Global Torelli theorem for hyperkähler manifolds

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7th Pacific Rim Complex Geometry Conference
August 10, 2012

Kyoto University

Holomorphically symplectic manifolds

DEFINITION: A holomorphically symplectic manifold is a complex manifold equipped with non-degenerate, holomorphic $(2,0)$-form.

REMARK: Hyperkähler manifolds are holomorphically symplectic. Indeed, $\Omega := \omega_J + \sqrt{-1}\,\omega_K$ is a holomorphic symplectic form on (M, I).

THEOREM: (Calabi-Yau) A compact, Kähler, holomorphically symplectic manifold admits a unique hyperkähler metric in any Kähler class.

DEFINITION: For the rest of this talk, **a hyperkähler manifold is a compact, Kähler, holomorphically symplectic manifold.**

DEFINITION: A hyperkähler manifold M is called **simple** if $\pi_1(M) = 0$, $H^{2,0}(M) = \mathbb{C}$.

Bogomolov's decomposition: Any hyperkähler manifold admits a finite covering which is a product of a torus and several simple hyperkähler manifolds.

Further on, all hyperkähler manifolds are assumed to be simple.

Hilbert schemes

THEOREM: (a special case of Enriques-Kodaira classification)
Let M be a compact complex surface which is hyperkähler. **Then M is either a torus or a K3 surface.**

DEFINITION: A **Hilbert scheme** $M^{[n]}$ of a complex surface M is a classifying space of all ideal sheaves $I \subset \mathcal{O}_M$ for which the quotient $\mathcal{O}_M/I$ has dimension n over $\mathbb{C}$.

REMARK: A Hilbert scheme **is obtained as a resolution of singularities** of the symmetric power $\operatorname{Sym}^n M$.

THEOREM: (Fujiki, Beauville) **A Hilbert scheme of a hyperkähler surface is hyperkähler.**

EXAMPLES.

EXAMPLE: A Hilbert scheme of K3 is simple and hyperkähler.

EXAMPLE: Let T be a torus. Then it acts on its Hilbert scheme freely and properly by translations. For $n = 2$, the quotient $T^{[n]}/T$ is a Kummer K3-surface. For $n > 2$, a universal covering of $T^{[n]}/T$ is called **a generalized Kummer variety**.

REMARK: There are 2 more "sporadic" examples of compact hyperkähler manifolds, constructed by K. O'Grady. **All known simple hyperkaehler manifolds are these 2 and the three series:** tori, Hilbert schemes of K3, and generalized Kummer.

QUESTION: Are there any other examples?

Deformations of holomorphically symplectic manifolds.

THEOREM: (Kodaira) **A small deformation of a compact Kähler manifold is again Kähler.**

COROLLARY: A small deformation of a holomorphically symplectic Kähler manifold M **is again holomorphically symplectic.**

Proof: A small deformation M' of M would satisfy $H^{2,0}(M') = H^{2,0}(M)$, however, a small deformation of a non-degenerate (2,0)-form remains non-degenerate. ■

COROLLARY: Small deformations of hyperkähler manifolds are hyperkähler.

REMARK: By **the moduli** of hyperkähler manifolds we shall understand the deformation space of complex manifolds admitting holomorphically symplectic and Kähler structure.

The Teichmüller space and the mapping class group

Definition: Let M be a compact complex manifold, and $\operatorname{Diff}_0(M)$ a connected component of its diffeomorphism group (**the group of isotopies**). Denote by $\widetilde{\operatorname{Teich}}$ the space of complex structures on M, and let $\operatorname{Teich} := \widetilde{\operatorname{Teich}} / \operatorname{Diff}_0(M)$. We call it **the Teichmüller space.**

Remark: Teich is **a finite-dimensional complex space** (Kuranishi), but often **non-Hausdorff**.

Definition: Let $\operatorname{Diff}_+(M)$ be the group of oriented diffeomorphisms of M. We call $\Gamma := \operatorname{Diff}_+(M)/\operatorname{Diff}_0(M)$ **the mapping class group**. The **coarse moduli space of complex structures on M** is a connected component of $\operatorname{Teich}/\Gamma$.

Remark: This terminology is **standard for curves.**

REMARK: For hyperkähler manifolds, it is convenient to take for Teich **the space of all complex structures of hyperkähler type**, that is, **holomorphically symplectic and Kähler**. It is open in the usual Teichmüller space.

REMARK: To describe the moduli space, we shall compute Teich and Γ.

The Bogomolov-Beauville-Fujiki form

THEOREM: (Fujiki). Let $\eta \in H^2(M)$, and $\dim M = 2n$, where M is hyperkähler. Then $\int_M \eta^{2n} = cq(\eta,\eta)^n$, for some primitive integer quadratic form q on $H^2(M,\mathbb{Z})$, and $c > 0$ an integer number.

