ . It is well-known that M is convex cocompact if and only if its convex core is a compact deformation retract of M .

Consider now a smooth 3-manifold with boundary \hat{M} with the following topological restrictions: \hat{M} is connected, oriented, compact, irreducible¹⁵, atoroidal¹⁶ and with infinite fundamental group. Let $M = \hat{M} \setminus \partial\hat{M}$ denote the interior of \hat{M} . For simplicity, we also assume that the boundary $\partial\hat{M}$ is incompressible¹⁷ and contains no tori, so that it consists of a finite number of surfaces S_1, \dots, S_N of genera at least 2. The Teichmüller space $\mathcal{T}(\partial\hat{M})$ is described as the direct product $\mathcal{T}(\partial\hat{M}) = \mathcal{T}(S_1) \times \dots \times \mathcal{T}(S_N)$, similarly $\mathcal{CP}(\partial\hat{M}) = \mathcal{CP}(S_1) \times \dots \times \mathcal{CP}(S_N)$ and there is a holomorphic “forgetful” projection $p = p_1 \times \dots \times p_N : \mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{T}(\partial\hat{M})$. Let $\text{pr}_k : \mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{CP}(S_k)$ denote the k^{th} projection map. Let us consider the space $\mathcal{HC}(M)$ of convex cocompact hyperbolic structures on M up to homotopy. In other words, we define $\mathcal{HC}(M)$ as the quotient of the set of convex cocompact hyperbolic metrics on M by the group of orientation-preserving diffeomorphisms of M that are homotopic to the identity. Let us mention that Marden [Mar74] and Sullivan [Sul85] showed that $\mathcal{HC}(M)$ is a connected component of the interior of the subset of discrete and faithful representations in the character variety $\mathcal{X}(M, PSL_2(\mathbb{C}))$. By the discussion above, any element of $\mathcal{HC}(M)$ determines a marked complex projective structure $Z \in \mathcal{CP}(\partial\hat{M})$. We thus have a map $\varphi : \mathcal{HC}(M) \rightarrow \mathcal{CP}(\partial\hat{M})$, and it is shown to be holomorphic, this is a straightforward consequence of the fact that the holonomy map is holomorphic (see section 4.3). Considering the induced conformal structure on $\partial\hat{M}$, define the map $\psi = p \circ \varphi$ as in the following diagram:

$$\begin{array}{ccc} \mathcal{HC}(M) & \xrightarrow{\varphi} & \mathcal{CP}(\partial\hat{M}) \\ & \searrow \psi & \downarrow p \\ & & \mathcal{T}(\partial\hat{M}) . \end{array}$$

The powerful theorem mainly due to Ahlfors, Bers, Kra, Marden, Maskit, Sullivan and Thurston¹⁸ says in this context that:

Theorem 2.1 (Ahlfors, Bers, Kra, Marden, Maskit, Sullivan, Thurston). *The map $\psi : \mathcal{HC}(M) \rightarrow \mathcal{T}(\partial\hat{M})$ is bijective.*

Let us mention that this statement has to be slightly modified if \hat{M} has compressible boundary. As a consequence of this theorem, we get

Proposition 2.2. *The map*

$$\beta = \varphi \circ \psi^{-1} : \mathcal{T}(\partial\hat{M}) \rightarrow \mathcal{CP}(\partial\hat{M}) \tag{13}$$

¹⁵meaning that every embedded 2-sphere bounds a ball.

¹⁶meaning that it does not contain any embedded, non-boundary parallel, incompressible tori.

¹⁷ meaning that the map $\iota_* : \pi_1(\partial\hat{M}) \rightarrow \pi_1(\hat{M})$ induced by the inclusion map ι is injective.

¹⁸see [CM04] chapter 7. for a detailed exposition of this theorem, containing in particular the description of the different contributions of the several authors. A non-exhaustive list of references includes [AB60], [Ahl64], [Ber87], [Kra72], [Mar74], [Mas71], [Sul85].

is a holomorphic section to $p : \mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{T}(\partial\hat{M})$.

We call β the (*generalized simultaneous uniformization section*). This map allows us to define “generalized Bers sections” and “generalized Bers embeddings” by letting only one of the boundary components’ conformal structure vary and by looking at the resulting complex projective structure on some other (or the same) boundary component. This idea is made precise as follows. If an index $j \in \{1, \dots, N\}$ and marked complex structures $X_i \in \mathcal{T}(S_i)$ are fixed for all $i \neq j$, we denote by $\iota_{(X_i)}$ the injection

$$\iota_{(X_i)} : \begin{array}{ccc} \mathcal{T}(S_j) & \rightarrow & \mathcal{T}(\partial\hat{M}) \\ X & \mapsto & (X_1, \dots, X_{j-1}, X, X_{j+1}, \dots, X_N) . \end{array} \quad (14)$$

Let $f_{(X_i),k} = \text{pr}_k \circ \beta \circ \iota_{(X_i)}$ as in the following diagram:

$$\begin{array}{ccc} \mathcal{T}(\partial\hat{M}) & \xrightarrow{\beta} & \mathcal{CP}(\partial\hat{M}) \\ \iota_{(X_i)} \uparrow & & \downarrow \text{pr}_k \\ \mathcal{T}(S_j) & \xrightarrow{f_{(X_i),k}} & \mathcal{CP}(S_k) . \end{array} \quad (15)$$

If $j = k$, then $\sigma_{(X_i)} := f_{(X_i),j}$ is a holomorphic section to $p_j : \mathcal{CP}(S_j) \rightarrow \mathcal{T}(S_j)$, that we call a *generalized Bers section*. On the other hand, if $j \neq k$, then $f_{(X_i),k}$ maps $\mathcal{T}(S_j)$ in the affine¹⁹ fiber $P(X_k) \subset \mathcal{CP}(S_k)$, we call a $f_{(X_i),k}$ a *generalized Bers embedding*. We apologize for this misleading terminology: a “generalized Bers embedding” is *not* an embedding in general.

Note that quasi-Fuchsian structures discussed in the previous paragraph just correspond to the case where $M = S \times \mathbb{R}$. Let us also mention that this discussion is easily adapted when ∂M contains tori or is no longer assumed incompressible, with a few precautions. When \hat{M} only has one boundary component, this gives the notion of a *Schottky section*.

3 The cotangent symplectic structures

3.1 $\mathcal{CP}(S)$ as an affine holomorphic bundle over $\mathcal{T}(S)$

The Schwarzian derivative

Given a locally injective holomorphic function $f : Z_1 \rightarrow Z_2$ where Z_1 and Z_2 are complex projective surfaces, define the *osculating map* \tilde{f} to f at a point $m \in Z_1$ as the germ of a (locally defined) projective map that has the best possible contact with f at m . In some sense, one can take a flat covariant derivative $\nabla \tilde{f}$ and identify it as holomorphic quadratic differential $\mathcal{S}f \in Q(X)$, called the *Schwarzian derivative* of f . We refer to [And98] and [Dum09] for details.

¹⁹see section 3.1.

In local projective charts, the Schwarzian derivative of f has the classical expression $\mathcal{S}f = Sf(z)dz^2$, where

$$Sf(z) = \frac{f'''(z)}{f'(z)} - \frac{3}{2} \left(\frac{f''(z)}{f'(z)} \right)^2 .$$

As a consequence of the definition, the Schwarzian operator enjoys the following properties:

Proposition 3.1.

- If f is a projective map, then $\mathcal{S}f = 0$ (the converse is also true).
- If $f : Z_1 \rightarrow Z_2$ and $g : Z_2 \rightarrow Z_3$ are locally injective holomorphic functions between complex projective surfaces, then

$$\mathcal{S}(g \circ f) = \mathcal{S}(f) + f^* \mathcal{S}(g) .$$

The Schwarzian derivative also satisfies an existence theorem:

Proposition 3.2. *If $U \subset \mathbb{C}$ is simply connected and $\varphi \in Q(U)$, then $\mathcal{S}f = \varphi$ can be solved for $f : U \rightarrow \mathbb{CP}^1$.*

An elementary and constructive proof of this fact is given in e.g. [Dum09], see also [And98] for a more abstract argument.

Schwarzian parametrization of a fiber

Recall that there is a holomorphic “forgetful” map $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$. Let X be a fixed point in $\mathcal{T}(S)$ and $P(X) := p^{-1}(\{X\})$ the set of marked projective structures on S whose underlying complex structure is X .

Given $Z_1, Z_2 \in P(X)$, the identity map $\text{id}_S : Z_1 \rightarrow Z_2$ is holomorphic but not projective if $Z_1 \neq Z_2$. Taking its Schwarzian derivative accurately measures the “difference” of the two projective structures Z_1 and Z_2 . Let us make this observation more precise. A consequence of Proposition 3.2 is that given $Z_1 \in P(X)$ and $\varphi \in Q(X)$, there exists $Z_2 \in P(X)$ such that $\mathcal{S}(\text{id}_S : Z_1 \rightarrow Z_2) = \varphi$. This defines a map $Q(X) \times P(X) \rightarrow P(X)$, which is now easily seen to be a freely transitive action of $Q(X)$ on $P(X)$ as a consequence of Proposition 3.1. In other words, $P(X)$ is equipped with a complex affine structure, modeled on the vector space $Q(X)$.

Recall that $Q(X)$ is also identified with the complex dual space $T_X^* \mathcal{T}(S)$. As a result of this discussion, $\mathcal{CP}(S)$ is an affine holomorphic bundle modeled on the holomorphic cotangent vector bundle $T^* \mathcal{T}(S)$.

Consequently, $\mathcal{CP}(S)$ can be identified with $T^* \mathcal{T}(S)$ by choosing a “zero section” $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$. Explicitly, we get an isomorphism of complex affine bundles $\tau^\sigma : Z \mapsto Z - \sigma(p(Z))$ as in the following diagram:

$$\begin{array}{ccc}
\mathcal{CP}(S) & \xrightarrow{\tau^\sigma} & T^*\mathcal{T}(S) \\
& \searrow p & \swarrow \pi \\
& & \mathcal{T}(S) .
\end{array} \tag{16}$$

τ^σ is characterized by the fact that $\tau^\sigma \circ \sigma$ is the zero section to $\pi : T^*\mathcal{T}(S) \rightarrow \mathcal{T}(S)$. It is an isomorphism of holomorphic bundles whenever σ is a holomorphic section to p , such as a (generalized) Bers section (see sections 2.2 and 2.3).

3.2 Complex symplectic structure on $T^*\mathcal{T}(S)$

It is a basic fact that if M is any complex manifold (in particular when $M = \mathcal{T}(S)$), the total space of its holomorphic cotangent bundle T^*M ²⁰ is equipped with a canonical complex symplectic structure. We briefly recall this and a few useful properties.

