

CLOSED SYMMETRIC 2-DIFFERENTIALS OF THE 1ST KIND

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To the memory of Andrey
Todorov, friend and colleague

Abstract: A closed symmetric differential of the 1st kind is a differential that locally is the product of closed holomorphic 1-forms. We show that closed symmetric 2-differentials of the 1st kind on a projective manifold X come from maps of X to cyclic or dihedral quotients of Abelian varieties and that their presence implies that the fundamental group of X (case of rank 2) or of the complement $X \setminus E$ of a divisor E with negative properties (case of rank 1) contains subgroup of finite index with infinite abelianization. Other results include the identification of the differential operator characterizing closed symmetric 2-differentials on surfaces (which provides in this case a connection to flat Riemannian metrics) and showing that if a closed symmetric 2-differential w on X is the product of two closed meromorphic 1-differentials defining distinct foliations, then either X has fibration over a curve of genus ≥ 1 or w is of the first kind.

0. INTRODUCTION

Our purpose is continue the study of the properties of symmetric tensors on algebraic manifolds, with a special emphasis on the case of algebraic surfaces. The class which we are interested in is composed of what we call closed symmetric differentials, which can be considered as a natural generalization of closed holomorphic 1-forms. The presence of holomorphic 1-forms imposes topological restrictions on the manifold, our ultimate goal is to establish a similar but weaker connection between the existence closed symmetric differentials and the topology of the manifold.

Key words and phrases. Symmetric differentials, Albanese, webs, closed meromorphic 1-forms.

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A closed symmetric differential is a symmetric differential which can be decomposed as a product of closed holomorphic 1-forms on a neighborhood of some point of the manifold. If differential has local decompositions of these type near every point of the manifold, then the closed differential is said to be of the 1st kind. A feature of closed symmetric differentials is that they are connected to (possibly degenerate) webs on the complex manifold while non closed symmetric differentials do not have necessarily this connection if the manifold has dimension greater than 2. Closed symmetric differentials are not necessarily of the 1st kind for degrees greater than 1. In section 2.1 we provide examples for each of the 3 causes of this failure. One of the causes of this failure has a striking manifestation, some closed symmetric differentials (holomorphic) only allow decompositions into products of closed 1-forms if some of the 1-forms have essential singularities.

In this article we study the case of degree 2 which is the first interesting case to consider and has some special features such as: 1) the local decompositions of a differential as a product of closed holomorphic 1-forms have rigidity properties for all degrees but for degree 2 this rigidity has the maximum strength, i.e. the 1-forms in the decomposition are unique up to a multiplicative constant; 2) symmetric 2-differentials on complex manifolds are analogous to Riemannian metrics in differential geometry. Using feature 2) we identify in theorem 2.1 the differential operator that characterizes closed symmetric 2-differentials on surfaces. This differential operator is just the natural translation of the Gaussian curvature operator to our case. We observe that a closed symmetric 2-differential on a surface is the direct analogue of the notion of a flat Riemannian metric on a real surface.

The rigidity of the local decompositions of a closed symmetric 2-differential as product of closed holomorphic 1-forms gives for differentials of 1st kind w on a projective manifold X a dual pair $(\mathbb{C}_w, \mathbb{C}_w^*)$ of local systems of rank 1 on X or on an unramified double cover of X (depending on whether w is split or non split). Moreover, 2-differential w of the 1st kind can be decomposed as $w = \phi_1\phi_2$ the product of twisted closed 1-forms ϕ_i (ϕ_1 twisted by \mathbb{C}_w and ϕ_2 twisted by \mathbb{C}_w^*). The work Beauville, Green-Lazarsfeld and Simpson on the cohomology loci (see references) will be an important tool used to establish that the local systems \mathbb{C}_w are torsion, which is one of the key ingredients in the proof of the result describing the geometric origins and features of symmetric 2-differentials of the 1st kind:

Theorem 3.2. *Let X be a smooth projective manifold with $w \in H^0(X, S^2\Omega_X^1)$ a non-trivial rank 2 closed differential of the 1st kind. Then:*

i) X has a holomorphic map to a cyclic or dihedral quotient of an abelian variety from which the symmetric differential w is induced from. More precisely, there is a commutative diagram

$$\begin{array}{ccc}
X' & \xrightarrow{a_{X'}} & \text{Alb}(X') \\
f \downarrow & & q \downarrow \\
X & \xrightarrow{a} & \text{Alb}(X')/G
\end{array}$$

and $f^*w = a_{X'}^*\omega$ with $\omega \in H^0(\text{Alb}(X'), S^2\Omega_{\text{Alb}(X')}^1)^G$ where $f : X' \rightarrow X$ is an unramified G -Galois covering and $a_{X'} : X' \rightarrow \text{Alb}(X')$ the Albanese map. The group G is \mathbb{Z}_m if w is split and D_{2m} if w is non split.

ii) $\pi_1(X)$ is infinite, more precisely $\exists \Gamma \triangleleft \pi_1(X)$ such that $\pi_1(X)/\Gamma$ is finite cyclic or dihedral and its abelianization, $\Gamma/[\Gamma, \Gamma]$, is an infinite group.

In the section 2.3 we prove that if a closed 2-differential is of the 1st kind outside of codimension 2, then it is of the 1st kind everywhere. We also show that the locus where a closed 2-differential fails to be of the 1st kind is contained in the divisorial part of the degeneracy locus, i.e. the locus of all points where the 2-differential fails to define two distinct hyperplanes on the tangent space.

In our last result, theorem 3.3, we describe the geometry of closed symmetric 2-differentials that are the product of two closed meromorphic 1-forms. There some points of interest in this result, one of them is that non-holomorphic 1-forms can occur as factors, the other is that this occurrence which a priori could invalidate any non triviality results on the fundamental group (closed meromorphic 1-differentials can exist in simply connected manifolds) in fact implies the geometric/topological properties 2) and 3) below which imply a large fundamental group.

Theorem 3.3. *Let X be a smooth projective manifold and $w \in H^0(X, S^2\Omega_X^1)$ be a closed differential of rank 2 with a decomposition:*

$$w = \phi_1\phi_2 \quad \text{with } \phi_i \in H^0(X, \Omega_{X,cl}^1(*)) \quad (3.7)$$

where $\Omega_{X,cl}^1(*)$ is the sheaf of closed meromorphic 1-forms. Then the Albanese dimension of $X \geq 2$ and either:

- 1) $w = \phi_1\phi_2$ with $\phi_i \in H^0(X, \Omega_X^1)$, or
- 2) X has a map to a curve of genus ≥ 1 , $f : X \rightarrow C$ and $w = (f^*\varphi + u)f^*\mu$, where $u \in H^0(X, \Omega_X^1)$, $\varphi \in H^0(C, \Omega_C^1(*))$ and $\mu \in H^0(C, \Omega_C^1)$.

1. PRELIMINARIES

A symmetric differential of degree m , $w \in H^0(X, S^m \Omega_X^1)$, defines at each point $x \in X$ an homogeneous polynomial of degree m on the tangent space $T_x X$. If X is a surface, then w defines at each tangent space, $T_x X$, m , not necessarily distinct, lines through the origin. Around a general point on X , one obtains $k \leq m$ integrable distributions of lines giving a k -web, i.e. a collection of k foliations. On higher dimensions this is no longer necessarily the case, since the pointwise splitting of $w(x)$ into linear factors might not hold and even if such splitting occurs the distributions of hyperplanes in $T_x X$ defined by w might not be integrable.

Let X be a complex manifold of dimension n . The \mathbb{P}^{n-1} -bundle $\mathbb{P}(\Omega_X^1)$ over X , $\pi : \mathbb{P}(\Omega_X^1) \rightarrow X$, and its tautological line bundles $\mathcal{O}_{\mathbb{P}(\Omega_X^1)}(m)$ are intimately connected to the theory of symmetric differentials. There is in particular a natural bijection between $H^0(X, S^m \Omega_X^1)$ and $H^0(\mathbb{P}(\Omega_X^1), \mathcal{O}_{\mathbb{P}(\Omega_X^1)}(m))$. To a symmetric differential $w \in H^0(X, S^m \Omega_X^1)$ on X one can associate an hypersurface:

$$Z_w \subset \mathbb{P}(\Omega_X^1) \quad (1.1)$$

such that $Z_w \cap \pi^{-1}(x)$ is an hypersurface of degree m (Z can also be viewed as the zero locus of the section of $\mathcal{O}_{\mathbb{P}(\Omega_X^1)}(m)$ corresponding to w).

The hypersurface Z_w can be reducible and non reduced. The irreducible components of Z_w are called horizontal if they dominate X via the map π and a vertical otherwise. Hence:

$$Z_w = Z_{w,h} + Z_{w,v} \quad (1.2)$$

with $Z_{w,h}$ and $Z_{w,v}$ the union of respectively the horizontal and the vertical irreducible components.

Definition 1.1. A symmetric differential $w \in H^0(X, S^m \Omega_X^1)$ on a smooth complex manifold X is said to be:

- a) split if either one of the following equivalent statements holds:
 - i) $w = \phi_1 \dots \phi_m$ with ϕ_i meromorphic 1-differentials.
 - ii) $Z_{w,h}$ is the union of m irreducible components.

b) split at x if there is a neighborhood of x on which w splits (or equivalently $w(x) \in S^m \Omega_{X,x}^1$ is a product of linear forms).