Definition: This form is called **Bogomolov-Beauville-Fujiki form**. **It is defined by the Fujiki's relation uniquely, up to a sign.** The sign is determined from the following formula (Bogomolov, Beauville)

$$\lambda q(\eta,\eta) = \int_X \eta\wedge\eta\wedge\Omega^{n-1}\wedge\overline{\Omega}^{n-1} - \\ - \frac{n-1}{n}\left(\int_X \eta\wedge\Omega^{n-1}\wedge\overline{\Omega}^{n}\right)\left(\int_X \eta\wedge\Omega^{n}\wedge\overline{\Omega}^{n-1}\right)$$

where Ω is the holomorphic symplectic form, and $\lambda > 0$.

Remark: **q has signature $(b_2-3,3)$.** It is negative definite on primitive forms, and positive definite on $\langle\Omega,\overline{\Omega},\omega\rangle$, where ω is a Kähler form.

Computation of the mapping class group

Theorem: (Sullivan) Let M be a compact, simply connected Kähler manifold, $\dim_{\mathbb{C}} M \geqslant 3$. Denote by Γ_0 the group of automorphisms of an algebra $H^*(M, \mathbb{Z})$ preserving the Pontryagin classes $p_i(M)$. Then **the natural map $\operatorname{Diff}_+(M)/\operatorname{Diff}_0 \longrightarrow \Gamma_0$ has finite kernel, and its image has finite index in Γ_0.**

Theorem: Let M be a simple hyperkähler manifold, and Γ_0 as above. Then
(i) $\Gamma_0\big|_{H^2(M,\mathbb{Z})}$ **is a finite index subgroup of $O(H^2(M, \mathbb{Z}), q)$.**
(ii) The map $\Gamma_0 \longrightarrow O(H^2(M, \mathbb{Z}), q)$ **has finite kernel.**

Proof. Step 1: Fujiki formula $v^{2n} = q(v, v)^n$ implies that Γ_0 **preserves the Bogomolov-Beauville-Fujiki up to a sign.** The sign is fixed, if n is odd.

Step 2: For even n, the sign is also fixed. Indeed, Γ_0 preserves $p_1(M)$, and (as Fujiki has shown) $v^{2n-2} \wedge p_1(M) = q(v, v)^{n-1}c$, for some $c \in \mathbb{R}$. The constant c is positive, **because the degree of $c_2(B)$ is positive** for any Yang-Mills bundle with $c_1(B) = 0$.

Computation of the mapping class group (cont.)

Step 3: $\mathfrak{o}(H^2(M,\mathbb{Q}),q)$ acts on $H^*(M,\mathbb{Q})$ by automorphisms preserving Pontryagin classes (V., 1995). Therefore $\Gamma_0\big|_{H^2(M,\mathbb{Q})}$ **is an arithmetic subgroup of $O(H^2(M,\mathbb{R}),q)$.**

Step 4: The kernel K of the map $\Gamma_0 \longrightarrow \Gamma_0\big|_{H^2(M,\mathbb{Q})}$ is finite, because it commutes with the Hodge decomposition and Lefschetz $\mathfrak{sl}(2)$-action, hence preserves the Riemann-Hodge form, which is positive definite. ■

REMARK: The same argument as in Step 4 also proves that **the group of automorphisms of $H^*(M,\mathbb{R})$ preserving p_1 is projected to $O(H^2(M,\mathbb{R}),q)$ with compact kernel**.

REMARK: (Huybrechts) **There are only finitely many connected components** of Teich.

REMARK: The mapping class group acts on the set of connected components of Teich.

COROLLARY: Let Γ_I be the group of elements of mapping class group preserving a connected component of Teichmüller space containing $I \in$ Teich. **Then Γ_I is also arithmetic.** Indeed, **it has finite index in Γ**.

The period map

Remark: For any $J \in$ Teich, (M, J) is also a simple hyperkähler manifold, hence $H^{2,0}(M, J)$ is one-dimensional.

Definition: Let P : Teich $\longrightarrow \mathbb{P}H^2(M, \mathbb{C})$ map J to a line $H^{2,0}(M, J) \in \mathbb{P}H^2(M, \mathbb{C})$. The map P : Teich $\longrightarrow \mathbb{P}H^2(M, \mathbb{C})$ is called **the period map**.

REMARK: P maps Teich into an open subset of a quadric, defined by

$$\mathbb{P}er := \{l \in \mathbb{P}H^2(M, \mathbb{C}) \ | \ q(l, l) = 0, q(l, \bar{l}) > 0.$$

It is called **the period space** of M.