The *canonical 1-form* ξ is the holomorphic $(1,0)$ -form on T^*M defined at a point $\varphi \in T^*M$ by $\xi_\varphi := \pi^*\varphi$, where $\pi : T^*M \rightarrow M$ is the canonical projection and φ is seen as a complex covector on M in the right-hand side of the equality. The *canonical complex symplectic form* on T^*M is then simply defined by $\omega_{\text{can}} = d\xi$ ²¹. If (z_k) is a system of holomorphic coordinates on M so that an arbitrary $(1,0)$ -form has an expression of the form $\alpha = \sum w_k dz_k$, then (z_k, w_k) is a system of holomorphic coordinates on T^*M for which $\xi = \sum w_k dz_k$ and $\omega_{\text{can}} = \sum dw_k \wedge dz_k$.

The canonical 1-form satisfies the following reproducing property. If α is any $(1,0)$ -form on M , it is in particular a map $M \rightarrow T^*M$ and as such it can be used to pull back differential forms from T^*M to M . It is then not hard to show that $\alpha^*\xi = \alpha$ and as a consequence $\alpha^*\omega_{\text{can}} = d\alpha$.

Note that if u is a vertical tangent vector to T^*M , *i.e.* $\pi_*u = 0$, then u can be identified with an element of the fiber containing its base point α (since the fibers of the projection are vector spaces). Under that identification, the symplectic pairing between u and any other tangent vector $v \in T_\alpha T^*M$ is just given by $\omega_{\text{can}}(u, v) = \langle u, \pi_*v \rangle$ where $\langle \cdot, \cdot \rangle$ is the duality pairing on $T_{\pi(\alpha)}M$.

Note that the fibers of the projection $\pi : T^*M \rightarrow M$ are Lagrangian submanifolds of T^*M , in other words π is a Lagrangian fibration. Also, the zero section $s_0 : M \hookrightarrow T^*M$ is a Lagrangian embedding. These are direct consequences of the previous observation.

3.3 Affine cotangent symplectic structures

As we have seen in section 3.1, any choice of a “zero section” $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ yields an affine isomorphism $\tau^\sigma : \mathcal{CP}(S) \xrightarrow{\sim} T^*\mathcal{T}(S)$. We can use this to pull back

²⁰In this context T^*M stands for the complex dual of the holomorphic tangent bundle $T^{1,0}M$, its (smooth) sections are the $(1,0)$ -forms.

²¹Note that some authors might take the opposite sign convention for ω_{can} .

the canonical symplectic structure of $T^*\mathcal{T}(S)$ on $\mathcal{CP}(S)$: define

$$\omega^\sigma := (\tau^\sigma)^* \omega_{\text{can}} . \quad (17)$$

It is clear that ω^σ is a complex symplectic form on $\mathcal{CP}(S)$ whenever σ is a holomorphic section to p . Otherwise, it is just a complex-valued non-degenerate 2-form on $\mathcal{CP}(S)$, whose real and imaginary parts are both real symplectic forms.

How is ω^σ affected by the choice of the “zero section” σ ? The following statement is both straightforward and key:

Proposition 3.3. *For any two sections σ_1 and σ_2 to $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$,*

$$\omega^{\sigma_2} - \omega^{\sigma_1} = -p^* d(\sigma_2 - \sigma_1) \quad (18)$$

where $\sigma_2 - \sigma_1$ is the “affine difference” between σ_2 and σ_1 , it is a 1-form on $\mathcal{T}(S)$. In particular, the symplectic structures induced by the respective choices of two sections agree if and only if their affine difference is a closed 1-form.

Proof. This is an easy computation:

$$\begin{aligned} -p^* d(\sigma_2 - \sigma_1) &= -p^* ((\sigma_2 - \sigma_1)^* \omega_{\text{can}}) \quad (\text{see (3.2)}) \\ &= (-(\sigma_2 - \sigma_1) \circ p)^* \omega_{\text{can}} \\ &= (\tau_2^\sigma - \tau_1^\sigma)^* \omega_{\text{can}} \\ &= (\tau^{\sigma_2})^* \omega_{\text{can}} - (\tau^{\sigma_1})^* \omega_{\text{can}} . \end{aligned}$$

Only the last step is not so trivial as it would seem because one has to be careful about base points. Also, note that in the identity

$$\tau^{\sigma_2}(Z) - \tau^{\sigma_1}(Z) = (Z - \sigma_2 \circ p(Z)) - (Z - \sigma_1 \circ p(Z)) = -(\sigma_2 - \sigma_1) \circ p(Z) ,$$

some minus signs are “affine” ones (hiding the Schwarzian derivative) and others are “genuine” minus signs, but this can be ignored in computation. \square

Moreover, a straightforward calculation gives an explicit expression of $\omega^\sigma(u, v)$ whenever u is a vertical tangent vector to $\mathcal{CP}(S)$, it is exactly the same as the one obtained for the symplectic structure on $T^*\mathcal{T}(S)$:

Proposition 3.4. *Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a section to p . Let Z be a point in $\mathcal{CP}(S)$, and u, v be tangent vectors at Z such that u is vertical, i.e. $p_*u = 0$. Then*

$$\omega^\sigma(u, v) = \langle u, p_*v \rangle . \quad (19)$$

In this expression, u is seen as an element of $\in T_X^*T(S)$ (where $X = p(Z)$) under the identification $T_Z P(X) = Q(X) = T_X^*T(S)$. Note that this expression not involving σ is compatible with the previous proposition, which implies that $\omega^{\sigma_2} - \omega^{\sigma_1}$ is a horizontal 2-form.

As a consequence, just like in the cotangent space, we have:

Proposition 3.5. *Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be any section. The projection $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$ is a Lagrangian fibration for ω^σ . Also, σ is a Lagrangian embedding.*

4 The character variety and Goldman's symplectic structure

4.1 The character variety

References for this section include [Gol84], [HP04], [Gol04] and [Dum09].

Let $G = PSL_2(\mathbb{C})$ and $\mathcal{R}(S)$ be the set of group homomorphisms from $\pi := \pi_1(S)$ to G . It has a natural structure of a complex affine algebraic set as follows. Choose a finite presentation $\pi = \langle \gamma_1, \dots, \gamma_N \mid (r_i)_{i \in I} \rangle$ of π . Evaluating a representation $\rho \in \mathcal{R}(S)$ on the generators γ_k embeds $\mathcal{R}(S)$ as an algebraic subset of G^N . This gives $\mathcal{R}(S)$ an affine structure indeed because of the identification $PSL_2(\mathbb{C}) \approx SO_3(\mathbb{C})$ (given by the adjoint representation of $PSL_2(\mathbb{C})$ on its Lie algebra $\mathfrak{g} = \mathfrak{sl}_2(\mathbb{C})$). One can check that this structure is independent of the presentation.

G acts algebraically on $\mathcal{R}(S)$ by conjugation. The character variety $\mathcal{X}(S)$ is defined as the quotient in the sense of invariant theory. Specifically, the action of G on $\mathcal{R}(S)$ induces an action on the ring of regular functions $\mathbb{C}[\mathcal{R}(S)]$. Denote by $\mathbb{C}[\mathcal{R}(S)]^G$ the ring of invariant functions, it is finitely generated because $\mathcal{R}(S)$ is affine and G is reductive.

Lemma 4.1 (see e.g. [HP04]). *In fact, it is generated in this case ($G = PSL_2(\mathbb{C})$) by a finite number of the complex valued functions on $\mathcal{R}(S)$ of the form $\rho \mapsto \text{tr}^2(\rho(\gamma))$.*

$\mathcal{X}(S)$ is the affine set such that $\mathbb{C}[\mathcal{X}(S)] = \mathbb{C}[\mathcal{R}(S)]^G$, it is called the *character variety* of S . A consequence of the lemma is that the points of $\mathcal{X}(S)$ are in one-to-one correspondence with the set of *characters*, i.e. complex-valued functions of the form $\gamma \in \pi \mapsto \text{tr}^2(\rho(\gamma))$.

The affine set $\mathcal{X}(S)$ splits into two irreducible components $\mathcal{X}(S)_l \cup \mathcal{X}(S)_r$, where elements of $\mathcal{X}(S)_l$ are characters of representations that lift to $SL(2, \mathbb{C})$.

The set-theoretic quotient $\mathcal{R}(S)/G$ is rather complicated, but G acts freely and properly on the subset $\mathcal{R}(S)^s$ of irreducible²² (“stable”) representations, so that the quotient $\mathcal{R}(S)^s/G$ is a complex manifold. Furthermore, an irreducible representation is determined by its character, so that $\mathcal{X}(S)^s := \mathcal{R}(S)^s/G$ embeds (as a Zariski-dense open subset) in the smooth locus of $\mathcal{X}(S)$. Its dimension is $6g - 6$. Let us mention that more generally, $\mathcal{X}(S)$ is in bijection with the set of orbits of “semistable” (i.e. reductive²³) representations.

It is relatively easy to see that the Zariski tangent space at a point $\rho \in \mathcal{R}(S)$ is described as the space of crossed homomorphisms $Z^1(\pi, \mathfrak{g}_{\text{Ad}\rho})$ (i.e. 1-cocycles in the sense of group cohomology), specifically maps $u : \pi \rightarrow \mathfrak{sl}_2(\mathbb{C})$ such that $u(\gamma_1\gamma_2) = u(\gamma_1) + \text{Ad}_{\rho(\gamma_1)}u(\gamma_2)$ ²⁴. The subspace corresponding to the tangent space of the G -orbit of ρ is the space of principal crossed homomorphisms $B^1(\pi, \mathfrak{g}_{\text{Ad}\rho})$ (i.e.

²² A representation $\rho : \pi \rightarrow PSL_2(\mathbb{C})$ is called *irreducible* if it fixes no point in \mathbb{CP}^1 .

²³ A nontrivial representation $\rho : \pi \rightarrow PSL_2(\mathbb{C})$ is called *reductive* if it is either irreducible or it fixes a pair of distinct points in \mathbb{CP}^1 .

²⁴ where of course $\text{Ad} : G \rightarrow \text{Autg}$ is the adjoint representation.

1-coboundaries in the sense of group cohomology), specifically maps $u : \pi \rightarrow \mathfrak{sl}_2(\mathbb{C})$ such that $u(\gamma) = \text{Ad}_{\rho(\gamma)}u_0 - u_0$ for some $u_0 \in \mathfrak{sl}_2(\mathbb{C})$. Hence for (at least) smooth points $[\rho] \in \mathcal{X}(S)$, the tangent space is given by $T_{[\rho]}\mathcal{X}(S) = H^1(\pi, \mathfrak{g}_{\text{Ad}\rho})$.

4.2 The complex symplectic structure on the character variety

By the general construction of [Gol84], the character variety enjoys a complex symplectic structure defined in this situation as follows.