Gauss lemma implies that if w is split at x , then there is a neighborhood U_x of x where w is the product of holomorphic 1-forms. A split symmetric differential is therefore locally the product of holomorphic 1-forms but the converse does not necessarily hold (e.g. Z_w is an unramified cover of X , with degree > 1). If w splits, then $w = \mu_1 \otimes \dots \otimes \mu_m$ with $\mu_i \in H^0(X, \Omega_X^1 \otimes L_i)$ where the L_i line bundles on X with $\prod L_i = \mathcal{O}(-D)$ with $\pi^* D = Z_{w,v}$.

The following fact will be used later, if the symmetric $w \in H^0(X, S^2\Omega_X^1)$ is split at a general point but it is not split, then there is a generically 2-1 ramified map $s_w : X' \rightarrow X$ for which s_w^*w is split and X' is smooth.

Definition 1.2. A symmetric differential $w \in H^0(X, S^m\Omega_X^1)$ on a smooth complex manifold X that splits at the general point is said to:

i) have rank k , $\text{rank}(w) = k$, if at a general point there are k distinct foliations defined by w (the foliations are defined by the 1-forms ϕ_i in a local decomposition $w|_{U_x} = \phi_1 \dots \phi_m$).

ii) have rank k at x , $\text{rank}_x(w) = k$, if $w(x)$ defines k distinct hyperplanes in $P(\Omega_{X,x}^1)$.

iii) be degenerate at x if $\text{rank}_x(w) < m$ or $w(x) = 0$. The locus consisting of the union of all points where w is degenerate is called the degeneracy locus of w , D_w .

The degeneracy locus D_w of a symmetric differential $w \in H^0(X, S^m\Omega_X^1)$ on a surface is the discriminant divisor of w which is defined locally where $w|_U = a_m(dz_1)^m + a_{m-1}(dz_1)^{m-1}dz_2 + \dots + a_0(dz_2)^m$ by the discriminant of $w|_U$ seen as a polynomial in $\mathcal{O}(U)[dz_1, dz_2]$. As a set D_w is the union of the points $x \in X$ such that $Z_w \cap \pi^{-1}(x)$ has multiple points.

2. CLOSED 2-DIFFERENTIALS AND DIFFERENTIALS OF THE 1ST KIND

2.1 General concepts.

Definition 2.1. A symmetric differential $w \in H^0(X, S^m\Omega_X^1)$ on a smooth complex manifold is said to have:

1) a holomorphic (meromorphic) exact decomposition if:

$$w = df_1 \dots df_m \quad f_i \in \mathcal{O}(X) \quad (f_i \in \mathcal{M}(X))$$

2) a holomorphic (meromorphic) exact decomposition at $x \in X$ if there is a neighborhood U_x of x where $w|_{U_x}$ has a holomorphic (meromorphic) exact decomposition.

3) a split closed decomposition if $w|_U = \phi_1 \dots \phi_m$ with ϕ_i closed holomorphic 1-differentials on a Zariski open U (the ϕ_i are not necessarily meromorphic on X).

Definition 2.2. A symmetric differential $w \in H^0(X, S^m \Omega_X^1)$ on a smooth complex manifold X is said to be:

- i) closed if w has a holomorphic exact decomposition at a general point of X .
- ii) closed of the 1st kind if w has a holomorphic exact decomposition at all points of X .

If w is a symmetric differential on a surface X , then there are always holomorphic functions f_i and f on a neighborhood of any general point of X , such that $w = f df_1 \dots df_m$ holds. The condition of w being closed asks for the existence of functions f_i such that f can be made constant. For degree 2 this condition can be seen as a flatness curvature type condition on w (see the next section).

For degree $m = 1$ the classes of closed and closed of the 1st kind differentials coincide. A symmetric differential of degree 1, i.e. a holomorphic 1-form, which is closed in the sense of definition 2.2 is also closed in the usual sense due to the principle of analytic continuation. Poincaré's lemma implies that a closed 1-form must be locally exact, i.e. of the 1st kind in the sense of definition 2.2. For degrees $m \geq 2$ the two classes no longer coincide. There are 3 consecutive levels of possible the failure of a closed symmetric differential w to be of the 1st kind at $x \in X$, which will be illustrated by examples below.

The first level of failure of a closed symmetric differential w to be of the 1st kind at $x \in X$ is the failing of w to split at x (1st kind must be split at every point by definition).

Example: (non-split at points) Let z_1 be a holomorphic coordinate of \mathbb{C}^n and $f \in \mathcal{O}(\mathbb{C}^n)$, set $w = z_1 (dz_1)^2 - (df)^2$. The differential is non split at all points in $\{z_1 = 0\}$ but it is closed since any point $y \in X \setminus \{z_1 = 0\}$ has a neighborhood U_y where $\sqrt{z_1}$ exists and hence w has a holomorphic exact decomposition $w|_{U_y} = d(\frac{2}{3}z_1^{\frac{3}{2}} + f)d(\frac{2}{3}z_1^{\frac{3}{2}} - f)$.

If the differential is locally split at x , then the 2nd layer of failure is due to monodromy around the locus where it fails to be of the 1st kind (which will be better understood in section 2.3).

Example (monodromy): Let $z \in \mathcal{O}(U)$, $u \in \mathcal{O}^*(U)$ with $dz \wedge du \neq 0$ and U be ball containing $0 \in \mathbb{C}^n$, set $w := u^{-\alpha} dz d(zu) = dz^{\alpha+1} d(zu)^{-\alpha+1}$ with $\alpha \notin \mathbb{Z}$. The 2-differential w is split but it does not have a split closed decomposition at points in $\{z = 0\}$. The reason for this is that there is a non trivial monodromy (in fact infinite monodromy if $\alpha \notin \mathbb{Q}$) of the split closed decompositions of w about $\{z = 0\}$.

If the differential is both locally split at x and no monodromy occurs, then w has a split closed decomposition at x and the 3rd level of failure is due to the singularities of the the 1-differentials on the decomposition.

Example: (singularities) This example shows that even essential singularities can occur, $w = e^{\frac{z_2}{1+z_1z_2}} dz_1 d[z_1(1+z_1z_2)]$. The 1-differentials in the split closed decomposition are unique up to constants, as it will be shown in section 2.3, and the constants will cancel each other so in fact the decomposition is unique and has the form

$$w = e^{\frac{z_2}{1+z_1z_2}} dz_1 d[z_1(1+z_1z_2)] = e^{-\frac{1}{z_1}} dz_1 e^{\frac{1}{z_1(1+z_1z_2)}} d[z_1(1+z_1z_2)]$$

with essential singularities occurring on the closed 1-forms at $\{z_1 = 0\}$.

Next are some cases and examples of globally defined closed symmetric differentials.

Example: the basic example of global closed symmetric differentials of the 1st kind are the global symmetric differentials of degree 1 on compact Kahler manifolds (the condition of compactness is essential). In the compact surface case one does not need the Kahler condition, the differential is closed by a direct application of the Stokes's theorem. For higher order closed symmetric differentials of the 1st kind, we have the elements $w \in S^m H^0(X, \Omega_X^1)$ which are the products $w = \mu_1 \dots \mu_m$ with $\mu_i \in H^0(X, \Omega_X^1)$.

On abelian varieties every symmetric differential is a linear combination over \mathbb{C} of closed symmetric differentials. On the case of curves the space of symmetric differentials of degree m is equal to $H^0(C, (\Omega_C^1)^{\otimes m}) = H^0(C, mK_C)$ and they are all closed.

One of its main themes of this article is the decomposition of a closed symmetric differential as a product of closed 1-differentials with torsion coefficients, i.e. sections of $\Omega_C^1 \otimes \mathcal{O}_{\chi_i}$ with \mathcal{O}_{χ_i} a flat line bundle. We proceed to consider the special case of symmetric differentials on curves. Any symmetric differential $w \in H^0(C, (\Omega_C^1)^{\otimes m})$ is defined modulo an invertible constant by the zero divisor of w , $(w)_0$. Hence if there is a splitting of $(w)_0$ into collections of $(2g-2)$ -points, then the splitting provides modulo constants a unique decomposition of w as a product of twisted 1-differentials, $w = \prod_{i=1}^m \phi_i$, where $\phi_i \in H^0(C, \Omega_C^1 \otimes \mathcal{O}_{\chi_i})$ and $\bigotimes_{i=1}^m \mathcal{O}_{\chi_i} = \mathcal{O}$. Thus we have a finite number of representations of w as a product of 1-differentials with torsion coefficients, namely there are exactly $((2g-2)m)!/((2g-2)!)^m$ such representations (modulo constants) if we add multiplicities. However, if we want to represent w as a product of untwisted 1-differentials, i.e. holomorphic 1-forms, then such representation does not exist for a generic symmetric differential w .

Example (Bo-De11): All symmetric differentials w of rank 1 on a projective manifold are closed.

Example: let $g: Y \rightarrow X$ be an unramified covering of X of degree m . Then the norm for the map g of an holomorphic 1-form $\mu \in H^0(Y, \Omega_Y^1)$, $n_g(\mu) \in H^0(X, S^m \Omega_X^1)$ is locally exact. Locally $n_g(\mu)$ is defined $n_g(\mu)|_U = df_1 \dots df_m$ where $df_i = \mu|_{U_i}$, $g^{-1}(U) = \prod_{i=1}^m U_i$ (U sufficiently small and the U_i are biholomorphic to U , so the f_i can also be viewed on U).