REMARK: $\mathbb{P}er = SO(b_2 - 3, 3)/SO(2) \times SO(b_2 - 3, 1)$

THEOREM: (Bogomolov) Let M be a simple hyperkähler manifold, and Teich its Teichmüller space. Then **The period map** P : Teich $\longrightarrow \mathbb{P}er$ **is locally a diffeomorphism.**

REMARK: Bogomolov's theorem implies that Teich **is smooth.** It is **non-Hausdorff** even in the simplest examples.

Hausdorff reduction

REMARK: A non-Hausdorff manifold is a topological space locally diffeomorphic to $\mathbb{R}^n$.

DEFINITION: Let M be a topological space. We say that $x, y \in M$ are **non-separable** (denoted by $x \sim y$) if for any open sets $V \ni x, U \ni y$, $U \cap V \neq \emptyset$.

THEOREM: (D. Huybrechts) If I_1, $I_2 \in$ Teich are non-separablee points, then $P(I_1) = P(I_2)$, and (M, I_1) **is birationally equivalent** to (M, I_2)

REMARK: Huybrechts proved this theorem for the **"marked moduli space"** Teich_m, which is a quotient of Teich by the subgroup $K \subset \Gamma$ acting trivially on cohomology. **It's extended on** Teich **using the Torelli theorem.**

DEFINITION: Let M be a topological space for which $M/\sim$ is Hausdorff. Then $M/\sim$ is called **a Hausdorff reduction** of M.

Problems:
1. **$\sim$ is not always an equivalence relation.**
2. **Even if $\sim$ is equivalence, the $M/\sim$ is not always Hausdorff.**

REMARK: A quotient $M/\sim$ is Hausdorff, if $M \longrightarrow M/\sim$ is open, and the graph $\Gamma_\sim \in M \times M$ is closed.

Weakly Hausdorff manifolds

DEFINITION: A point $x \in X$ is called **Hausdorff** if $x \not\sim y$ for any $y \neq x$.

DEFINITION: Let M be an n-dimensional real analytic manifold, not necessarily Hausdoff. Suppose that **the set $Z \subset M$ of non-Hausdorff points is contained in a countable union of real analytic subvarieties** of codim $\geqslant 2$. Suppose, moreover, that

(S) For every $x \in M$, there is a closed neighbourhood $B \subset M$ of x and a continuous surjective map $\Psi : B \longrightarrow \mathbb{R}^n$ to a closed ball in $\mathbb{R}^n$, **inducing a homeomorphism** on an open neighbourhood of x.

Then M is called **a weakly Hausdorff manifold**.

REMARK: The period map satisfies (S). Also, the non-Hausdorff points of Teich **are contained in a countable union of divisors.**

THEOREM: A **weakly Hausdorff manifold X admits a Hausdorff reduction.** In other words, the quotient $X/\sim$ is a Hausdorff. Moreover, $X \longrightarrow X/\sim$ is locally a homeomorphism.

This theorem is proven using 1920-ies style point-set topology.

Birational Teichmüller moduli space

DEFINITION: The space $\operatorname{Teich}_b := \operatorname{Teich}/\sim$ is called **the birational Teichmüller space** of M.

THEOREM: The period map $\operatorname{Teich}_b \xrightarrow{\operatorname{Per}} \mathbb{P}\mathrm{er}$ **is an isomorphism,** for each connected component of Teich_b.

Sketch of a proof: 0. Since $\mathbb{P}\mathrm{er} = SO(b_2-3,3)/SO(2)\times SO(b_2-3,1)$ **is simply connected, it will suffice to show that** Per **a covering.**

1. **It is etale** (Bogomolov).

2. For each hyperkähler structure (I,J,K) on M, **there is a whole** S^2 **of complex structures** $L=aI+bJ+cK$ on M, for $a^2+b^2+c^2=1$.

3. For any point $x\in \mathbb{P}\mathrm{er}$, let $NS(x)$ be the corresponding lattice of integer $(1,1)$-classes in $H^2(M)$. Then **the set** $\mathcal{K}\subset H^{1,1}(M,\mathbb{R})$ **of Kaehler classes can be determined explicitly** when $\operatorname{rk} NS(x)=0$:

$$\mathcal{K} := \{\nu\in H^{1,1}(M,\mathbb{R}) \ \mid\ q(\nu,\nu)>0\}$$

4. Every Kaehler class gives a hyperkaehler structure, hence a line in Teich_b. Such a line is called **generic hyperkähler curve** (GHK curve) if it passes through a point $x\in\mathbb{P}\mathrm{er}$ with $\operatorname{rk} NS(x)=0$.