Recall that the Lie algebra $\mathfrak{g} = \mathfrak{sl}_2(\mathbb{C})$ is equipped with its complex Killing form B . It is a non-degenerate complex bilinear symmetric form preserved by G under the adjoint action. Let $\tilde{B} = \frac{1}{4}B$, it is explicitly given by $\tilde{B}(u, v) = \text{tr}(uv)$ where $u, v \in \mathfrak{sl}_2(\mathbb{C})$ are represented by trace-free 2×2 matrices.

One can compose the standard cup-product in group cohomology with \tilde{B} ²⁵ as “coefficient pairing” to get a dual pairing

$$H^1(\pi, \mathfrak{g}_{\text{Ad}\rho}) \times H^1(\pi, \mathfrak{g}_{\text{Ad}\rho}) \xrightarrow{\cup} H^2(\pi, \mathfrak{g}_{\text{Ad}\rho} \otimes \mathfrak{g}_{\text{Ad}\rho}) \xrightarrow{\tilde{B}} H^2(\pi, \mathbb{C}) \cong \mathbb{C}. \quad (20)$$

This pairing defines a non-degenerate complex bilinear alternate 2-form on the complex vector space $H^1(\pi, \mathfrak{g}_{\text{Ad}\rho}) \approx T_{[\rho]}\mathcal{X}(S)$. It globalizes into a non-degenerate 2-form ω_G on $\mathcal{X}(S)^s$. By arguments of Goldman ([Gol84]) following Atiyah-Bott ([AB83]) this form is closed, in other words it is a complex symplectic form on the smooth quasi-affine variety $\mathcal{X}(S)^s$ ²⁶.

4.3 Holonomy of projective structures

Just like any geometric structure, a complex projective structure Z defines a *developing map* and a *holonomy representation* (see e.g. [Thu97]). The developing map is a locally injective projective map $f : \tilde{Z} \rightarrow \mathbb{CP}^1$ and it is equivariant with respect to the holonomy representation $\rho : \pi \rightarrow PSL_2(\mathbb{C})$ in the sense that $f \circ \gamma = \rho(\gamma) \circ f$ for any $\gamma \in \pi$.

Holonomy of complex projective structures defines a map

$$\text{hol} : \mathcal{CP}(S) \rightarrow \mathcal{X}(S).$$

It is differentiable and its differential is “the identity map” in the sense that it is the canonical identification

$$d\text{hol} : T_Z\mathcal{CP}(S) = \check{H}^1(Z, \Xi_Z) \xrightarrow{\sim} H^1(\pi, \mathfrak{g}_{\text{Ad}\rho}) = T_{[\text{hol}(Z)]}\mathcal{X}(S).$$

A consequence of this observation is that hol is a local biholomorphism.

The holonomy representation ρ of a complex projective structure satisfies the following properties:

²⁵It would look somewhat more natural to use the actual Killing form B instead of $\tilde{B} = \frac{1}{4}B$, but we choose to go with \tilde{B} because it is the convention used by most authors. Moreover, it gives a slightly simpler expression of our theorems 6.10, 6.15 and 6.19.

²⁶In fact, it defines an algebraic tensor on the whole character variety, see [Gol84].

- ρ is liftable to $SL_2(\mathbb{C})$ (a lift is provided by the monodromy of the Schwarzian equation). The image of the holonomy map thus lies in the irreducible component $\mathcal{X}(S)_I$ of $\mathcal{X}(S)$.
- The action of $\Gamma := \rho(\pi)$ on hyperbolic 3-space \mathbb{H}^3 does not fix any point or ideal point, nor does it preserve any geodesic. Representations having this property are called non-elementary. They are in particular irreducible representations, hence smooth points of the character variety as expected.

Conversely, Gallo-Kapovich-Marden showed that any non-elementary liftable representation is the holonomy of a complex projective structure ([GKM00]).

Although the holonomy map $hol : \mathcal{CP}(S) \rightarrow \mathcal{X}(S)$ is a local biholomorphism, it is neither injective nor a covering onto its image ([Hej75]). Nonetheless, we get a complex symplectic structure on $\mathcal{CP}(S)$ simply by pulling back that of $\mathcal{X}(S)^s$ by the holonomy map. Abusing notations, we will still call this symplectic structure ω_G . Alternatively, one could directly define ω_G on $\mathcal{CP}(S)$ in terms of the exterior product of 1-forms with values in some flat bundle (recall that $T_Z\mathcal{CP}(S) = \check{H}^1(Z, \Xi_Z)$, where Ξ_Z is the sheaf of projective vector fields on Z , see section 2.1). We will consider ω_G as the *standard complex symplectic structure on $\mathcal{CP}(S)$* (notably because it does not depend on any choice).

4.4 Fuchsian structures and a theorem of Goldman

Let $\mathcal{F}(S)$ be the space of marked hyperbolic structures on S (we abusively use the same notation as for the Fuchsian space). More precisely, $\mathcal{F}(S)$ is the space of complete hyperbolic metrics on S quotiented by $\text{Diff}_0^+(S)$. In terms of geometric structures, $\mathcal{F}(S)$ is the deformation space of $(\mathbb{H}^2, PSL_2(\mathbb{R}))$ -structures on S (this is a consequence of Cartan-Hadamard's theorem). Holonomy identifies $\mathcal{F}(S)$ as the connected component of the character variety $\mathcal{X}(S, PSL_2(\mathbb{R}))$ corresponding to faithful and discrete representations. $\mathcal{F}(S)$ is sometimes called the Fricke space of S .

The uniformization theorem states that there is a unique hyperbolic metric in each conformal class of Riemannian metrics on S . Since S is oriented, the choice of a conformal structure on S is equivalent to that of a complex structure on S . The uniformization theorem thus provides a bijective map

$$u : \mathcal{T}(S) \rightarrow \mathcal{F}(S) .$$

By definition of the Fuchsian section $\sigma_{\mathcal{F}}$, the map u is precisely identified as $\sigma_{\mathcal{F}}$ if hyperbolic structures are considered as special examples of complex projective structures. Putting it differently, the following diagram commutes:

$$\begin{array}{ccc}
 \mathcal{CP}(S) & \xrightarrow{\quad hol \quad} & \mathcal{X}(S, PSL_2(\mathbb{C})) \\
 \sigma_{\mathcal{F}} \uparrow & & \uparrow \iota \\
 \mathcal{T}(S) & \xrightarrow{\quad u \quad} & \mathcal{F}(S) \hookrightarrow \mathcal{X}(S, PSL_2(\mathbb{R})) .
 \end{array} \tag{21}$$

It is derived from this diagram that $\sigma_{\mathcal{F}}$ is a maximal totally real²⁷ analytic embedding of $\mathcal{T}(S)$ in $\mathcal{CP}(S)$.

By Goldman's general construction in [Gol84] (described above in the case of $G = PSL_2(\mathbb{C})$), $\mathcal{X}(S, PSL_2(\mathbb{R}))$ is equipped with a real symplectic structure $\omega_{G, PSL_2(\mathbb{R})}$. Of course it is just the restriction of the symplectic structure $\omega_G = \omega_{G, PSL_2(\mathbb{C})}$ on $\mathcal{X}(S, PSL_2(\mathbb{R}))$. Recall that $\mathcal{T}(S)$ is also equipped with a symplectic structure, the Weil-Petersson Kähler form ω_{WP} . In the same paper, Goldman shows that they are the same. More precisely, this is expressed in our setting as follows:

Theorem 4.2 (Goldman [Gol84]).

$$(\sigma_{\mathcal{F}})^* \omega_G = \omega_{WP} . \quad (22)$$

4.5 A Lagrangian embedding

Let \hat{M} be a compact 3-manifold as in section 2.3. We will use here the same notations as in section 2.3, let us briefly recall these. The boundary $\partial\hat{M}$ is the disjoint union of N surfaces S_k of genera at least 2. The Teichmüller space of the boundary is given by $\mathcal{T}(\partial\hat{M}) = \mathcal{T}(S_1) \times \cdots \times \mathcal{T}(S_N)$, and similarly $\mathcal{CP}(\partial\hat{M}) = \mathcal{CP}(S_1) \times \cdots \times \mathcal{CP}(S_N)$. The forgetful projection is the holomorphic map $p = p_1 \times \cdots \times p_N : \mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{T}(\partial\hat{M})$, and $\beta : \mathcal{T}(\partial\hat{M}) \rightarrow \mathcal{CP}(\partial\hat{M})$ is the ‘‘simultaneous uniformization section’’.

By Goldman's construction discussed above, $\mathcal{CP}(\partial\hat{M})$ is equipped with a complex symplectic structure ω_G , which is obtained here as

$$\omega_G = \text{pr}_1^* \omega_G^{(1)} + \cdots + \text{pr}_N^* \omega_G^{(N)} , \quad (23)$$

where $\omega_G^{(k)}$ is the complex symplectic structure on $\mathcal{CP}(S_k)$ and pr_k is the k^{th} projection map $\mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{CP}(S_k)$.

There is a general argument, discovered in this setting by Steven Kerckhoff, which shows that

Theorem 4.3. $\beta : \mathcal{T}(\partial\hat{M}) \rightarrow \mathcal{CP}(\partial\hat{M})$ is a Lagrangian embedding.

Although this is a consequence of our theorem 6.14, we briefly explain this nice argument, based on Poincaré duality in cohomology. This could be done directly on the manifolds $\mathcal{HC}(M)$ and $\mathcal{CP}(\partial\hat{M})$, but we prefer to transport the situation to character varieties, where it is simpler.

Recall that the simultaneous uniformization section β was defined as the composition $\beta = \psi \circ \varphi^{-1}$, where $\psi : \mathcal{HC}(M) \rightarrow \mathcal{CP}(\partial\hat{M})$ is the map which assigns the induced projective structure on $\partial\hat{M}$ to each cocompact hyperbolic structure on the interior M of \hat{M} , and $\varphi = p \circ \psi : \mathcal{HC}(M) \rightarrow \mathcal{T}(\partial\hat{M})$ is a biholomorphism. By definition, the embedding β is Lagrangian if it is isotropic ($\beta^* \omega_G = 0$) and $\dim \mathcal{CP}(\partial\hat{M}) = 2 \dim \mathcal{T}(\partial\hat{M})$. We already know the second statement to be true

²⁷see section 6.1 for a definition of this notion and a different argument for this fact.

(see section 2.1). It remains to show that β is isotropic, but since ϕ is a diffeomorphism, this amounts to showing that $\psi : \mathcal{HC}(M) \rightarrow \mathcal{CP}(\partial\hat{M})$ is isotropic.