Example: Let X be a projective manifold and $f : X \rightarrow C$ be a fibration onto a smooth curve of genus ≥ 1 , $f : X \rightarrow C$, consider the $w \in H^0(X, S^2\Omega_X^1)$ of the form $w = (f^*\varphi + u)f^*\mu$, where $u \in H^0(X, \Omega_X^1)$, $\varphi \in H^0(C, \Omega_C^1(*))$ and $\mu \in H^0(C, \Omega_C^1)$ ($\Omega_C^1(*)$ is the sheaf of meromorphic 1-differentials). All closed symmetric 2-differentials that are the product of two closed meromorphic 1-forms are of the above form, some of these are not of the 1st kind (see section 3.3 for all the details).

2.2 Differential operator for closed 2-differentials on surfaces.

Poincare lemma states that locally exact symmetric differentials w of degree 1 are the solutions of the first order differential equation $dw = 0$, where d is the exterior derivative. For higher degrees, we saw in the last section, the illustrative examples of how a symmetric differential that has almost everywhere a local holomorphic exact decomposition can fail to have it at points where the differential is degenerate, i.e. in the discriminant locus D_w . The reasons for this failure, e.g. monodromy about the the divisor D_w (giving a local cohomological obstruction to the existence of a holomorphic exact decomposition), can not be detected via a differential operator. A differential operator can only be expected to detect the existence of local holomorphic decompositions where the symmetric differential is non degenerate, which by the way is enough to guarantee that the symmetric differential is closed. The result of this section states that the property of a symmetric 2-differential being closed is indeed determined by a differential operator. We expect the same to happen for higher degrees (see the end of the section).

A symmetric 2-differential $w \in H^0(X, S^2\Omega_X^1)$ is locally given by:

$$w(z)|_U = a_{11}(z)dz_1^2 + a_{12}(z)dz_1dz_2 + a_{22}(z)dz_2^2 \quad (2.1)$$

with $a_{ij}(z) \in \mathcal{O}(U)$, can formally be considered as a (degenerate) "complex metric" on X . This perspective illustrates once more the distinction between rank 1 and rank 2. Only the case of rank 2 benefits from this perspective, since rank 1 would correspond to an everywhere degenerate metric. The reasoning that follows connecting the property of being closed to flatness concerns rank 2 alone. The case of rank 1 is distinct and related to the case of 1-forms, we have that locally near a general point $w|_U = f(z)(dz_1)^2$ and w is closed if and only if $df \wedge dz_1 = 0$. Moreover, global arguments give that all symmetric differentials of rank 1 defined on a compact Kahler manifold are closed, see [BodeO11].

The Gaussian curvature R operator on 2-dimensional real manifolds acts on sections of $S^2(T_x^{\mathbb{R}}M)^*$ representing metrics and sends them to functions. We call $R^{\mathbb{C}}$ the natural "complexification" of this operator (replace the $\frac{\partial}{\partial x_i}$ by $\frac{\partial}{\partial z_i}$) which gives a map:

$$R^{\mathbb{C}} : H^0(X, S^2\Omega_X^1) \rightarrow \mathcal{M}(X)$$

Associated with the symmetric differential of rank 2 w one has $\det(w)$ the section of $2K_X$, given locally by $\det(w)(z) = a_{11}(z)a_{22}(z) - \frac{1}{4}a_{12}(z)^2$.

Theorem 2.1. *Let X be a smooth complex surface and $w \in H^0(X, S^2\Omega_X^1)$ a symmetric differential of rank 2. Set $P_2w = \det(w)^2R^{\mathbb{C}}$. Then the nonlinear differential operator*

$$P_2 : H^0(X, S^2\Omega_X^1) \rightarrow H^0(X, 4K_X) \quad (2.2)$$

is such that w is closed if and only if $P_2w = 0$. Moreover, $P_2w = 0$ implies w is of the 1st kind on $X \setminus D_w$.

Proof. The complexified Gaussian curvature $R^{\mathbb{C}}$ operator applied to the symmetric 2-differential w which is locally expressed in the form (2.1) gives according to the Brioschi formula:

$$R^{\mathbb{C}}w|_U = \frac{1}{\det(w|_U)^2} \left[\begin{array}{ccc|ccc} -\frac{1}{2}(\frac{\partial^2 a_{11}}{\partial z_2^2} + \frac{\partial^2 a_{22}}{\partial z_1^2} - \frac{\partial^2 a_{12}}{\partial z_1 \partial z_2}) & \frac{1}{2} \frac{\partial a_{11}}{\partial z_1} & \frac{1}{2}(\frac{\partial a_{12}}{\partial z_1} - \frac{\partial a_{11}}{\partial z_2}) & 0 & \frac{1}{2} \frac{\partial a_{11}}{\partial z_2} & \frac{1}{2} \frac{\partial a_{22}}{\partial z_1} \\ \frac{1}{2}(\frac{\partial a_{12}}{\partial z_2} - \frac{\partial a_{22}}{\partial z_1}) & a_{11} & \frac{1}{2} a_{12} & \frac{1}{2} \frac{\partial a_{11}}{\partial z_2} & a_{11} & \frac{1}{2} a_{12} \\ \frac{1}{2} \frac{\partial a_{22}}{\partial z_2} & \frac{1}{2} a_{12} & a_{22} & \frac{1}{2} \frac{\partial a_{22}}{\partial z_1} & \frac{1}{2} a_{12} & a_{22} \end{array} \right]$$

Globally one obtains a meromorphic function $R^{\mathbb{C}}w$ whose poles come from the zeros of $\det(w)^2$ and (2.2) follows.

Every point outside of the discriminant locus of w , $x \in X \setminus D_w$, has an open neighborhood U_x with $w|_{U_x} = \mu_1\mu_2$ with μ_i nowhere vanishing holomorphic 1-forms on U_x . The existence of local non vanishing holomorphic integrating factors for nowhere vanishing holomorphic 1-forms implies that after possibly shrinking once more U_x one has:

$$w|_{U_x} = f(u)du_1du_2 \quad (2.3)$$

with $f \in \mathcal{O}(U_x)$ and (u_1, u_2) a holomorphic coordinate chart of U_x .

The "Gaussian curvature" for "complex metric" in the form (2.3) is given by:

$$R^{\mathbb{C}}w|_{U_x} = -\frac{2}{f} \frac{\partial^2 \log f}{\partial u_1 \partial u_2} \quad (2.4)$$

(f is non vanishing).

The condition $R^{\mathbb{C}}w|_{U_x} = 0$ (i.e. $\frac{\partial^2 \log f}{\partial u_1 \partial u_2} = 0$) is equivalent to $f(u) = f_1(u_1)f_2(u_2)$ on some ball B_x centered at x . Hence w has a holomorphic exact decomposition on B_x

$$w(u) = dF_1(u_1)dF_2(u_2)$$

where the F_i are the primitives of the f_i . Hence the condition that $P_2w = 0$ is equivalent to the existence of a locally exact decomposition of w at every point in $X \setminus D_w$, which implies the theorem.

Question. *Is there a differential operator P_m , $m > 2$, generalizing P_2 and characterizing closed symmetric m -differential on surface X ?*

The following is a sketch of an approach to show that such operators or better said a family of such differential operators do exist. Let w be a symmetric m -differential on a surface X . Locally on an sufficiently small open neighborhood U_x of a generic point $x \in X$ the symmetric tensor w is given by the product

$$w|_{U_x} = \mu_1^{m_1} \dots \mu_k^{m_k}$$

with $\mu_i \in H^0(U_x, \Omega_X^1)$ and $\mu_i \wedge \mu_j$ nowhere vanishing for $i \neq j$. In this case w defines a nonsingular k -web \mathcal{W}_w , i.e. a family of k distinct foliations \mathcal{F}_i on X which are pairwise transversal and smooth on U_x . Let $\{z_i\}_{i=1, \dots, k}$ with $z_i \in \mathcal{O}(U_x)$ be a set of local functions such that: 1) dz_i are nowhere vanishing and 2) whose level sets are the leaves of the foliations \mathcal{F}_i on U_x . For such a collection $\{z_i\}_{i=1, \dots, k}$ one gets the decomposition $w|_{U_x} = f \prod_{i=1}^k dz_i^{m_i}$ with $f \in \mathcal{O}(U_x)$.

Let us consider the germ a nonsingular m -web \mathcal{W} at a point $x \in X$ defined by the symmetric differential $dz_1 \dots dz_m$ with $\{z_i\}_{i=1, \dots, m}$ a collection as above. Any germ w_x of a symmetric differential w at x with $\mathcal{W}_{w_x} = \mathcal{W}$ can be written in the form

$$w_x = f \prod_{i=1}^m dz_i \tag{2.5}$$

with $f \in \mathcal{O}_x$. The jet of n -th order of a symmetric m -differential defining \mathcal{W} is determined by $(n+2)(n+1)/2$ coefficients (from the Taylor series of f), giving the dimension of $J^n(\mathcal{W}, x)$, the space of n -th order jets of symmetric m -differentials defining the m -web germ \mathcal{W} . We denote by $J^n(\mathcal{W}, x)_{cl} \subset J^n(\mathcal{W}, x)$ the space of n -th order jets of closed m -differentials defining the m -web \mathcal{W} . The symmetric differential w_x is closed if and only if the function f is of the form $f = \prod_{i=1}^m f_i(z_i)$. The n -th order jets of each function f_i (determined by $n+1$ coefficients) are involved in the n -th order jet of the product function f and the constant term of the product f imposes only one condition of the n -th order jets of the f_i . Consequently, $J^n(\mathcal{W}, x)_{cl}$ is a subvariety of $J^n(\mathcal{W}, x)$ of dimension at most $mn+1$ and hence it is a proper subvariety once $n > 2m-3$.