Birational Teichmüller moduli space (cont'd)

5. **"Surgectivity on GHK curves".**
For every such line C, $P^{-1}(C)$ is a disconnected union of rational curves bijectively mapped to C. Indeed, for each $\tilde{x} \in$ Teich mapping to x, the set of GHK lines passing through $\tilde{x}$ is identified with its Kähler cone $\mathcal{K}$, which is independent from the choice of $\tilde{x} \in \mathsf{Per}^{-1}(x)$.

6. **The whole Teichmüller space is covered by GHK curves.**

7. Surjectivity on GHK curves leads to the following condition.

(*) Let $\mathsf{Teich}_b \xrightarrow{P} \mathbb{P}\mathsf{er}$ be the period map. Then for each open subset $V \subset \mathbb{P}\mathsf{er}$ with smooth boundary, and each connected component $W \subset P^{-1}(V)$, **the restriction $W \xrightarrow{P} V$ is surjective.**

8. The condition (*) **always implies that P is a covering.** It is, again, a (non-trivial) exercise in point-set topology.

9. The period space is simply connected, hence **P is an isomorphism on each connected component.** ■

Global Torelli theorem

DEFINITION: Let M be a hyperkaehler manifold, Teich_b its birational Teichmüller space, and Γ the mapping class group. The quotient Teich_b/Γ is called **the birational moduli space** of M.

REMARK: The birational moduli space is obtained from the usual moduli space **by gluing some (but not all) non-separable points. It is still non-Hausdorff.**

THEOREM: Let (M,I) be a hyperkähler manifold, and W a connected component of its birational moduli space. **Then W is isomorphic to $\mathbb{P}\mathrm{er}/\Gamma_I$, where $\mathbb{P}\mathrm{er} = SO(b_2-3,3)/SO(2)\times SO(b_2-3,1)$ and Γ_I is an arithmetic group in $O(H^2(M,\mathbb{R}),q)$.**

A CAUTION: Usually "the global Torelli theorem" is understood as a theorem about Hodge structures. For K3 surfaces, **the Hodge structure on $H^2(M,\mathbb{Z})$ determines the complex structure**. For $\dim_{\mathbb{C}} M > 2$, **it is false**.

The Hodge-theoretic Torelli theorem

REMARK: The group $O(p,q)$ ($p,q > 0$) has **4 connected components**, corresponding to the orientations of positive p-dimensional and negative q-dimensional planes.

DEFINITION: Let M be a hyperkaehler manifold. One says that **the Hodge-theoretic Torelli theorem holds for M** if

$$\mathrm{Teich}/\Gamma_I \longrightarrow \mathbb{P}\mathrm{er}/O^+(H^2(M,\mathbb{Z}),q),$$

where $O^+(H^2(M,\mathbb{Z}),q)$ is a subgroup of $O(H^2(M,\mathbb{Z}),q)$ preserving orientation on positive 3-planes. Equivalently, **it is true if M is uniquely determined by its Hodge structure**.

REMARK: The Hodge-theoretic Torelli theorem **is true for K3 surfaces**. **It is false** for all other known examples of hyperkaehler manifolds.

Problems:
1. The moduli space Teich/Γ **is not Hausdorff** (Debarre, 1984). Indeed, bimeromorphically equivalent hyperkähler manifolds have isomorphic Hodge structures.
2. **The covering $\mathrm{Teich}_b/\Gamma_I \longrightarrow \mathbb{P}\mathrm{er}/O^+(H^2(M,\mathbb{Z}),q)$ is non-trivial**, because the map $\Gamma_I \longrightarrow O^+(H^2(M,\mathbb{Z}),q)$ is not surjective (Namikawa, 2002).

The birational Hodge-theoretic Torelli theorem

DEFINITION: The birational Hodge-theoretic Torelli theorem is true for M if Γ_I (the stabilizer of a Torelli component in the mapping class group) **is isomorphic to** $O^+(H^2(M,\mathbb{Z}),q)$**.**

REMARK: If a birational Hodge-theoretic Torelli theorem holds for M, then any deformation of M is up to a bimeromorphic equivalence **determined by the Hodge structure on** $H^2(M)$**.**

THEOREM: (Markman) The for $M = K3^{[n]}$, the group Γ_I **is a subgroup of** $O^+(H^2(M,\mathbb{Z}),q)$ **generated by oriented reflections.**

THEOREM: Let $M = K3^{[n+1]}$ with n a prime power. Then the (usual) global Torelli theorem holds birationally: **two deformations of a Hilbert scheme with isomorphic Hodge structures are bimeromorphic**. **For other** n**, it is false** (Markman).