Let us have a look at the equivalent statement on holonomy: there is a commutative diagram

$$\begin{array}{ccc} \mathcal{HC}(M) & \xrightarrow{\psi} & \mathcal{CP}(\partial\hat{M}) \\ \downarrow \text{hol} & & \downarrow \text{hol} \\ \hat{\mathcal{X}}(M, PSL_2(\mathbb{C})) & \xrightarrow{f} & \mathcal{X}(\partial\hat{M}, PSL_2(\mathbb{C})) \end{array} ,$$

where $f : \mathcal{X}(M, PSL_2(\mathbb{C})) \rightarrow \mathcal{X}(\partial\hat{M}, PSL_2(\mathbb{C}))$ is the map between character varieties induced by the “restriction” map $\iota_* : \pi_1(\partial\hat{M}) \rightarrow \pi_1(\hat{M})$ ²⁸. Since the property of being isotropic is local, it is enough to show the following proposition:

Proposition 4.4. *The map $f : \mathcal{X}(\hat{M}, PSL_2(\mathbb{C})) \rightarrow \mathcal{X}(\partial\hat{M}, PSL_2(\mathbb{C}))$ is isotropic.*

Proof. Let $[\rho] \in \mathcal{X}(\hat{M}, PSL_2(\mathbb{C}))$. The map

$$df : T_{[\rho]} \mathcal{X}(\hat{M}, PSL_2(\mathbb{C})) \rightarrow T_{[\rho \circ \iota_*]} \mathcal{X}(\partial\hat{M}, PSL_2(\mathbb{C}))$$

is the map α that appears in long exact sequence in cohomology of the pair $(M, \partial M)$ as follows. This exact diagram shows a piece of this sequence written in terms of group cohomology, where vertical arrows are given by Poincaré duality:

$$\begin{array}{ccccc} H^1(\pi_1(\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho}) & \xrightarrow{\alpha} & H^1(\pi_1(\partial\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho}) & \xrightarrow{\beta} & H^2(\pi_1(\hat{M}), \pi_1(\partial\hat{M}); \mathfrak{g}_{\text{Ad}\circ\rho}) \\ \downarrow & & \downarrow & & \downarrow \\ H^2(\pi_1(\hat{M}), \pi_1(\partial\hat{M}); \mathfrak{g}_{\text{Ad}\circ\rho})^* & \xrightarrow{\beta^*} & H^1(\pi_1(\partial\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho})^* & \xrightarrow{\alpha^*} & H^1(\pi_1(\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho})^* \end{array}$$

Note that if $u \in H^1(\pi_1(\partial\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho})$, the Poincaré dual of u is defined by the relation $\langle u^*, v \rangle = \tilde{B}(u \cup v) \cap [\partial\hat{M}]$ for all $v \in H^1(\pi_1(\partial\hat{M}), \mathfrak{g}_{\text{Ad}\circ\rho})$, where $[\partial\hat{M}]$ is the fundamental class of $\partial\hat{M}$. This is precisely saying that $\langle u^*, v \rangle = \omega_G(u, v)$. It follows that α is isotropic: using the commutativity and exactness of the diagram, we can write

$$\begin{aligned} \omega_G(\alpha(u), \alpha(v)) &= \langle \alpha(u)^*, \alpha(v) \rangle \\ &= \langle \beta^*(u^*), \alpha(v) \rangle \\ &= \langle u^*, \beta \circ \alpha(v) \rangle \\ &= 0 . \end{aligned}$$

□

²⁸Note that if $\partial\hat{M}$ is disconnected, we define its fundamental group $\pi_1(\partial\hat{M})$ as the free product of the fundamental groups of its components, so that a representation $\rho : \pi_1(\partial\hat{M}) \rightarrow PSL_2(\mathbb{C})$ is just a N -tuple of representations $\rho_k : \pi_1(S_k) \rightarrow PSL_2(\mathbb{C})$.

Remark 4.5. Note that in the quasi-Fuchsian situation $M = S \times \mathbb{R}$, Theorem 4.3 is trivial, or rather its formulation in terms of holonomy (cf. Proposition 4.4 above). Indeed, the map $f : \mathcal{X}(\hat{M}, PSL_2(\mathbb{C})) \rightarrow \mathcal{X}(\partial\hat{M}, PSL_2(\mathbb{C}))$ in that case is just the diagonal embedding of $\mathcal{X}(\pi, PSL_2(\mathbb{C}))$ ²⁹ into $\mathcal{X}(\pi, PSL_2(\mathbb{C})) \times \mathcal{X}(\pi, PSL_2(\mathbb{C}))$ ³⁰.

5 Complex Fenchel-Nielsen coordinates and Platis' symplectic structure

5.1 Fenchel-Nielsen coordinates on Teichmüller space and Wolpert theory

Pants decomposition and Fenchel-Nielsen coordinates

In this paragraph, we consider the Fuchsian (or Fricke) space $\mathcal{F}(S)$ of marked hyperbolic structures on S (or marked Fuchsian projective structures) rather than Teichmüller space of $\mathcal{T}(S)$ (see section 4.4). Let us first briefly recall the construction of the classical Fenchel-Nielsen coordinates on $\mathcal{F}(S)$, as it will be useful for the subsequent paragraphs. These depend on the choice of a *pants decomposition* of S , *i.e.* an ordered maximal collection of distinct, disjoint³¹, nontrivial free homotopy classes of simple³² closed curves $\alpha = (\alpha_1, \dots, \alpha_N)$.

The following are classical facts:

- $N = 3g - 3$.
- If c_1, \dots, c_N are disjoint representatives of $\alpha_1, \dots, \alpha_N$ (respectively), then $S \setminus \bigcup_{i=1}^N c_i$ is a disjoint union of $M = 2g - 2$ topological pair of pants P_k (thrice-punctured spheres).
- If X is a hyperbolic structure on S , every nontrivial free homotopy class of simple closed curves γ is uniquely represented by a simple closed geodesic γ^X .

Given a hyperbolic structure X on S , denote by $l_\gamma(X)$ the hyperbolic length of γ^X . This defines a *length function* $l_\gamma : \mathcal{F}(S) \rightarrow \mathbb{R}_{>0}$. In particular, given a pants decomposition α , one gets a function $l_\alpha : \mathcal{F}(S) \rightarrow (\mathbb{R}_{>0})^N$. The components l_{α_i} of l_α are called the *Fenchel-Nielsen length parameters*.

²⁹where $\pi = \pi_1(\hat{M}) = \pi_1(S)$.

³⁰Here $\mathcal{X}(\pi, PSL_2(\mathbb{C})) \times \mathcal{X}(\pi, PSL_2(\mathbb{C}))$ is equipped with with the complex symplectic structure $\text{pr}_1^* \omega_G - \text{pr}_2^* \omega_G$ (the minus sign is due to the opposite orientation of $\partial^+ \hat{M}$ and $\partial^- \hat{M}$). The fact that the diagonal is Lagrangian is a particular case of the following general fact: if (X, ω) is a symplectic manifold and $X \times X$ is equipped with the symplectic structure $\text{pr}_1^* \omega - \text{pr}_2^* \omega$, then the graph of a function $h : X \rightarrow X$ is a Lagrangian submanifold of $X \times X$ if and only if h is a symplectomorphism.

³¹in the sense that for $j \neq k$, there exists disjoint representatives of α_j and α_k .

³²meaning that there exist simple representatives.

Any hyperbolic structure X on S induces a hyperbolic structure (with geodesic boundary) on each one of the closed pair of pants $\overline{P_k}$ in the decomposition $S \setminus \bigcup_{i=1}^N \alpha_i^X = \bigsqcup_{k=1}^M P_k$. It is well-known that a hyperbolic structure on a closed pair of pants is uniquely determined by the lengths of its three boundary components. This follows from the observation that a hyperbolic pair of pants is obtained by gluing two isometric oppositely oriented right-angled hexagons in \mathbb{H}^2 and the following elementary theorem in plane hyperbolic geometry:

Proposition 5.1. *Up to isometry, there exists a unique right-angled hexagon in \mathbb{H}^2 with prescribed lengths on every other side.*

As a consequence, a hyperbolic structure on S is completely determined by the lengths of the curves α_i , and the parameters τ_i that prescribe how the gluing occurs along these curves, *i.e.* by which amount of “twisting”. However, these parameters τ_i are not very well defined: there is no obvious choice of the hyperbolic structure obtained by “not twisting at all before gluing”. Also, note that assuming that such a choice is made, each of these parameters should live in \mathbb{R} indeed and not $\mathbb{R}/2\pi\mathbb{Z}$: although there is a natural isometry $f : X \rightarrow Y$ where Y is obtained by 2π -twisting X along some curve α_i , f is not homotopic to the identity.

Let us make this more precise. For any nontrivial free homotopy class of simple closed curves γ , there is a flow (an \mathbb{R} -action) called *twisting along γ*

$$\text{tw}_\gamma : \mathbb{R} \times \mathcal{F}(S) \rightarrow \mathcal{F}(S) . \quad (24)$$

The flow is freely transitive in the fibers of l_γ . Let us mention that twist deformations along simple closed curves are naturally generalized first to weighted multicurves, then to the completion $\mathcal{ML}(S)$ of measured laminations. This generalization is the notion of *earthquake* introduced by Thurston (see e.g. [Ker83]).

Denote by tw_α the \mathbb{R}^N -action $\text{tw}_\alpha = (\text{tw}_{\alpha_1}, \dots, \text{tw}_{\alpha_N}) : \mathbb{R}^N \times \mathcal{F}(S) \rightarrow \mathcal{F}(S)$. The fact that a hyperbolic structure on S is uniquely determined by the lengths parameters l_{α_i} and the amount of twisting along each α_i is precisely stated as: the \mathbb{R}^N -action tw_α is freely transitive in the fibers of l_α , and the reunion of these fibers is the whole Fricke space $\mathcal{F}(S)$. In particular,

Theorem 5.2. *Choosing a smooth section to l_α determines a diffeomorphism*

$$(l_\alpha, \tau_\alpha) : \mathcal{F}(S) \rightarrow (\mathbb{R}_{>0})^N \times \mathbb{R}^N .$$

The function τ above is naturally defined by $\text{tw}_\alpha(\tau_\alpha, \sigma \circ l_\alpha) = \text{id}_{\mathcal{F}(S)}$, where σ is the chosen section. The components $\tau_{\alpha_1}, \dots, \tau_{\alpha_N}$ of τ are called the *Fenchel-Nielsen twist parameters*. The theorem above thus says that Fenchel-Nielsen length and twist parameters are global coordinates on $\mathcal{F}(S)$. In particular, one recovers $\dim_{\mathbb{R}} \mathcal{T}(S) = \dim_{\mathbb{R}} \mathcal{F}(S) = 2N = 6g - 6$. It also appears that $\mathcal{T}(S) \approx \mathcal{F}(S)$ is topologically a cell, and it follows that $\mathcal{CP}(S)$ is also a cell.

Note that although the coordinates τ_{α_i} depend on the choice on a section to l_α , the 1-forms $d\tau_{\alpha_i}$ and the vector fields $\frac{\partial}{\partial \tau_{\alpha_i}}$ do not. In fact, $\frac{\partial}{\partial \tau_\gamma}$ is well-defined for any nontrivial free homotopy class of simple closed curve γ , and its flow is of course the twist flow $\text{tw}_\gamma : \mathbb{R} \times \mathcal{F}(S) \rightarrow \mathcal{F}(S)$.