Let $J^n(m, x)$ ($J^n(m, x)_{cl}$) be the set of n -th order jets of symmetric (closed) m -differentials at x . From the previous discussion it follows that once $n > 2m-3$ the closure $\bar{J}^n(m, x)_{cl}$ of set $J^n(m, x)_{cl}$ is a proper affine subvariety of $J^n(m, x)$. On $J^n(m, x)$ we have the natural action of $J^n \text{Aut}(\mathbb{B}^2)$ which is the group of n -th order jets of holomorphic

automorphisms of the ball the 2-ball (\mathbb{B}^2). The group $J^n \text{Aut}(\mathbb{B}^2)$ is an algebraic group which is finite-dimensional nilpotent extension of $GL(2)$. The subvariety $\bar{J}^n(m, x)_{cl}$ is naturally invariant under the above action of $J^n \text{Aut}(\mathbb{B}^2)$.

Let F be a regular function on $J^n(m, x)$ which vanishes on $\bar{J}^n(m, x)_{cl}$ and satisfies $F(gw_x) = \chi^N(g)F(w_x) \forall w_x \in J^n(m, x)$ and $\forall g \in J^n \text{Aut}(\mathbb{B}^2)$ with $\chi : J^n \text{Aut}(\mathbb{B}^2) \rightarrow GL(2) \rightarrow C^*$ natural projection and $N \in \mathbb{N}^+$ (the function F with the latter property will be called a semi-invariant function relative to the group action). Standard invariant theory gives that there is a finite set of semi-invariant regular functions F generating the ideal of semi-invariant functions vanishing on $\bar{J}^n(m, x)_{cl}$. Thus the function F defines a nonlinear map of vector bundles over X :

$$F' : J^n(m, x) \rightarrow NK_X$$

with F' mapping the (nonlinear) sub-fibration $\bar{J}^n(m, x)_{cl}$ into zero section of NK_X . The map F' on the n -th order jets of symmetric m -differential induces a differential operator of order n

$$D_F : H^0(X, S^m \Omega_X^1) \rightarrow H^0(X, NK_X)$$

which is trivial on the closed symmetric m -differentials which define nonsingular m -webs. Our previous discussion stating that if $n > 2m - 3$, then $\bar{J}^n(m, x)_{cl} \subsetneq J^n(m, x)$ implies that the n -th order differential operators just described will vanish on the closed symmetric m -differentials but will be nontrivial on generic symmetric m -differentials. Note that for the case of $m = 2$ this approach gives that we need to go to jets of order 2 to obtain a differential operator which vanishes on closed but not on generic symmetric differentials (this matches result in theorem 2.1). The construction just described raises up many interesting questions. The most fundamental questions are clearly how to find such semi-invariant functions F and operators D_F naturally for arbitrary m and what are the properties of such operators.

2.3 1st kind, local systems and global decompositions.

In this section we describe the analytical and topological objects (respectively twisted holomorphic closed 1-forms and local systems) that can be associated to a closed symmetric 2-differential of the 1st kind and establish two basic facts about the locus where a closed symmetric 2-differential fails to be of the 1st kind. In the next section we will determine the properties and geometric consequences of these objects. We remind the reader that the case of interest concerns 2-differentials of rank 2, the case of rank 1 will be mentioned just in passing (for full details see [BoDeO11]).

The local holomorphic exact decompositions of a closed symmetric differential w which are the form

$$w|_U = (df_1)^{m_1} \dots (df_k)^{m_k} \quad (2.6)$$

with $df_i \wedge df_j \neq 0$, have rigidity properties. The strength of the rigidity is dependent on a notion coming from the theory of webs, the abelian rank of the k -web associated to the differential w on U (for the notion of abelian rank see for example [ChGr78]). In the case of interest, i.e. differentials of degree 2, then the decomposition (2.6) has the strongest form of rigidity, i.e. the f_i are unique up to a multiplicative constant and an additive constant (in the case of rank 2 this is a manifestation of the triviality of the abelian rank of the 2-web and will be directly explained below).

Remark 2.2. *i) A rank 2 symmetric 2-differential of the 1st kind is always locally of the form (2.6) (by definition).*

ii) The case of a rank 1 symmetric 2-differential of the 1st kind is distinct, there might be points where w can not be locally written in the form (2.6). The example to have in mind is $w = z_1(dz_1)^2$, which can not be put in the form (2.6) on any open set intersecting $\{z_1 = 0\}$ (due to the absence of a well defined square root). In general, let $(w)_0 = \sum_i l_i D_i$, be the irreducible decomposition of $(w)_0$. The local decomposition of type (2.6) exist in a neighborhood of every point outside of the divisor:

$$E_w = \sum_{j \in \{i | m \nmid l_i\}} D_j$$

The presence of E_w has an impact on the topological properties that can be derived from the presence of a rank 1 symmetric differential (see section 3.1 and [BoDeO11] for full details).

Lemma 2.3. *Let X be a smooth complex manifold and w a symmetric 2-differential having a closed decomposition, i.e. $w|_U = \phi_1 \phi_2$, with $\phi_i \in H^0(U, \Omega_{c_1}^1)$ for some Zariski open set $U \subset X$.*

i) If w is of rank 2, then the closed decomposition of w is unique, up to factor multiplication by constants. More precisely, if $V \subset X$ is open and connected and $\phi_1 \phi_2 = w|_V = \psi_1 \psi_2$ are two closed decompositions of $w|_V$, then:

$$\psi_i = c_i \phi_i \quad c_2 = c_1^{-1} \in \mathbb{C}^*$$

ii) If w is of rank 1, then the closed decompositions of w are not unique. However, any two decompositions of the form $w = (\phi)^2 = (\psi)^2$ with $\phi, \psi \in H^0(V, \Omega_{c_1}^1)$, $V \subset X$ open, are also unique, up to factor multiplication by constants ($\psi = \pm \phi$).

Proof. The case of rank 1 is clear. Consider the case where w is of rank 2. Let $x \in X$ and U_x be an open neighborhood of x where $\phi_i|_{U_x} = df_i$ and $\psi_i|_{U_x} = dg_i$ with $f_i, g_i \in \mathcal{O}(U_x)$.

The differential w being of rank 2 implies that we could have chosen $x \in X$ such that $df_1(x) \wedge df_2(x) \neq 0$, i.e. f_1 and f_2 can be viewed as local holomorphic coordinates around x .

After reordering, one can make $df_i \wedge dg_i \equiv 0$ for $i = 1, 2$. The relation $df_i \wedge dg_i \equiv 0$ implies that near x the g_i is a function of f_i , $g_i = g_i(f_i)$. Hence $dg_1 dg_2 = df_1 df_2$ implies that $g'_1(f_1)g'_2(f_2) = 1$ must hold, which can only happen if $g'_1(f_1)$ and $g'_2(f_2)$ are nontrivial constant functions (since $df_1(x) \wedge df_2(x) \neq 0$). So $\psi_i = c_i \phi_i$ on a neighborhood of x and hence on the whole V via the principle of analytic continuation.

Remark/Notation 2.4. *A symmetric 2-differential of the 1st kind and rank 2 on a complex manifold X is either split or there is an associated unramified double cover of X*

$$s_w : X' \rightarrow X \quad (2.7)$$

such that $s_w^* w$ splits.

The ordering at each point of X of the two foliations associated to w might not be possible to be made consistent on the whole X . In fact, any from any choice of local orderings of the two foliations we get a representation of $\rho : \pi_1(X) \rightarrow S_2$, the regular cover associated with this representation is the desired cover s_w .

The next proposition derives from a split 2-differential of the 1st kind w a dual pair of local systems and a decomposition of w as a product of twisted closed holomorphic 1-forms. This decomposition will be used in section 3 to derive the geometric/topological properties of X . If the w is non split, then the remark above tell us that the pair $(X', s_w^* w)$ has this decomposition from which we derive again the geometric/topological properties of X .

Proposition 2.5. *Let X be a smooth complex manifold and $w \in H^0(X, S^2 \Omega_X^1)$ be split and closed of the 1st kind.*

i) (rank 1) w has a decomposition on $X \setminus E_w$, $w|_{E_w} = \phi^2$ with $\phi \in H^0(X \setminus E_w, \Omega_{\mathbb{C}l}^1 \otimes_{\mathbb{C}} \mathbb{C}_w)$, where \mathbb{C}_w is a local system of rank 1 associated to a 1-cocycle with values in \mathbb{Z}_2 .

ii) (rank 2) w has a decomposition:

$$w = \phi_1 \phi_2 \quad (2.8)$$

with $(\phi_1, \phi_2) \in H^0(X, \Omega_{\mathbb{C}l}^1 \otimes_{\mathbb{C}} (\mathbb{C}_w \oplus \mathbb{C}_w^))$ where \mathbb{C}_w is a local system of rank 1 whose isomorphism class is uniquely determined (up to its dual) by w .*

Proof. Case of rank 1, see [BoDeO11]. Case of rank 2. Let $\mathcal{U} = \{U_i\}_{i \in I}$ be a covering of X by holomorphic balls such that their intersection are contractible. This covering can be chosen such that $w|_{U_i} = df_{1i} df_{2i}$ with $f_{1i}, f_{2i} \in \mathcal{O}(U_i)$ (1st kind) and $df_{1i} \wedge df_{1j} \equiv 0$ on $U_i \cap U_j$ (split). Applying Lemma 2.3, it follows that:

$$df_{\alpha i} = c_{\alpha, ij} df_{\alpha j} \quad \text{with } c_{2, ij} = c_{1, ij}^{-1} \quad (2.9)$$

with $c_{\alpha, ij} \in \mathbb{C}^*$ giving for each $\alpha = 1, 2$ one 1-cocycle $\{c_{k, ij}\} \in Z^1(\mathcal{U}, \mathbb{C}^*)$. It follows from (2.9) that:

$$(\phi_1, \phi_2) := (\{df_{1i}\}_{i \in I}, \{df_{2i}\}_{i \in I}) \in H^0(X, \Omega_{\mathbb{C}^1}^1 \otimes (\mathbb{C}_w \oplus \mathbb{C}_w^*))$$

where \mathbb{C}_w is the local system of rank 1 determined by the 1-cocycle $\{c_{1, ij}\}$.