Wolpert theory

We recall a few notions of symplectic geometry and the language of Hamiltonian mechanics. If (M^{2N}, ω) is a symplectic manifold, ω determines a bundle map $\omega^\flat : TM \rightarrow T^*M$ defined by $\omega^\flat(u) = \omega(u, \cdot)$. Since ω is non-degenerate, ω^\flat is an isomorphism, its inverse is denoted by $\omega^\sharp : T^*M \rightarrow TM$. If α is a one-form on M , $\omega^\sharp(\alpha)$ is thus the unique vector field X such that $i_X\omega = \alpha$. If f is a function on M , the vector field $X_f := \omega^\sharp(df)$ is called the *Hamiltonian* (or symplectic gradient) of f . Note that a vector field X is Hamiltonian if and only if the 1-form $i_X\omega$ ³³ is exact, it follows that X satisfies $\mathcal{L}_X\omega = 0$ ³⁴ by Cartan's magic formula. Vector fields X such that $\mathcal{L}_X\omega = 0$ are the vector fields whose flows preserve ω , they are called symplectic vector fields. The *Poisson bracket* of two functions f and g is defined by $\{f, g\} = \omega(X_f, X_g)$. f and g are said to Poisson-commute (or to be in involution) if $\{f, g\} = 0$. It is easy to see that f and g Poisson-commute if and only if f is constant along the integral curves of X_g (and vice-versa). If $f = (f_1, \dots, f_N) : M \rightarrow \mathbb{R}^N$ is a regular map such that the f_i Poisson-commute, then f is a Lagrangian fibration. Moreover, the flows of the $-X_{f_i}$ (if they are complete) define a transitive \mathbb{R}^N -action that is transverse to the fibers of f (the reason for the choice of this minus sign will be apparent shortly). Notice already the analogy with the lengths functions and twist flows above. Such functions f_i are said to define a (*completely*) *integrable Hamiltonian system* on (M, ω) . As in theorem 5.2, choosing a section to f yields coordinates $g = (g_1, \dots, g_N) : M \rightarrow \mathbb{R}^N$ ³⁵ such that the \mathbb{R}^N -action is given by the flows of the $\frac{\partial}{\partial g_i}$, in other words $\frac{\partial}{\partial g_i} = -X_{f_i}$. In general though, (f_i, g_i) is not a system of Darboux coordinates ³⁶ for ω , but the classical Arnold-Liouville theorem states that such a choice of coordinates is possible in a way that is compatible with the Lagrangian fibration and the \mathbb{R}^N -action (see e.g. [Dui80] for a precise statement and proof of this theorem). The Darboux coordinates obtained by Arnold-Liouville's theorem are called *action-angle coordinates*.

In [Wol82], [Wol83] and [Wol85], Wolpert developed a very nice theory describing the symplectic geometry of $\mathcal{F}(S)$ in relation to Fenchel-Nielsen coordinates. Let us present some of his results. In the following, $\mathcal{F}(S)$ is equipped with its standard symplectic structure $\omega_G (= \omega_{WP}$ under the identification $\mathcal{T}(S) \approx \mathcal{F}(S)$, see section 4.4).

Theorem 5.3 (Wolpert). *Let γ be any nontrivial free homotopy class of simple closed curves on S . The flow of the Hamiltonian vector field $-X_{\iota_\gamma}$ is precisely the twist flow tw_γ .*

³³ where $i_X\omega$ is the contraction of ω with the vector field X .

³⁴ where \mathcal{L}_X is the Lie derivative along the vector field X .

³⁵ To be accurate, g takes values in $\mathbb{R}^{N-k} \times \mathbb{T}^k$ in general, where k is some integer and \mathbb{T}^k is the k -dimensional torus.

³⁶ By definition, (f_i, g_i) are called *Darboux coordinates* on (M, ω) if they are canonical for the symplectic structure: $\omega = \sum_{i=1}^N df_i \wedge dg_i$. The celebrated theorem of Darboux says that there always exists Darboux coordinates locally on any symplectic manifold.

In other words,

$$\frac{\partial}{\partial \tau_\gamma} = -X_{l_\gamma} . \quad (25)$$

Theorem 5.4 (Wolpert). *Let γ and γ' be distinct nontrivial free homotopy classes of simple closed curves on S . Then at any point $X \in \mathcal{F}(S)$,*

$$\omega_G \left(\frac{\partial}{\partial \tau_\gamma}, \frac{\partial}{\partial \tau_{\gamma'}} \right) = \sum_{p \in (\gamma^X \cap \gamma'^X)} \cos \theta_p , \quad (26)$$

where θ_p is the angle between the geodesics γ^X and γ'^X at p .

A direct consequence of these two theorems is:

Theorem 5.5. *If α is a pants decomposition of S , then Fenchel-Nielsen length functions l_{α_i} define an integrable Hamiltonian system. The Hamiltonian \mathbb{R}^N -action associated to this system is the twist flow tw_γ .*

Wolpert also shows that

Proposition 5.6 (Wolpert). *If α is a pants decomposition of S , then for any $i, j \in \{1, \dots, N\}$*

$$\omega_G \left(\frac{\partial}{\partial l_{\alpha_i}}, \frac{\partial}{\partial l_{\alpha_j}} \right) = 0 . \quad (27)$$

It follows that we are in the best possible situation:

Theorem 5.7 (Wolpert). *Let α be a pants decomposition of S . Fenchel-Nielsen length and twist parameters associated to α are respectively action and angle variables for the integrable Hamiltonian system defined by the functions l_{α_i} . In particular, Fenchel-Nielsen coordinates are Darboux coordinates for the symplectic structure:*

$$\omega_G = \sum_{i=1}^N dl_{\alpha_i} \wedge d\tau_{\alpha_i} . \quad (28)$$

It is remarkable in particular that this does not depend on the choice of the pants decomposition α .

5.2 Complex Fenchel-Nielsen coordinates

Kourouniotis (in [Kou94], see also [Kou91] and [Kou92]) and Tan (in [Tan94]) introduced a system of global holomorphic coordinates $(l^{\mathbb{C}}, \tau^{\mathbb{C}}) : \mathcal{QF}(S) \rightarrow \mathbb{C}^N \times \mathbb{C}^N$ that can be thought of as a complexification of Fenchel-Nielsen coordinates on the Fuchsian slice $\mathcal{F}(S)$. We outline this construction and refer to [Kou94], [Tan94] and also [Ser01] for details.

Complex distance and displacement in hyperbolic space

Let α and β be two geodesics in the hyperbolic space \mathbb{H}^3 . The *complex distance* between α and β is the complex number $\sigma = \sigma(\alpha, \beta)$ (defined modulo $2i\pi\mathbb{Z}$) such that $\operatorname{Re}(\sigma)$ is the hyperbolic distance between α and β and $\operatorname{Im}(\sigma)$ is the angle between them (meaning the angle between the two planes containing their common perpendicular and either α or β). In the upper half-space model $\mathbb{H}^3 = \mathbb{C} \times \mathbb{R}_+^*$, after applying an isometry so that α has endpoints $(u, -u)$ and β has endpoints $(p, -p)$ (where $u, p \in \mathbb{CP}^1$), σ is determined by $e^\sigma u = p$. Note that one has to be careful about orientations and sign to define σ unambiguously, see [Kou94] and [Ser01] for details.

Let f be a non-parabolic isometry of \mathbb{H}^3 different from the identity, and β a geodesic perpendicular to the axis of f . The *complex displacement* of f is the complex distance φ between β and $f(\beta)$. If f is represented by a matrix $A \in SL_2(\mathbb{C})$, the complex displacement of f is given by

$$2 \cosh\left(\frac{\varphi}{2}\right) = \operatorname{tr}(A). \quad (29)$$

The complex displacement and oriented axis of a non-parabolic isometry determine it uniquely.

Right-angled hexagons and pair of pants in hyperbolic space

An (oriented skew) *right-angled* hexagon in \mathbb{H}^3 is a cyclically ordered set of six oriented geodesics α_k indexed by $k \in \mathbb{Z}/6\mathbb{Z}$, such that α_k intersects α_{k+1} orthogonally. Define the complex length of the “side” α_k by $\sigma_k = \sigma(\alpha_{k-1}, \alpha_{k+1})$.

Proposition 5.8. *The following relations are showed in [Fen89]:*

Sine rule:

$$\frac{\sinh \sigma_1}{\sinh \sigma_4} = \frac{\sinh \sigma_3}{\sinh \sigma_6} = \frac{\sinh \sigma_5}{\sinh \sigma_2} \quad (30)$$

Cosine rule:

$$\cosh \sigma_n = \frac{\cosh \sigma_{n+3} - \cosh \sigma_{n+1} \cosh \sigma_{n-1}}{\sinh \sigma_{n+1} \sinh \sigma_{n-1}} \quad (31)$$

Using these formulas, one shows that assigning complex lengths on every other side determines a unique right-angled hexagon in \mathbb{H}^3 up to (possibly orientation-reversing) isometry. In [Kou94] and [Tan94], it is showed the the construction of a hyperbolic pair of pants by gluing two right-angled hexagons can be extended to \mathbb{H}^3 . Such a pair of pants is thus uniquely determined by the complex lengths of its boundary components. In terms of holonomy ([Kou94]):

Proposition 5.9. *Let P be a topological pair of pants and $\sigma_1, \sigma_2, \sigma_3 \in \mathbb{C}_+$ (i.e. with $\operatorname{Re}(\sigma_i) > 0$). There is a unique representation up to conjugation*

$$\rho : \pi_1(P) = \langle c_1, c_2, c_3 \mid c_1 c_2 c_3 = 1 \rangle \rightarrow PSL_2(\mathbb{C})$$

such that $\operatorname{tr}(\rho(c_i)) = -2 \cosh \sigma_i$.

Complex lengths and complex twisting in the quasi-Fuchsian space

Let $Z \in \mathcal{QF}(S)$ be a quasi-Fuchsian structure on S and $\rho : \pi_1(S) \rightarrow PSL_2(\mathbb{C})$ its holonomy representation. For any nontrivial free homotopy class of simple closed curves γ , define the *complex length* of γ as the complex displacement of the hyperbolic isometry $\rho(\gamma)$. This defines a holomorphic function $l_\gamma^{\mathbb{C}} : \mathcal{QF}(S) \rightarrow \mathbb{C}_+$. In the quasi-Fuchsian 3-manifold M , $\rho(\gamma)$ corresponds to a geodesic of complex length $l_\gamma^{\mathbb{C}}$, *i.e.* of hyperbolic length $\operatorname{Re}(l_\gamma^{\mathbb{C}})$ and torsion $\operatorname{Im}(l_\gamma^{\mathbb{C}})$. It is easy to see that if Z is a Fuchsian structure, then $l_\gamma^{\mathbb{C}}(Z) = l_\gamma(Z)$. If $\alpha = (\alpha_1, \dots, \alpha_N)$ is a pants decomposition of S , we call

$$l_\alpha^{\mathbb{C}} = (l_{\alpha_1}^{\mathbb{C}}, \dots, l_{\alpha_N}^{\mathbb{C}}) : \mathcal{QF}(S) \rightarrow (\mathbb{C}_+)^N \quad (32)$$

the *complex Fenchel-Nielsen length parameters*.