The pair of local systems $(\mathbb{C}_w, \mathbb{C}_w^*)$ is uniquely determined up to isomorphism (and order, of course) by the 2-differential of the 1st kind w . Let $\mathcal{V} = \{V_k\}$ be another cover of X for which the $w|_{V_k}$ are holomorphically exact decomposable with $w|_{V_k} = dg_{1k} dg_{2k}$ and let $\mathcal{W} = \{W_r\}$ a Leray cover relative to locally constant sheaves of X such that each W_r is such that $W_r \subset U_{i(r)}$ and $W_r \subset V_{k(r)}$. The induced decompositions $w|_{W_r} = df_{1i(r)}|_{W_r} df_{2i(r)}|_{W_r}$ and $w|_{W_r} = dg_{1k(r)}|_{W_r} dg_{2k(r)}|_{W_r}$ following the argument above can be used to derive two pairs of 1-cocycles with values in \mathbb{C}^* relative to the cover \mathcal{W} . Since by lemma 2.3 the following $df_{\alpha i(r)}|_{W_r} = c_{\alpha, r} dg_{\alpha k(r)}|_{W_r}$ holds for $\alpha = 1, 2$, it follows that the 1-cocycles are cohomologous and hence the pairs of associated local systems are isomorphic.

Example: The presence of twisting, i.e. the nontriviality of the local system associated to a closed symmetric differential, occurs. Let C_1 and C_2 be two curves with an involution without fixed points. The surface $Y = C_1 \times C_2 / \mathbb{Z}_2$ where \mathbb{Z}_2 acts diagonally is such that $q(C_1 \times C_2) - q(Y) \geq g(C_1)/2 - 1$ where $g(C_1) \geq g(C_2)$. So if $g(C_1) \geq 6$ there are anti-invariant holomorphic 1-forms on $C_1 \times C_2$ that are not proportional. If two such forms define the same foliation, then they would define a fibration and would come from a curve.

The next lemma shows that the locus where a closed differential fails to be of the 1st kind has no isolated points and hence is of pure codimension 1.

Lemma 2.6. *Let X be a complex manifold and $w \in H^0(X, S^2\Omega_X^1)$ be closed of the 1st kind outside of codimension 2. Then w is closed of the 1st kind on X .*

Proof. Let $Z \subset X$ be the locus of codimension at least 2 consisting of all the points of X where w might fail to have holomorphic exact decomposition at. Pick any $x \in Z$ and $B_x \subset X$ a ball centered at x . Let $\mathcal{U} = \{U_i\}$ be an open covering of $B_x \setminus Z$ on which:

$$w|_{U_i} = df_{1i} df_{2i} \quad (2.10)$$

with $f_{1i}, f_{2i} \in \mathcal{O}(U_i)$. Since $\pi_1(B_x \setminus Z) = 0$ we can order for each i the functions f_{ki} such that on the intersections U_{ij} $df_{ki} \wedge df_{kj} = 0$. By lemma 2.3 the equalities

$$df_{ki} = c_{k, ij} df_{kj}$$

hold on U_{ij} giving rise to two 1-cocycles (for $k=1$ and 2):

$$\{c_{k,ij}\} \in Z^1(\mathcal{U}, \mathbb{C}^*)$$

These cocycles must be coboundaries since $B_x \setminus Z$ is simply connected. Hence for each k there is a 0-cochain $\{c_{k,i}\}$ with values in \mathbb{C}^* such that $d(c_{k,i}f_{k,i}) = d(c_{k,j}f_{k,j})$ on U_{ij} . One can make $c_{2,i} = c_{1,i}^{-1}$ and hence $w|_{U_i} = d(c_{1,i}f_{1i})d(c_{2,i}f_{2i})$. The collections $\{d(c_{k,i}f_{ki})\}$ glue to give two closed 1-forms on $B_x \setminus Z$:

$$\mu_1, \mu_2 \in H^0(B_x \setminus Z, \Omega_{\text{cl}}^1)$$

with $w|_{B_x \setminus Z} = \mu_1\mu_2$. Again since $\pi_1(B_x \setminus Z) = 0$ it follows that the forms μ_i are actually exact, i.e. $\mu_i = df_i$ with $f_1, f_2 \in \mathcal{O}(B_x \setminus Z)$. Hartog's extension theorem gives the holomorphic extensions $\bar{f}_1, \bar{f}_2 \in \mathcal{O}(B_x)$ of respectively f_1 and f_2 and hence w has the holomorphic exact decomposition $w|_{B_x} = d\bar{f}_1d\bar{f}_2$ on B_x proving the lemma.

Proposition 2.7. *Let X be a smooth complex manifold and $w \in H^0(X, S^2\Omega_X^1)$ a closed differential of rank 2. Then the locus where w fails to be of the 1st kind is contained in the union of the codimension 1 irreducible components of the degeneracy locus D_w .*

Proof. The result follows from lemma 2.6 if one shows that the locus where w fails to be of the 1st kind lies in D_w . Since $X \setminus D_w$ is connected and the locus where w is of the 1st kind is open and nonempty, it is enough to prove the claim that the set where w is of the 1st kind is also closed in $X \setminus D_w$.

So we proceed to prove the claim, that is: if $x \in X \setminus D_w$ is such that all balls B_x centered at x have a point $y \in B_x$ where w has a holomorphic exact decomposition at, then w also has a holomorphic exact decomposition at x . Since $x \in X \setminus D_w$ then w is split at x and one has a ball B_x centered at x where

$$w|_{B_x} = \mu_1\mu_2$$

with $\mu_i \in H^0(B_x, \Omega_X^1)$. Using the hypothesis of the claim there is a point $y \in B_x$ at which w has a holomorphic exact decomposition at,

$$w|_{U_y} = dh_1dh_2 \tag{2.11}$$

with $h_i \in \mathcal{O}(U_y)$. It follows from (2.11) that the μ_i are completely integrable on the whole B_x . Since $\mu_i(x) \neq 0$ and the μ_i are completely integrable one can shrink B_x so that the μ_i have first integrals $u_i \in \mathcal{O}(B_x)$, i.e. $\mu_i = f_i du_i$ with $f_i, u_i \in \mathcal{O}(B_x)$. Since $\mu_1 \wedge \mu_2$ is nowhere vanishing on B_x , again by shrinking B_x we can assume u_1 and u_2 are two coordinates of a holomorphic chart (u_1, \dots, u_n) for B_x . So one has

$$w|_{B_x} = h(u)du_1du_2$$

(with $h(u) = f_1 f_2 \in \mathcal{O}(B_x)$). In the ball B_x there is a point y where w has a holomorphic exact decomposition at, still describe this decomposition by (2.1). From $dh_1 dh_2 = h du_1 du_2$ on U_y it follows that $h_i = h_i(u_i)$ and $h(u) = h'_1(u_1)h'_2(u_2)$ on U_y . This in turn implies that $h(u) = h(u_1, u_2)$ on the whole B_x and $h(u_1, u_2) = h'_1(u_1)h'_2(u_2)$ on U_y . The latter condition, as discussed in the proof of theorem 2.1, implies that that h satisfies the differential equation $\frac{\partial^2 \log h}{\partial u_1 \partial u_2} = 0$ on U_y and consequently on B_x . Hence the function h satisfies the just mentioned differential equation on a neighborhood of x and it depends only on z_1 and z_2 , this implies $h = h_1(u_1)h_2(u_2)$ on a neighborhood of x and w therefore has a holomorphic exact decomposition at x .

3. GLOBAL GEOMETRIC PROPERTIES

In the first part of this section we determine the topological restrictions and geometric features that are implied by closed symmetric 2-differentials of the 1st kind. Here we are mainly interested in the properties of the fundamental group and the existence of varieties (and maps into them) from which the differentials would be induced. The case of 2-differentials of rank 1 follows from a previous work by the authors [BoDeO11], hence the focus lies in the rank 2 case. In the last subsection, we describe the geometry of a very natural class of closed 2-differentials (not necessarily of the 1st kind), the class consisting of products of two closed meromorphic 1-forms.

3.1 1st kind of rank 1.

In [BoDeO11] the authors studied symmetric differentials of rank 1 of all degrees on projective manifolds. We present here, for the sake of completeness, the statement of the result concerning the case of interest, i.e. degree 2, with a small modification concerning the condition of being of 1st kind plus a few remarks. The main result of that paper gives for the case of interest:

Theorem 3.1. [BoDeO11] *Let X be a smooth projective manifold and $w \in H^0(X, S^2\Omega_X^1)$ a nontrivial differential of rank 1. Then:*

- i) w is closed on X and closed of the 1st kind outside of codimension 2.*
- ii) There is a cover of X which is generically 2 to 1 $g : X' \rightarrow X$ such that $g^*w = \mu^{\otimes 2}$ with $\mu \in H^0(X', \Omega_{X'}^1)$.*
- iii) There is a holomorphic map from X to a \mathbb{Z}_2 -quotient of an abelian variety with isolated singularities $a_w : X \rightarrow A_w/\mathbb{Z}_2$, such that $w = a_w^*(u)$ and $u \in H^0(A_w/\mathbb{Z}_2, S_{\text{orb}}^m \Omega_{A_w/\mathbb{Z}_2}^1)$.*

iv) There is a 2-negative divisor $E \subset (w)_0 \subset X$ such that $\pi_1(X \setminus E)$ is infinite. More precisely, $\pi_1(X \setminus E)$ has a normal subgroup Γ of finite index for which $\pi_1(X \setminus E)/\Gamma$ is cyclic and its abelianization, $\Gamma/[\Gamma, \Gamma]$, is an infinite group.