As a consequence of the previous discussion, if the complex lengths $l_{\alpha_1}^{\mathbb{C}}, \dots, l_{\alpha_N}^{\mathbb{C}}$ are fixed, a quasi-Fuchsian structure on S is determined by how the gluings of pair of pants occur along their common boundaries. Analogously to the Fuchsian case, this is prescribed by a complex parameter $\tau_{\alpha_i}^{\mathbb{C}}$, that we will call a complex twist parameter, that describes both the amount of twisting (by $\operatorname{Re}(\tau_{\alpha_i}^{\mathbb{C}})$) and the amount of bending (by $\operatorname{Im}(\tau_{\alpha_i}^{\mathbb{C}})$) before gluing. $\tau_{\alpha_i}^{\mathbb{C}}$ can be more or less well defined as the complex distance between two adequate geodesics in \mathbb{H}^3 , but the definition is clearer in terms of the effect of complex-twisting by $\tau_{\alpha_i}^{\mathbb{C}}$ on the holonomy of the glued pairs of pants (see [Kou94], [Gol04]).

As in the Fuchsian case, it is the complex twist flow $\operatorname{tw}_\gamma^{\mathbb{C}}$ along a simple closed curve γ that is well-defined rather than the twist parameter $\tau_{\alpha_i}^{\mathbb{C}}$ itself, although the complex twist vector field $\frac{\partial}{\partial \tau_\gamma^{\mathbb{C}}}$ is well-defined. Let us mention this flow is called *bending* by Kourouniotis and corresponds to (or is a generalization of) what other authors have called *quakebends* or *complex earthquakes* discussed by Epstein-Marden [EM87], Goldman [Gol04], McMullen [McM98], Series [Ser01] among others. It is not hard to see that starting from a Fuchsian structure Z , complex twisting by $t = t_1 + it_2 \in \mathbb{C}$ is described as the composition of twisting by t_1 on $\mathcal{F}(S)$ and then *projective grafting* by t_2 (see e.g. [Dum09] for a presentation of projective grafting).

Choosing a holomorphic section to $l_\alpha^{\mathbb{C}}$ determines *complex twist coordinates* $\tau_\alpha^{\mathbb{C}} = (\tau_{\alpha_1}^{\mathbb{C}}, \dots, \tau_{\alpha_N}^{\mathbb{C}}) : \mathcal{QF}(S) \rightarrow \mathbb{C}^N$. We will call $(l_\alpha^{\mathbb{C}}, \tau_\alpha^{\mathbb{C}})$ complex Fenchel-Nielsen coordinates. The conclusion of our discussion is the theorem:

Theorem 5.10 (Kourouniotis, Tan). *Complex Fenchel-Nielsen coordinates $(l_\alpha^{\mathbb{C}}, \tau_\alpha^{\mathbb{C}})$ are global holomorphic coordinates on $\mathcal{QF}(S)$. They restrict to the classical Fenchel-Nielsen coordinates (l_α, τ_α) on the Fuchsian slice $\mathcal{F}(S)$.*

5.3 Platis' symplectic structure

In [Pla01], Platis develops a complex version of Wolpert's theory on the quasi-Fuchsian space, here are some of his results.

First there is a complex version of Wolpert's formula 5.4:

Theorem 5.11. *There exists a complex symplectic structure ω_P on $\mathcal{QF}(S)$ such that if γ and γ' are distinct nontrivial free homotopy classes of simple closed curves on S , then at any point $Z \in \mathcal{QF}(S)$ with holonomy ρ*

$$\omega_P \left(\frac{\partial}{\partial \tau_\gamma^{\mathbb{C}}}, \frac{\partial}{\partial \tau_{\gamma'}^{\mathbb{C}}} \right) = \sum_{p \in (\gamma \cap \gamma')} \cosh \sigma_p, \quad (33)$$

where σ_p is the complex distance between the geodesics $\rho(\gamma)$ and $\rho(\gamma')$.

He also shows the complex analogous of theorem 5.3 in the complex symplectic manifold $(\mathcal{QF}(S), \omega_P)$:

Theorem 5.12. *Let γ be any nontrivial free homotopy class of simple closed curves on S . The complex flow of the Hamiltonian vector field $-X_{I_\gamma^{\mathbb{C}}}$ is precisely the complex twist flow $\text{tw}_\gamma^{\mathbb{C}}$.*

As in the Fuchsian case, it follows from these two theorems that complex Fenchel-Nielsen length functions associated to a pants decomposition define a complex Hamiltonian integrable system. Furthermore, he proves that the striking theorem 5.7 is still true in its complex version on $(\mathcal{QF}(S), \omega_P)$:

Theorem 5.13. *If α is any pants decomposition of S , complex Fenchel-Nielsen coordinates are Darboux coordinates for the complex symplectic structure ω_P :*

$$\omega_P = \sum_{i=1}^N dI_{\alpha_i}^{\mathbb{C}} \wedge d\tau_{\alpha_i}^{\mathbb{C}}. \quad (34)$$

6 Comparing symplectic structures

6.1 Analytic continuation

We are going to show the following proposition, which implies that two complex symplectic structures agree on $\mathcal{CP}(S)$ if and only if they agree in restriction to tangent vectors to the Fuchsian slice $\mathcal{F}(S)$:

Proposition 6.1. *Let ω be a closed $(2,0)$ -form on $\mathcal{CP}(S)$ and $\sigma_{\mathcal{F}} : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be the Fuchsian section (as in (12)). If $\sigma_{\mathcal{F}}^* \omega$ vanishes on $\mathcal{T}(S)$, then ω vanishes on $\mathcal{CP}(S)$.*

The proof of this proposition is based on analytic continuation. In order to use this argument, we recall a few definitions and show some elementary facts regarding totally real submanifolds of complex manifolds.

Definition 6.2. Let M be a complex manifold and $N \subset M$ be a real submanifold. N is called *totally real* if the following holds:

$$\forall x \in N, \quad T_x N \cap J T_x N = \{0\}, \quad (35)$$

where J is the almost complex structure on M .

If moreover, N has maximal dimension $\dim_{\mathbb{R}} N = \dim_{\mathbb{C}} M$, we say that N is a *maximal totally real submanifold* of M . There are several characterizations of maximal totally real analytic submanifolds, seemingly stronger than the definition, as in the following:

Proposition 6.3. *Let M be a complex manifold of dimension n and $N \subset M$ be a real submanifold. The following are equivalent:*

- (i) N is a maximal totally real analytic submanifold of M .
- (ii) $N \subset M$ locally looks like $\mathbb{R}^n \subset \mathbb{C}^n$. More precisely: for any $x \in N$, there is a holomorphic chart $z : U \rightarrow V$ where U is an open set in M containing x and V is an open set in \mathbb{C}^n , such that $z(U \cap N) = V \cap \mathbb{R}^n$.
- (iii) There is an antiholomorphic involution $\chi : M' \rightarrow M'$ where M' is a neighborhood of N in M , such that N is the set of fixed points of χ .

If N satisfies one (equivalently all) of these conditions, M is said to be a *complexification* of N . Let us mention that any real-analytic manifold can be complexified.

Proof. It is fairly easy to see that both (ii) and (iii) imply (i), and that in fact (ii) and (iii) are equivalent. Let us show that (i) implies (ii). Using holomorphic charts, it is clearly enough to prove this in the case where N is a maximal totally real analytic submanifold of \mathbb{C}^n . Let $m \in N \subset \mathbb{C}^n$, there is a real-analytic parametrization $\varphi : D \rightarrow N$, where D is a small open disk centered at the origin in \mathbb{R}^n , such that $\varphi(0) = m$ and $d\varphi(0) \neq 0$. The map φ is given by a convergent power series $\varphi(x) = \sum_{|\alpha|=n} a_{\alpha} x^{\alpha}$ for all $x \in D$, where the sum is taken over all multi-indices α of length n , and the a_{α} are coefficients in \mathbb{C}^n . In order to extend φ to a holomorphic map $\Phi : D' \rightarrow M$ where D' is the disk in \mathbb{C}^n such that $D = D' \cap \mathbb{R}^n$, we can just replace $x \in D$ by $z \in D'$ in the expression of φ : define $\Phi(z) = \sum_{|\alpha|=n} a_{\alpha} z^{\alpha}$. This power series converges in D' because it has the same radius of convergence as its real counterpart. Moreover, if D' is small enough, Φ is a biholomorphism onto its image because $d\Phi(0) = d\varphi(0) \neq 0$. This shows that (i) implies (ii) (just take the chart given by Φ^{-1})³⁷. \square

Keeping in mind that we want to consider the Fuchsian slice in $\mathcal{CP}(S)$, we make this last general observation on totally real submanifolds:

Proposition 6.4. *Let V be a complex manifold. The diagonal Δ in $V \times \bar{V}$ ³⁸ is a maximal totally real analytic submanifold.*

Proof. This is a direct consequence of characterization (iii) in the previous proposition: just take the antiholomorphic involution $\chi : V \times \bar{V} \rightarrow V \times \bar{V}$ defined by $\chi(x, y) = (y, x)$. \square

³⁷Note that the simplicity of this proofs relies on a little trick: the actual complexification of φ is a map $\varphi : D' \rightarrow \mathbb{C}^{2n}$ (and not \mathbb{C}^n), where a_{α} is seen as a real vector in \mathbb{C}^n .

³⁸ \bar{V} denotes the manifold V equipped with the opposite complex structure.

An immediate application of this is that the Fuchsian slice $\mathcal{F}(S)$ is a maximal totally real analytic submanifold of $\mathcal{CP}(S)$ (as was already pointed out in section 4.4): it is the image of the diagonal of $\mathcal{T}(S) \times \overline{\mathcal{T}(S)}$ ³⁹ by the holomorphic embedding β^+ (see section 2.2). Another way to see this is that the quasi-Fuchsian space $\mathcal{QF}(S) = \text{Im}(\beta^+) \subset \mathcal{CP}(S)$ is equipped with a canonical antiholomorphic involution, which just consists in “turning a quasi-Fuchsian 3-manifold upside down”, and $\mathcal{F}(S)$ is the set of fixed points of this involution.