Remarks: 1) A divisor D is said to be 2-negative if for all smooth surfaces $S \subset X$, the divisor $D \cap S$ of S is negative.

2) item iii) states that geometrically a symmetric 2-differential of rank 1 (of 1st kind or not) comes from an orbifold symmetric differential on a \mathbb{Z}_2 -quotient of an abelian variety. If $w = \mu^{\otimes 2}$ with $\mu \in H^0(X, \Omega_X^1)$, then a_X is the natural a_w , where a_X is the Albanese morphism.

3) The divisor E lies inside the ramification divisor of the covering map g in ii) (which in turn lies inside the union of the irreducible components of $(w)_0$ with odd multiplicity).

4) For the case of closed 2-differentials of the 1st kind of rank 2 we will see below that one obtains topological conditions for the whole complex manifold X , while in this case (of rank 1) the conditions are for the complement $X \setminus E$. The reason for this distinction is the fact that for 2-differentials of the first kind of rank 1 the rigidity of the holomorphic exact decompositions at the points in E is weakened (outside of E one can write $w = (df)^2$ and such decomposition is unique up to multiplication by ± 1 but for example $w = z^3(dz)^2$ has no natural exact decomposition that is unique).

5) There are projective manifolds with a closed symmetric 2-differential of the 1st kind and rank 1 which are simply connected (see [BoDeO11]).

3.2 1st kind of rank 2.

In order to extract the geometrical/topological properties associated to closed symmetric 2-differentials of the 1st kind we are going to take full advantage of their global decomposition of as products of twisted closed 1-differentials. As seen in proposition 2.5, if w is split $w = \phi_1 \phi_2$, with $(\phi_1, \phi_2) \in H^0(X, \Omega_{\text{cl}}^1 \otimes_{\mathbb{C}} (\mathbb{C}_w \oplus \mathbb{C}_w^*))$ where $(\mathbb{C}_w \oplus \mathbb{C}_w^*)$ is the dual pair of local systems associated to w via the closed decomposition.

There are 2 elements in the above decomposition with a geometric meaning. One is the dual pair of local systems $(\mathbb{C}_w, \mathbb{C}_w^*)$ giving us a pair of dual characters of the fundamental group. The other are the twisted closed 1-differentials ϕ_i which topologically define elements of 1st cohomology group of X with coefficients in the local system \mathbb{C}_w or \mathbb{C}_w^* and geometrically define special type of foliations, e.g. if $\mathbb{C}_w \otimes \mathcal{O}$ is non-torsion the foliations are algebraic (it follows from the work Beauville, Green-Lazarsfeld and Simpson on the cohomology loci (see references)) and if torsion the foliations share the same properties as foliations defined by global holomorphic 1-forms. A key ingredient of next result is that if X is projective, then the isomorphism class of the local system \mathbb{C}_w must be torsion. Hence in the projective case, if w is split, then up to finite

cyclic unramified covers, rank 2 differentials of the 1st kind are just products of closed 1-differentials.

Theorem 3.2. *Let X be a smooth projective manifold with $w \in H^0(X, S^2\Omega_X^1)$ a non-trivial rank 2 closed differential of the 1st kind. Then:*

i) X has a holomorphic map to a cyclic or dihedral quotient of an abelian variety from which the symmetric differential w is induced from. More precisely, there is a commutative diagram

$$\begin{array}{ccc} X' & \xrightarrow{a_{X'}} & \text{Alb}(X') \\ f \downarrow & & q \downarrow \\ X & \xrightarrow{a} & \text{Alb}(X')/G \end{array}$$

*and $f^*w = a_{X'}^*\omega$ with $\omega \in H^0(\text{Alb}(X'), S^2\Omega_{\text{Alb}(X')}^1)^G$ where $f : X' \rightarrow X$ is an unramified G -Galois covering and $a_{X'} : X' \rightarrow \text{Alb}(X')$ the Albanese map. The group G is \mathbb{Z}_m if w is split and D_{2m} if w is non split.*

ii) $\pi_1(X)$ is infinite, more precisely $\exists \Gamma \triangleleft \pi_1(X)$ such that $\pi_1(X)/\Gamma$ is finite cyclic or dihedral and its abelianization, $\Gamma/[\Gamma, \Gamma]$, is an infinite group.

Proof. We start by considering the case when w is split. A split closed 2-differential of the first kind and rank 2 has as stated in proposition 2.5 the decomposition:

$$w = \phi_1\phi_2 \tag{3.1}$$

with $(\phi_1, \phi_2) \in H^0(X, \Omega_{\mathbb{C}}^1 \otimes_{\mathbb{C}} (\mathbb{C}_w \oplus \mathbb{C}_w^*))$ where \mathbb{C}_w is a local system of rank 1 whose isomorphism class is uniquely determined up to its dual by w . We will first show how the theorem follows if the isomorphism class of local system \mathbb{C}_w is torsion and then prove that the class of \mathbb{C}_w is indeed torsion.

Assume: the isomorphism class of \mathbb{C}_w is torsion.

Associated to the local system \mathbb{C}_w (whose isomorphism class is torsion) we have a finite character $\rho_w : \pi_1(x) \rightarrow \mathbb{C}^*$, with image a cyclic group \mathbb{Z}_m . The unramified cyclic Galois cover

$$f : X' \rightarrow X$$

associated to the character ρ_w is such that $f^*\mathbb{C}_w$ is isomorphic to the trivial local system \mathbb{C} on X' .

First we show how to use the pullback of the decomposition (3.1) to X' to obtain the decomposition

$$f^*w = \mu_1\mu_2$$

with $\mu_i \in H^0(X', \Omega_{X'}^1)$ (despite the $f^*\phi_i$ not being the 1-forms μ_i). Let $\mathcal{U} = \{U_i\}_{i \in I}$ be a Leray open covering of X' relative to locally constant sheaves. On the contractible open sets U_i one has $f^*\phi_k|_{U_i} = dg_{k,i}$ with $g_{k,i} \in \mathcal{O}(U_i)$ for $k = 1, 2$. As in the proposition 2.5, on the intersections $U_i \cap U_j$, $dg_{k,i} = b_{k,ij}dg_{k,j}$, with $b_{1,ij} = b_{2,ij}^{-1}$ and $\{b_{1,ij}\}$ the 1-cocycle relative to \mathcal{U} giving the local system $f^*\mathbb{C}_w$. Since the local system $f^*\mathbb{C}_w$ is isomorphic to the trivial local system \mathbb{C} on X' there are 0-cochains relative to \mathcal{U} with values in \mathbb{C}^* , $\{b_{k,i}\}_{i \in I}$ ($b_{1,i} = b_{2,i}^{-1}$), whose coboundaries are the 1-cocycles $\{b_{k,ij}\}$ for $k = 1, 2$. To obtain the 1-forms μ_k giving $f^*w = \mu_1\mu_2$ one untwists the collections $\{dg_{k,i}\}_{i \in I}$ using the 0-cochains $\{b_{k,i}\}_{i \in I}$

$$\mu_k = \{b_{k,i}dg_{k,i}\}_{i \in I}$$

The \mathbb{Z}_m action on the Galois covering space X' of X induces due to the universal properties of the Albanese variety of X' an action on $Alb(X')$ and the Albanese morphism $a_{X'} : X' \rightarrow Alb(X')$ descends to the morphism $a : X \rightarrow Alb(X')/\mathbb{Z}_m$ asked in part i) of the theorem. It follows from $f^*w = \mu_1\mu_2$ with $\mu_k \in H^0(X', \Omega_{X'}^1)$ that $f^*w = a_{X'}^*\omega$ with $\omega \in H^0(A, S^2\Omega_X^1)^{\mathbb{Z}_m}$. Finally the topological consequence, part ii), is a direct consequence of i).

Claim: the isomorphism class of \mathbb{C}_w is torsion.

Case: isomorphism class of \mathbb{C}_w is non torsion but $L_w = \mathbb{C}_w \otimes \mathcal{O}$ is torsion.

Since X is a compact kahler manifold there is an unique isomorphism class of unitary local systems giving any fixed flat line bundle. Let \mathbb{C}_u be a unitary local system such that $L_w \simeq \mathbb{C}_u \otimes \mathcal{O}$. From L_w being torsion plus the uniqueness of the isomorphism class of unitary local systems giving the trivial line bundle it follows that the isomorphism class of \mathbb{C}_u is also torsion. Therefore, as above, there is a finite unramified covering $f : X' \rightarrow X$ such that $f^*\mathbb{C}_u \simeq \mathbb{C}$ and hence $f^*L_w \simeq \mathcal{O}$. Note that $f^*\mathbb{C}_w$ is not isomorphic to the trivial local system.

Consider the pullback, $f^*w = f^*\phi_1f^*\phi_2$, of the decomposition (3.1) to X' . Let $\mathcal{U} = \{U_i\}_{i \in I}$ be a Leray open covering of X' relative to locally constant sheaves where $\{f^*\phi_k|_{U_i}\}_{i \in I} = \{dg_{k,i}\}_{i \in I}$ with $g_{k,i} \in \mathcal{O}(U_i)$ and $k = 1, 2$. Hence

$$f^*w|_{U_i} = dg_{1,i}dg_{2,i} \tag{3.2}$$

On the intersections $U_i \cap U_j$, $dg_{k,i} = b_{k,ij}dg_{k,j}$, with $\{b_{1,ij}\}$ the 1-cocycle relative to \mathcal{U} giving the local system $f^*\mathbb{C}_w$ and $b_{1,ij} = b_{2,ij}^{-1}$.

The first paragraph of this case tells us that while the cohomology class $[\{b_{1,ij}\}] \in H^1(X', \mathcal{O}^*)$ is trivial, the cohomology class $[\{b_{1,ij}\}] \in H^1(X', \mathbb{C}^*)$ is nontrivial. Let $\{h_i\}_{i \in I}$ be the 0-cochain with values in \mathcal{O}^* whose coboundary is $\{b_{1,ij}\}$ then set

$$\mu_1 = \{h_i dg_{1,i}\}_{i \in I} \quad \text{and} \quad \mu_2 = \{h_i^{-1} dg_{2,i}\}_{i \in I}$$

By construction both collections $\{h_i dg_{1,i}\}_{i \in I}$ and $\{h_i^{-1} dg_{2,i}\}_{i \in I}$ match on the intersections making $\mu_k \in H^0(X', \Omega_{X'}^1)$ of $k = 1, 2$. Since X' is compact kahler $d\mu_k = 0$ and hence

$$\{h_i dg_{1,i}\}_{i \in I} = \{d\hat{g}_{1,i}\}_{i \in I} \quad \text{and} \quad \{h_i^{-1} dg_{2,i}\}_{i \in I} = \{d\hat{g}_{2,i}\}_{i \in I} \quad (3.3)$$

for some $\hat{g}_{1,i}, \hat{g}_{2,i} \in \mathcal{O}(U_i)$. Therefore we get for each U_i

$$f^*w|_{U_i} = d\hat{g}_{1,i}d\hat{g}_{2,i} \quad (3.4)$$

and end up with two holomorphic exact decompositions of $w|_{U_i}$, (3.2) and (3.4). Since w is of rank 2, it follows from lemma 2.3 that the h_i are actually constant. Hence $\{h_i\}_{i \in I}$ is 0-cochain with values in \mathbb{C}^* but this leads to $[\{b_{1,ij}\}] \in H^1(X, \mathbb{C}^*)$ being trivial, a contradiction.

Case: L_w (and \mathbb{C}_w) is non-torsion.

In this case we will use the geometric properties of twisted holomorphic differentials which were studied in [GrLa87], [Be92], [Si93] and [Ar] to understand the cohomology locus $S_m^1(X) = \{L \in Pic^\tau(X) | \dim H^1(X, L) \geq m\}$, where $Pic^\tau(X)$ is the variety of line bundles with trivial Chern class.

Consider an irreducible component Z of $S_m^1(X)$ containing L_w with $m = \dim H^0(X, L_w)$ and let $\alpha \in H^1(X, L_w)$ be the image of ϕ_2 from (3.1) via the complex anti-linear isomorphism

$$H^0(X, \Omega_X^1 \otimes L_w^*) \rightarrow H^1(X, L_w) \quad (3.5)$$

provided by conjugation. The work of Simpson [Si93] states that since the line bundle L_w is non-torsion, the variety Z must positive dimensional. By the construction hypothesis of Z one has that $\dim H^1(X, L) \geq \dim H^1(X, L_w)$ (in fact equality holds due to Grauert's semi-continuity theorem) for L in Z hence the class α is preserved under small deformations of L_w along Z . Using the work of [GrLa87] on the deformation theory of line bundles in $S_m^1(X)$, the class α being preserved by small deformations along Z implies that

$$\phi_2 \wedge u_1 = 0 \quad (3.6)$$

where $u_1 \in H^0(X, \Omega_X^1)$ is the conjugate of $v_1 \in T_{L_w^*} Pic^\tau(X) = H^1(X, \mathcal{O})$ giving a 1st order deformation of L_w in Z preserving α .

Beauville [Be92] obtained a Castelnuovo-De Franchis type theorem for twisted forms from the condition $\phi_2 \wedge u_1 = 0$. The Beauville-Castelnuovo-De Franchis theorem states that there is a connected fibration $f_1 : X \rightarrow C_1$, C_1 a smooth curve, such that:

- 1) $u_1 \in f_1^* H^0(C_1, \Omega_{C_1}^1)$
- 2) $L_w, L_w^* \in \text{Pic}^\tau(X, f_1)$

where $\text{Pic}^\tau(X, f_1)$ is the subvariety of $\text{Pic}^\tau(X)$ consisting of line bundles whose restrictions on the smooth fibers of f_k are trivial. The conditions (3.6) and 1) imply that the fibers f_1 are the leaves of the foliation defined by ϕ_2 .

Now repeat the previous argument replacing the line bundle L_w by the line bundle L_w^* and obtain a map $f_2 : X \rightarrow C_2$, where C_2 is a smooth curve, such that the fibers of f_2 are the leaves of the foliation defined by ϕ_1 and $L_w, L_w^* \in \text{Pic}^\tau(X, f_2)$.

In conclusion, we have that the non-torsion line bundle L_w is trivial along the smooth fibers of both fibrations $f_1 : X \rightarrow C_1$ and $f_2 : X \rightarrow C_2$. This can only happen if the fibrations share all fibers and hence the foliations ϕ_1 and ϕ_2 have the same leaves, which can not happen since w has rank 2.

If the symmetric differential w is non split, then consider the unramified double cover

$$s_w : X'' \rightarrow X$$

described in the remark 2.4 which was built such that $(s_w)^*w$ is split. Apply the previous results for the pair $(X'', (s_w)^*w)$ to obtain an unramified \mathbb{Z}_m covering $f : X' \rightarrow X''$ such that $(s_w \circ f')w = \mu_1 \mu_2$ with the $\mu_i \in H^0(X', \Omega_{X'}^1)$. The covering $f := (s_w \circ f') : X' \rightarrow X$ is an unramified Galois cover of X with Galois group D_{2m} and the result follows as above.

3.3 Products of closed meromorphic 1-differentials.

In this section we describe the geometry associated to closed holomorphic symmetric 2-differentials w of rank 2 which are the product of two closed meromorphic 1-forms, $w = \phi_1 \phi_2$. We show that w might not be of the 1st kind, but in this case there must exist a fibration over a curve of genus ≥ 1 and the Albanese dimension of X will (still) be greater or equal to 2.

Theorem 3.3. *Let X be a smooth projective manifold and $w \in H^0(X, S^2 \Omega_X^1)$ be a closed differential of rank 2 with a decomposition:*

$$w = \phi_1 \phi_2 \quad \text{with } \phi_i \in H^0(X, \Omega_{X,cl}^1(*)) \quad (3.7)$$

where $\Omega_{X,cl}^1(*)$ is the sheaf of closed meromorphic 1-forms. Then the Albanese dimension of $X \geq 2$ and either:

- 1) $w = \phi_1 \phi_2$ with $\phi_i \in H^0(X, \Omega_X^1)$, or
- 2) X has a map to a curve of genus ≥ 1 , $f : X \rightarrow C$ and $w = (f^* \varphi + u) f^* \mu$, where $u \in H^0(X, \Omega_X^1)$, $\varphi \in H^0(C, \Omega_C^1(*))$ and $\mu \in H^0(C, \Omega_C^1)$.

Proof. If the differentials ϕ_i have no poles, then 1) holds and the Albanese dimension is ≥ 2 since $\phi_1 \wedge \phi_2 \neq 0$. In the case the ϕ_i have poles, we can assume that $(\phi_i)_0 \cap (\phi_i)_\infty = \emptyset$ for $i = 1, 2$, where $(\phi_i)_0$ is the divisorial component of the zero locus of ϕ_i . This follows from the next lemma and the fact that if 2) holds for a pair X' and σ^*w , where $\sigma : X' \rightarrow X$ is a modification of X , then it also holds for the pair X and w .

Lemma 3.4. *Let X be a smooth projective manifold and $\phi \in H^0(X, \Phi_X^1(*))$ be a closed meromorphic 1-differential on X . Then there is a modification of X $\sigma : X' \rightarrow X$ such that:*

$$(\sigma^*\phi)_0 \cap (\sigma^*\phi)_\infty = \emptyset$$

and both divisors are normal crossings divisors.

Proof. There is a map $\sigma : X' \rightarrow X$ consisting of a finite sequence of blow ups such that the union of the divisor of poles and zeros of $\sigma^*\phi$ is a divisor with normal crossings. Locally near any $x \in (\sigma^*\phi)_0 \cap (\sigma^*\phi)_\infty$ the closed differential $\sigma^*\phi$ is of the form

$$\sigma^*\phi|_{U_x} = c \frac{dz_1}{z_1} + df$$

where (z_1, \dots, z_n) is a local chart near x such that $(\sigma^*\phi)_0 = \{z_2 = 0\}$, $c \in \mathbb{C}$ and $f \in \mathcal{M}(U_x)$. First observation is that $c = 0$ (no logarithmic pole), since $\sigma_1^*\phi|_{\{z_2=0\}} = 0$ implies the residue of $\sigma^*\phi$ along $\{z_1 = 0\}$ is 0. So $x \in (df)_0 \cap (df)_\infty$ must be a point of indeterminacy of f . After a finite number of further blowing ups one can resolve the indeterminacies of f and the result follows (note that this lemma is not true without the assumption that ϕ is closed).