Now, we prove this first elementary analytic continuation theorem:

Proposition 6.5. *Let M be a connected complex manifold and $N \subset M$ be a maximal totally real submanifold. If $f : M \rightarrow \mathbb{C}$ is a holomorphic function that vanishes on N , then f vanishes on M .*

Proof. By the identity theorem for holomorphic functions, it is enough to show that f vanishes on a small open neighborhood U of some point $x \in N$. If N is analytic, this is a straightforward consequence of characterization (ii) in Proposition 6.3. Let us produce a proof that does not assume analyticity of N . Since the restriction $f|_N$ vanishes identically, we have $(df)|_{TN} = 0$. Using the fact that $T_x M = T_x N \oplus JT_x N$ for all $x \in N$ and the holomorphicity of f , it is easy to derive that df vanishes at all points of N . In particular, if $z = (z_k)_{1 \leq k \leq n} : U \rightarrow \mathbb{C}^n$ is a holomorphic chart, the partial derivatives $\frac{\partial f}{\partial z_k}$ vanish on N . But those are again holomorphic functions, so we can use the same argument: their partial derivatives must vanish on N . By an obvious induction, we see that all partial derivatives of f (at any order) vanish at points of N . Since f is holomorphic, this implies that $f = 0$. \square

We can now finally prove:

Proposition 6.6. *Let M be a connected complex manifold and $\sigma : N \rightarrow M$ be a maximal totally real embedding. If ω is a closed $(2, 0)$ -form on M such that $\sigma^* \omega = 0$, then $\omega = 0$.*

Proof. We can assume that $N \subset M$, so the hypothesis is that $\omega|_{TN} = 0$. Since $T_x M = T_x N \oplus JT_x N$ for any $x \in N$ and ω is of type $(2, 0)$, it is easy to see that ω vanishes at points of N . Now, recall that a closed $(2, 0)$ -form is holomorphic. Let $z = (z_k)_{1 \leq k \leq n} : U \rightarrow \mathbb{C}^n$ be a holomorphic chart in a neighborhood of a point $x \in N$, ω has an expression of the form $\omega = \sum_{j,k} f_{jk} dz_j \wedge dz_k$ where f_{jk} are holomorphic functions on U . Since ω vanishes at points of N , the functions f_{jk} vanish on $U \cap N$, and we derive from the previous proposition that they actually vanish on U . We thus have $\omega|_U = 0$, and it follows once again from the identity theorem (taken in charts) that ω vanishes on M . \square

An immediate consequence of this, together with (22), is that a complex symplectic structure on $\mathcal{CP}(S)$ agrees with the standard complex symplectic structure if and only if it induces the Weil-Petersson Kähler form on the Fuchsian slice:

³⁹ Recall that $\mathcal{T}(\overline{S})$ is canonically identified with $\overline{\mathcal{T}(S)}$.

Theorem 6.7. *Let ω be a complex symplectic structure on $\mathcal{CP}(S)$. Then $\omega = \omega_G$ if and only if $(\sigma_{\mathcal{F}})^*\omega = \omega_{WP}$.*

Proof. By the previous proposition, $\omega = \omega_G$ if and only if $(\sigma_{\mathcal{F}})^*(\omega - \omega_G) = 0$. But by (22), $\sigma_{\mathcal{F}}^*\omega_G = \omega_{WP}$, therefore $(\sigma_{\mathcal{F}})^*(\omega - \omega_G) = (\sigma_{\mathcal{F}})^*\omega - \omega_{WP}$. \square

6.2 The affine cotangent symplectic structures

Recall (see section 3.3) that any section $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ determines an affine identification $\tau^\sigma : \mathcal{CP}(S) \xrightarrow{\sim} T^*\mathcal{T}(S)$ and thus a complex-valued non-degenerate 2-form $\omega^\sigma = (\tau^\sigma)^*\omega$ on $\mathcal{CP}(S)$. ω^σ is a complex symplectic structure on $\mathcal{CP}(S)$ if and only if σ is a holomorphic section to p . We will now answer the question: for which holomorphic sections σ does ω^σ agree with the standard symplectic structure ω_G ?

As a direct consequence of theorem 6.7, together with Proposition 3.3, we show:

Theorem 6.8. *Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a section to p . Then ω^σ agrees with the standard complex symplectic structure ω_G on $\mathcal{CP}(S)$ if and only if $\sigma_{\mathcal{F}} - \sigma$ is a primitive for the Weil-Petersson metric on $\mathcal{T}(S)$:*

$$\omega^\sigma = \omega_G \Leftrightarrow d(\sigma_{\mathcal{F}} - \sigma) = \omega_{WP} . \quad (36)$$

More generally, if c is some complex constant,

$$\omega^\sigma = c\omega_G \Leftrightarrow d(\sigma_{\mathcal{F}} - \sigma) = c\omega_{WP} . \quad (37)$$

Proof. By Theorem 6.7, $\omega^\sigma = \omega_G$ if and only if $(\sigma_{\mathcal{F}})^*\omega^\sigma = \omega_{WP}$. However, it follows from Proposition 3.3 that

$$\begin{aligned} (\sigma_{\mathcal{F}})^*\omega^\sigma &= (\sigma_{\mathcal{F}})^*[\omega_{\mathcal{F}}^\sigma - p^*d(\sigma - \sigma_{\mathcal{F}})] \\ &= (\sigma_{\mathcal{F}})^*((\tau^{\sigma_{\mathcal{F}}})^*\omega_{\text{can}}) - (\sigma_{\mathcal{F}})^*(p^*d(\sigma - \sigma_{\mathcal{F}})) \\ &= (\tau^{\sigma_{\mathcal{F}}} \circ \sigma_{\mathcal{F}})^*\omega_{\text{can}} - (p \circ \sigma)^*d(\sigma - \sigma_{\mathcal{F}}) \\ &= s_0^*\omega_{\text{can}} - \text{id}^*d(\sigma - \sigma_{\mathcal{F}}) \\ &= -d(\sigma - \sigma_{\mathcal{F}}) . \end{aligned}$$

Let us make a couple of comments on this calculation: recall that ω_{can} denotes the canonical symplectic structure on $T^*\mathcal{T}(S)$; $\tau^\sigma \circ \sigma = s_0$ is the characterization of τ^σ ; and $s_0^*\omega = 0$ because the zero section s_0 is a Lagrangian in $T^*\mathcal{T}(S)$ (see section 3.2). Of course, the proof of the apparently more general second statement is just the same. \square

Now, McMullen proved in [McM00] the following theorem:

Theorem 6.9 (McMullen [McM00]). *If σ is any Bers section, then*

$$d(\sigma_{\mathcal{F}} - \sigma) = -i\omega_{WP} . \quad (38)$$

Using this result, we eventually obtain as a corollary of Theorem 6.8:

Theorem 6.10. *If $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ is any Bers section, then*

$$\omega^\sigma = -i\omega_G . \quad (39)$$

In particular, we can deduce from this identification the following properties:

Corollary 6.11. *Consider the space $\mathcal{CP}(S)$ equipped with its standard symplectic structure ω_G . Then*

1. *The canonical projection $p : \mathcal{CP}(S) \rightarrow \mathcal{T}(S)$ is a Lagrangian fibration.*
2. *Bers slices are the leaves of a Lagrangian foliation of the quasi-Fuchsian space $\mathcal{QF}(S)$.*

We also derive an explicit expression of $\omega_G(u, v)$ when u is a vertical tangent vector (by Proposition 3.4):

Corollary 6.12. *Let u, v be tangent vectors at $Z \in \mathcal{CP}(S)$ such that u is vertical, i.e. $p_*u = 0$. Then*

$$\omega_G(u, v) = i\langle u, p_*v \rangle . \quad (40)$$

Looking back at Proposition 3.3, we also get the expression of the 2-form $\omega^{\sigma_{\mathcal{F}}}$ obtained under the Fuchsian identification:

Corollary 6.13. *Let $\sigma_{\mathcal{F}} : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be the Fuchsian section. Then*

$$\omega^{\sigma_{\mathcal{F}}} = -i(\omega_G - p^*\omega_{WP}) . \quad (41)$$

It should not come as a surprise that we see from this equality that $\omega^{\sigma_{\mathcal{F}}}$ vanishes on the Fuchsian slice. Notice the equality between real symplectic structures:

$$\operatorname{Re}(\omega^{\sigma_{\mathcal{F}}}) = \operatorname{Im}(\omega_G) \quad (42)$$

and that $\operatorname{Re}(\omega^{\sigma_{\mathcal{F}}})$ is (half) the real canonical symplectic structure on $T^*\mathcal{T}(S)$ pulled back by the Fuchsian identification.

Finally, we note that McMullen's *quasi-Fuchsian reciprocity* theorem showed in [McM00] can be seen as a consequence of Theorem 6.10. We will give a precise statement and proof of a generalized version of this theorem in the setting of convex cocompact 3-manifolds (Theorem 6.18).

Generalizations in the setting of convex cocompact hyperbolic 3-manifolds

Let \hat{M} be a compact 3-manifold as in section 2.3. We will use here the same notations as in 2.3. Recall that we have defined there a canonical holomorphic section $\beta : \mathcal{T}(\partial\hat{M}) \rightarrow \mathcal{CP}(\partial\hat{M})$.

McMullen and Takhtajan-Teo gave generalized versions of quasi-Fuchsian reciprocity, which they called *Kleinian reciprocity*, notably in [McM00] (Appendix) and [TT03]. In particular, **Theorem 6.3** in [TT03] says the following:

Theorem. Let $\sigma_{\mathcal{F}} : \mathcal{T}(\partial\hat{M}) \rightarrow \mathcal{CP}(\partial\hat{M})$ denote the Fuchsian section. Then

$$d(\sigma_{\mathcal{F}} - \beta) = -i\omega_G .$$

Since our theorem 6.8 above does not assume that S is connected, we obtain:

Theorem 6.14. Let ω_G be the standard complex symplectic structure on $\mathcal{CP}(\partial\hat{M})$ and $\omega^\beta = (\tau^\beta)^*\omega$ be the complex symplectic structure obtained by the identification $\tau^\beta : \mathcal{CP}(\partial\hat{M}) \xrightarrow{\sim} T^*\mathcal{T}(\partial\hat{M})$ as in section 3.3. Then

$$\omega^\beta = -i\omega_G . \quad (43)$$

A first immediate corollary is that we recover Theorem 4.3: β is a Lagrangian embedding.

Another consequence of this theorem and of the fact that the projections $p_k : \mathcal{CP}(S_k) \rightarrow \mathcal{T}(S_k)$ are Lagrangian (Theorem 6.11) is a generalization of Theorem 6.10:

Theorem 6.15. Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a generalized Bers section (see section 2.3). Then

$$\omega^\sigma = -i\omega_G . \quad (44)$$

Proof. By definition, σ is map defined by $\sigma = f_{(X_i),j}$ as in section 2.3, where $S = S_j$ and X_i is a fixed point in $\mathcal{T}(S_i)$ for $i \neq j$. Recall that

$$\omega_G = (\text{pr}_1)^*\omega_G^{(1)} + \cdots + (\text{pr}_N)^*\omega_G^{(N)}$$

where $\omega_G^{(k)}$ is the standard complex symplectic structure on $\mathcal{CP}(S_k)$, and similarly

$$\omega = (\text{pr}_1)^*\omega^{(1)} + \cdots + (\text{pr}_N)^*\omega^{(N)40}$$

where $\omega^{(k)}$ is the canonical complex symplectic structure on $T^*\mathcal{T}(S_k)$. The equality (43) can thus be rewritten:

$$(\text{pr}_1 \circ \tau^\beta)^*\omega^{(1)} + \cdots + (\text{pr}_N \circ \tau^\beta)^*\omega^{(N)} = -i \left[(\text{pr}_1)^*\omega_G^{(1)} + \cdots + (\text{pr}_N)^*\omega_G^{(N)} \right] .$$

Fix $Z_i \in P(X_i)$ for $i \neq j$ and let us pull back this equality on $\mathcal{CP}(S_j)$ by the map

$$\iota_{(\tilde{Z}_i)} : \begin{array}{ccc} \mathcal{CP}(S_j) & \rightarrow & \mathcal{CP}(\partial\hat{M}) \\ Z & \mapsto & (Z_1, \dots, Z_{j-1}, Z, Z_{j+1}, \dots, X_N) . \end{array}$$

For $k \neq j$, the map $\text{pr}_k \circ \tau^\beta \circ \iota_{(\tilde{Z}_i)}$ takes values in the fiber $T_{X_k}^*\mathcal{T}(S_k)$, so that $(\tilde{\iota}_{(Z_i)})^* \left((\text{pr}_k \circ \tau^\beta)^*\omega^{(k)} \right) = 0$. Similarly, the map $\text{pr}_k \circ \tilde{\iota}_{(Z_i)}$ maps into the fiber $P(X_k) \subset \mathcal{CP}(S_k)$, so that $(\tilde{\iota}_{(Z_i)})^* \left((\text{pr}_k)^*\omega_G^{(k)} \right) = 0$ because p_k is a Lagrangian fibration. For $k = j$, $\text{pr}_k \circ \tau^\beta \circ \tilde{\iota}_{(Z_i)}$ is the map $\tau^\sigma : \mathcal{CP}(S_j) \rightarrow T^*\mathcal{T}(S_j)$ and $\text{pr}_k \circ \tilde{\iota}_{(Z_i)}$ is the identity in $\mathcal{CP}(S_j)$. We therefore obtain the desired equality $(\tau^\sigma)^*\omega^{(j)} = -i\omega_G^{(j)}$. \square

⁴⁰ Be wary that in this equality, pr_k stands for the k^{th} projection map $T^*\mathcal{T}(\partial\hat{M}) \rightarrow T^*\mathcal{T}(S_k)$ (whereas it stood for the k^{th} projection map $\mathcal{CP}(\partial\hat{M}) \rightarrow \mathcal{CP}(S_k)$ in the previous equality). We apologize for these (slightly) misleading notations.

An immediate corollary of this is:

Corollary 6.16. *Generalized Bers sections $\mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ are Lagrangian embeddings.*

Another corollary of Theorem 6.15 and Theorem 6.8 is a generalization of McMullen's Theorem 6.9:

Corollary 6.17. *Let $\sigma : \mathcal{T}(S) \rightarrow \mathcal{CP}(S)$ be a generalized Bers section. Then*

$$d(\sigma_{\mathcal{F}} - \sigma) = -i\omega_{WP} . \quad (45)$$

Finally, we show a generalized version of McMullen's "quasi-Fuchsian reciprocity". To this end, we introduce the notion of "reciprocal generalized Bers embeddings": with the notations of section 2.3, we say that $f : \mathcal{T}(S_j) \rightarrow \mathcal{CP}(S_k)$ and $g : \mathcal{T}(S_k) \rightarrow \mathcal{CP}(S_j)$ are *reciprocal generalized Bers embeddings* if $f = f_{(X_i)_{i \neq j, k}}$ and $g = f_{(X_i)_{i \neq k, j}}$ for some fixed $X = (X_1, \dots, X_N) \in \mathcal{T}(\partial \hat{M})$. Since f and g take values in affine spaces, one can consider their derivatives:

$$D_{X_j} f : T_{X_j} \mathcal{T}(S_j) \rightarrow T_{X_k}^* \mathcal{T}(S_k) \quad (46)$$

$$D_{X_k} g : T_{X_k} \mathcal{T}(S_k) \rightarrow T_{X_j}^* \mathcal{T}(S_j) \quad (47)$$

Theorem 6.18. *Let $f : \mathcal{T}(S_j) \rightarrow \mathcal{CP}(S_k)$ and $g : \mathcal{T}(S_k) \rightarrow \mathcal{CP}(S_j)$ be reciprocal generalized Bers embeddings as above. Then $D_{X_j} f$ and $D_{X_k} g$ are dual maps. In other words, for any $\mu \in T_{X_j} \mathcal{T}(S_j)$ and $\nu \in T_{X_k} \mathcal{T}(S_k)$,*

$$\langle D_{X_j} f(\mu), \nu \rangle = \langle \mu, D_{X_k} g(\nu) \rangle . \quad (48)$$

Proof. The fact that $\beta : \mathcal{T}(\partial \hat{M}) \rightarrow \mathcal{CP}(\partial \hat{M})$ is Lagrangian is written

$$\beta^* \omega_G = (\text{pr}_1 \circ \beta)^* \omega_G^{(1)} + \dots + (\text{pr}_N \circ \beta)^* \omega_G^{(N)} = 0 ,$$

where $\omega_G^{(i)}$ is the standard complex symplectic structure on the component $\mathcal{CP}(S_i)$. Let $\mu \in T_{X_j} \mathcal{T}(S_j)$ and $\nu \in T_{X_k} \mathcal{T}(S_k)$, and define $U, V \in T_X \mathcal{T}(\partial \hat{M})$ by

$$U_i = \begin{cases} 0 & \text{for } i \neq j \\ \mu & \text{for } i = j \end{cases}$$

and

$$V_i = \begin{cases} 0 & \text{for } i \neq k \\ \nu & \text{for } i = k \end{cases} .$$

Note that $(\text{pr}_i \circ \beta)_* U$ is vertical in $\mathcal{CP}(S_i)$ whenever $i \neq j$ (resp. $(\text{pr}_i \circ \beta)_* V$ is vertical in $\mathcal{CP}(S_i)$ whenever $i \neq k$). Since the fibers of $\mathcal{CP}(S_i)$ are isotropic (see Theorem 6.11), it follows that $((\text{pr}_i \circ \beta)^* \omega_G^{(i)})(U, V) = 0$ whenever $i \notin \{j, k\}$. For $i = k$, $(\text{pr}_i \circ \beta)_* U = D_{X_j} f(\mu)$ is still vertical and $(\text{pr}_k)_* ((\text{pr}_i \circ \beta)_* V) = \nu$ so we can derive from Theorem 6.12 that $((\text{pr}_k \circ \beta)^* \omega_G^{(k)})(U, V) = i \langle D_{X_j} f(\mu), \nu \rangle$. Similarly, for $i = j$ we have

$$\left((\text{pr}_j \circ \beta)^* \omega_G^{(j)} \right) (U, V) = - \left((\text{pr}_j \circ \beta)^* \omega_G^{(j)} \right) (V, U) = -i \langle D_{X_k} g(\nu), \mu \rangle .$$

In the end, $0 = (\beta^* \omega_G)(U, V) = i \langle D_{X_j} f(\mu), \nu \rangle - i \langle D_{X_k} g(\nu), \mu \rangle$ as desired. \square

Note that Corollary 6.17 is not an immediate consequence of “Kleinian reciprocity”: the proof requires Lagrangian information. On the other hand, Steven Kerckhoff pointed out to me that Theorem 6.18 can be derived from Kleinian reciprocity without using our previous results, rightly so (the proof is easily adapted taking ω^β instead of ω_G , avoiding the use of the symplectic structure on $\mathcal{CP}(S)$).

6.3 Darboux coordinates

It is an immediate consequence of the analytical continuation property 6.7 and Wolpert’s theorem 5.7 that complex Fenchel-Nielsen coordinates are Darboux coordinates for the standard symplectic structure on the quasi-Fuchsian space:

Theorem 6.19. *Let α be any pants decomposition of S . Complex Fenchel-Nielsen coordinates $(l_\alpha^\mathbb{C}, \tau_\alpha^\mathbb{C})$ on the quasi-Fuchsian space $\mathcal{QF}(S)$ are Darboux coordinates for the standard complex symplectic structure:*

$$\omega_G = \sum_{i=1}^N dl_{\alpha_i}^\mathbb{C} \wedge d\tau_{\alpha_i}^\mathbb{C}. \quad (49)$$

Proof. Of course, Theorem 6.7 is still true when replacing $\mathcal{CP}(S)$ by any connected neighborhood of the Fuchsian slice $\mathcal{F}(S)$, such as the quasi-Fuchsian space $\mathcal{QF}(S)$. Let $\omega = \sum_{i=1}^N dl_{\alpha_i}^\mathbb{C} \wedge d\tau_{\alpha_i}^\mathbb{C}$. Since $l_{\alpha_i}^\mathbb{C}$ and $\tau_{\alpha_i}^\mathbb{C}$ are holomorphic, ω is a complex symplectic structure on $\mathcal{QF}(S)$. In restriction to the Fuchsian slice, $\iota^*\omega = \sum_{i=1}^N dl_{\alpha_i} \wedge d\tau_{\alpha_i}$ where (l_α, τ_α) are the classical Fenchel-Nielsen coordinates. By Wolpert’s Theorem 5.7, it follows that $(\sigma^\mathcal{F})^*\omega = \omega_{WP}$. This proves that $\omega = \omega_G$ according to Theorem 6.7. \square

Of course, this shows in particular:

Corollary 6.20. *Platis’ symplectic structure ω_P is equal to the standard complex symplectic structure ω_G in restriction to the quasi-Fuchsian space $\mathcal{QF}(S)$.*

Notice how the analytic continuation argument provides a very simple alternative proof of Platis’ result that the symplectic structure $\sum_{i=1}^N dl_{\alpha_i}^\mathbb{C} \wedge d\tau_{\alpha_i}^\mathbb{C}$ does not depend on a choice of a pants decomposition (relying, of course, on Wolpert’s result).

In [Gol04], Goldman gives a fairly extensive description of the complex symplectic structure ω_G on the character variety $\mathcal{X}(S, SL_2(\mathbb{C}))$, discussing in particular the “Hamiltonian picture”. We recover that the Hamiltonian flow of a complex length function is the associated complex twist flow.

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