Assume from now on that the differential ϕ_1 has poles. Denote by

$$P \subset (\phi_1)_\infty$$

the support (a reduced divisor) of a connected component of $(\phi_1)_\infty$. Since $w = \phi_1\phi_2$ is holomorphic, then

$$P \subset Z \subset (\phi_2)_0$$

where Z is the support of the connected component of $(\phi_2)_0$ containing P .

The following shows how the presence of P (and then Z) implies the existence of a fibration with $P = Z$ as a set theoretic fiber and ϕ_2 is induced from the base of the fibration.

Since Z is a closed analytic subvariety, Z has a neighborhood U such that Z is a deformation retract of U (moreover, due to $(\phi_2)_0 \cap (\phi_2)_\infty = \emptyset$, U can be chosen so that $(\phi_2)_\infty \cap U = \emptyset$). This implies that the periods of ϕ_2 on U are just the periods of ϕ_2 on Z and hence they all vanish and we can integrate ϕ_2 to get a holomorphic function

$\hat{f} = \int \phi_2$ on U . By construction Z is contained in a level of \hat{f} , since $Z \subset (\phi_2)_0$. In fact, we have more:

Claim: Z is a connected component of a level set of \hat{f} .

We reduce the problem to dimension 2. Let S be a general 2-dimensional complete intersection of X , $P' = P \cap S$ and $Z' = Z \cap S$. Suppose that the claim does not hold, then Z' is not a connected component of a level set of $\hat{f}|_{S \cap U}$. A slight modification of the Zariski's lemma (lemma 8.2 of [BHPV03]) gives that Z' is a negative divisor. This leads to a contradiction since we have $P' \subset Z'$ and

Subclaim: P' is not a negative divisor.

Assume P' is negative. Let $P' = \sum_{r=1}^m P'_r$ be the irreducible decomposition of P' and $U' \subset S$ a sufficiently small open neighborhood of P' such that $(\phi_1|_S)_\infty \cap U' = P'$. Set $i_S : S \hookrightarrow X$ to be the inclusion map and

$$\phi_{S,1} := i_S^* \phi_1$$

Note that P' is the support of one of its connected components of $(\phi_{S,1})_\infty$.

First we show that the differential $\phi_{S,1}$ is of the 2nd kind, i.e. it does not have residues, on U' . The residues of $\phi_{S,1}$ occur at the divisors D for which the complex number $c = \frac{1}{2\pi i} \int_\gamma \phi_{S,1}$, where γ is a simple loop around D , is nontrivial (c is then called the residue of $\phi_{S,1}$ at D). The residues of $\phi_{S,1}$ on U' can only occur at the irreducible components P'_r of P' . Since the simple loops γ_r around the P'_r are torsion in $H_1(U' \setminus P', \mathbb{Z})$ ([Mu61]) this implies that $\phi_{S,1}$ has no residues on U' ($c_r = \frac{1}{2\pi i} \int_{\gamma_r} \phi_{S,1} = 0$).

The differential $\phi_{S,1}$ being of the 2nd kind on U' implies that there is a Leray open covering $\mathcal{U} = \{U_i\}$ relative to locally constant sheaves of U' such that:

$$\phi_{S,1}|_{U_i} = dg_i \tag{3.8}$$

with $g_i \in \mathcal{M}(U_i)$ and that

$$(\phi_{S,1})_\infty \cap U' = \sum_{r=1}^m n_r P'_r \tag{3.9}$$

and $n_r \geq 2$ for all r . Set $P'' = \sum_{r=1}^m (n_r - 1)P'_r$. It follows from (3.8) and (3.9) that $(g_i)_\infty = P''|_{U_i}$. If $\{h_i = 0\}$, $h_i \in \mathcal{O}(U_i)$, are the equations defining the divisor P'' , then

$$g_i = \frac{v_i}{h_i}$$

with $v_i \in \mathcal{O}(U_i)$ such that $v_i|_{P'_r} \neq 0$. It follows from (3.8) that on $U_i \cap U_j$ the equality $g_i = g_j + d_{ij}$ holds with $d_{ij} \in \mathbb{C}$ and therefore also:

$$v_i = \frac{h_i}{h_j} v_j + d_{ij} h_i \tag{3.10}$$

According to (3.10) the collection $\{v_i\}$ gives a section:

$$t := \{v_i\} \in H^0(P'', \mathcal{O}_{P''}(P''))$$

which does not vanish identically on any irreducible component P'_r of P'' . Hence $P'_r.P'' \geq 0$ for all r and then by linearity one has $(P'')^2 \geq 0$ which contradicts the assumption that P' is negative and ends the proof of the claim.

Assume Z is a connected component of the level set $\hat{f}^{-1}(0)$. Using the compactness of Z we can shrink U so that $Z = \hat{f}^{-1}(0)$ as a set. The open mapping theorem plus Z being compact imply that there is an open disc $0 \in \Delta \subset \mathbb{C}$ such that

$$\hat{f}|_{\hat{f}^{-1}(\Delta)} : \hat{f}^{-1}(\Delta) \rightarrow \Delta \quad (3.11)$$

is a proper fibration onto Δ with $\text{Supp} \hat{f}^{-1}(0) = Z$.

The local fibration $\hat{f}|_{\hat{f}^{-1}(\Delta)} : \hat{f}^{-1}(\Delta) \rightarrow \Delta$ implies the existence of a global connected fibration $f : X \rightarrow C$ where C is a smooth curve and $P = Z$ occur (set theoretically) as a fiber and $\phi_2 = f^*\mu$ with $\mu \in H^0(C, \Omega_C^1(*))$.

The fact that the local fibration (3.11) implies the existence of a global fibration is a well known result. For completeness we mention a result of this type (stronger than we need) that asserts that if X has 3 connected effective divisors that are pairwise disjoint and belong to the same rational cohomology class in $H^2(X, \mathbb{Q})$, then X has a unique connected fibration onto a smooth curve with the divisors as fibers, see [To00].

The conclusion that $\phi_2 = f^*\mu$ for some $\mu \in H^0(C, \Omega_C^1(*))$ is a consequence of

$$\phi_2 \wedge f^*\eta = 0 \quad (3.12)$$

where η is any meromorphic 1-form on C . The vanishing of $\phi_2 \wedge f^*\eta$ holds since by construction the fibers of f are leaves of the foliation defined ϕ_2 . It follows from (3.12) that $\phi_2 = gf^*\eta$ for some $g \in \mathcal{M}(X)$, but since both ϕ_2 and $f^*\eta$ are closed, one has $dg \wedge f^*\eta = 0$, hence g is constant along the fibers of f and comes from $\hat{g} \in \mathcal{M}(C)$ giving $\phi_2 = f^*\mu$ with $\mu = \hat{g}\eta$.

The fibration $f : X \rightarrow C$ has also the crucial property that the polar divisors of both differentials ϕ_1 and ϕ_2 occur as fibers. More precisely, one has that the connected components of $(\phi_1)_\infty$ and $(\phi_2)_\infty$ occur as full fibers of f . This follows from the connected components of $(\phi_1)_\infty$ and $(\phi_2)_\infty$ not being exceptional and the fact that, other than P , they can not intersect the fiber of f , $P = Z$.

The next step is to show that ϕ_2 is actually holomorphic. Suppose $(\phi_2)_\infty \neq \emptyset$, then the argument that gave the existence of the connected fibration $f : X \rightarrow C$ from $(\phi_1)_\infty \neq \emptyset$ gives that there is a connected fibration $f' : X \rightarrow C'$ such that $\phi_1 = f'^*\mu'$ with $\mu' \in H^0(C, \Omega_C^1(*))$. According to the previous paragraph both connected fibrations $f : X \rightarrow C$ and $f' : X \rightarrow C'$ share the fiber $P = Z$. This implies that the fibrations

must coincide (see next paragraph). However the fibrations can not coincide since this would imply that symmetric differential w would not be of rank 2.

Each fibration gives a holomorphic function on a neighborhood U of P . If the fibrations were distinct, then only finitely many level sets of the two functions would be common to both functions (the level sets of a function are fibers of the corresponding fibration). Hence the function coming from one fibration would provide a non constant holomorphic function on some fiber of the other fibration, which can not happen. This forces the connected fibrations f and f' to coincide.

In the final step to prove 2) we obtain the description of the differential ϕ_1 . The differential ϕ_1 induces on the general fiber F of f a holomorphic 1-form $i^*\phi_1 \in H^0(F, \Omega_F^1)$, where $i : F \hookrightarrow X$ is the inclusion map. The differential $i^*\phi_1$ is holomorphic since all connected components of $(\phi_1)_\infty$ must be, as shown as above, fibers of f . The global invariant cycle theorem by Deligne [De71] states that if $i^*\phi_1$ remains invariant under the monodromy action of $\pi_1(C \setminus S)$, S the critical values of f , then there is a

$$u \in H^0(X, \Omega_X^1) \quad \text{such that} \quad i^*u = i^*\phi_1 \quad (3.13)$$

The invariance of $i^*\phi_1$ under the monodromy action is guaranteed by ϕ_1 being a closed holomorphic 1-form on $f^{-1}(C \setminus S)$. The pullback of difference $\phi_1 - u$ to the general fiber of f vanishes and hence $\phi_1 - u = f^*\varphi$ with φ meromorphic differential on C , completing the proof of 2). The Albanese dimension in the case 2) is also ≥ 2 , the two holomorphic 1-forms $f^*\mu$ and u must satisfy $f^*\mu \wedge u \neq 0$ since w has rank 2.

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