Kobayashi hyperbolicity and ergodic theory

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Seminário de Álgebra,

IMPA, August 23, 2017

Geometric structures

DEFINITION: "Geometric structure" on a manifold is a collection of tensors satisfying a certain set of differential equations.

Let me give some examples.

DEFINITION: Let M be a smooth manifold. An **almost complex structure** is an operator $I: TM \longrightarrow TM$ which satisfies $I^2 = -\operatorname{Id}_{TM}$.

The eigenvalues of this operator are $\pm\sqrt{-1}$. The corresponding eigenvalue decomposition is denoted $TM \otimes \mathbb{C} = T^{0,1}M \oplus T^{1,0}(M)$.

DEFINITION: An almost complex structure is **integrable** if $\forall X, Y \in T^{1,0}M$, one has $[X, Y] \in T^{1,0}M$. In this case I is called **a complex structure operator**. A manifold with an integrable almost complex structure is called **a complex manifold**.

DEFINITION: Symplectic form on a manifold is a non-degenerate differential 2-form ω satisfying $d\omega = 0$.

Teichmüller space of geometric structures

Let $\mathcal{C}$ be the set of all geometric structures of a given type, say, complex, or symplectic. We put topology of uniform convergence with all derivatives on $\mathcal{C}$. Let $\operatorname{Diff}_0(M)$ be the connected component of its diffeomorphism group $\operatorname{Diff}(M)$ (**the group of isotopies**).

DEFINITION: The quotient $\mathcal{C}/\operatorname{Diff}_0$ is called **Teichmüller space** of geometric strictures of this type.

DEFINITION: The group $\Gamma := \operatorname{Diff}(M)/\operatorname{Diff}_0(M)$ is called **the mapping class group** of M. It acts on Teich by homeomorphisms.

DEFINITION: The orbit space $\mathcal{C}/\operatorname{Diff} = \operatorname{Teich}/\Gamma$ is called **the moduli space** of geometric structure of this type.

Today I will describe Teich and Γ for complex structures on holomorphically symplectic manifolds and explain some important concepts, such as **ergodicity of Γ-action.**

Ergodic complex structures

DEFINITION: Let M be a smooth manifold. **A complex structure** on M is an endomorphism $I \in \operatorname{End} TM$, $I^2 = -\operatorname{Id}_{TM}$, such that the eigenspace bundles of I are **involutive**, that is, satisfy $[T^{1,0}M, T^{1,0}M] \subset T^{1,0}M$.

Let Comp be the space of such tensors equipped with a topology of convergence of all derivatives on all compact subsets.

DEFINITION: The diffeomorphism group Diff is a Fréchet Lie group acting on Comp in a natural way. A complex structure is called **ergodic** if its Diff-orbit is dense in Comp.

REMARK: The "moduli space" of complex structures (if it exists) is identified with Comp / Diff; **existence of ergodic complex structures guarantees that the quotient Comp / Diff has no Hausdorff open subsets,** because all open sets of the quotient intersect.

THEOREM: Let M be a compact torus, $\dim_{\mathbb{C}} M \geqslant 2$. **A complex structure on M is ergodic if and only if $\operatorname{Pic}(M)$ is not of maximal rank.**

REMARK: Similar result is true for hyperkähler manifolds.

Teichmüller spaces

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 Comp the space of complex structures on M, and let Teich := Comp / $\operatorname{Diff}_0(M)$. We call it **the Teichmüller space.**

REMARK: In all known cases Teich is **a finite-dimensional complex space** (Kodaira-Spencer-Kuranishi-Douady), but often **non-Hausdorff**.

DEFINITION: A **Calabi-Yau manifold** is a compact, Kähler manifold M with $c_1(M) = 0$.

THEOREM: (Bogomolov-Tian-Todorov) Teich **is a complex manifold when M is Calabi-Yau**.

Definition: Let $\operatorname{Diff}(M)$ be the group of diffeomorphisms of M. We call $\Gamma := \operatorname{Diff}(M)/\operatorname{Diff}_0(M)$ **the mapping class group**. The quotient Teich $/\Gamma$ **is identified with the set of equivalence classes of complex structures.**

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

Holomorphically symplectic manifolds

DEFINITION: A **holomorphic symplectic form** is a non-degenerate, closed, holomorphic 2-form.

DEFINITION: A **hyperkähler structure** on a manifold M is a Riemannian structure g and a triple of complex structures I, J, K, satisfying quaternionic relations $I \circ J = -J \circ I = K$, such that g is Kähler for I, J, K.

REMARK: This produces a triple of symplectic forms on M: $\omega_I(\cdot,\cdot) = g(\cdot, I\cdot), \omega_J(\cdot,\cdot) = g(\cdot, J\cdot), \omega_K(\cdot,\cdot) = g(\cdot, K\cdot)$.

CLAIM: A hyperkähler manifold is holomorphically symplectic: $\omega_J + \sqrt{-1}\,\omega_K$ is a holomorphic symplectic form on (M, I).

Proof: It's closed and has Hodge type (2,0), hence holomorphic. It is non-degenerate because ω_J and ω_K are non-degenerate. ∎

REMARK: Converse is also true: any holomorphic symplectic compact Kähler manifold is hyperkähler.

Calabi-Yau theorem

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 compact hyperkähler manifold M is called **simple**, or **IHS**, or **maximal holonomy**, 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 compact and of maximal holonomy.

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

EXAMPLES.

EXAMPLE: A Hilbert scheme of K3 is of maximal holonomy 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 maximal holonomy hyperkaehler manifolds are these 2 and two series:** Hilbert schemes of K3, and generalized Kummer.

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. We shall use this notation further on.

Computation of the mapping class group

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 $c > 0$ a rational number.

DEFINITION: The form q is called **Bogomolov-Beauville-Fujiki form**. It has signature $(3, b_2-3)$, positive on $\langle \omega_I, \omega_J, \omega_K\rangle$, and negative on the primitive (1,1)-classes.

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 $\Gamma := \operatorname{Diff}(M)/\operatorname{Diff}_0 \longrightarrow \Gamma_0$ has finite kernel, and its image has finite index in Γ_0.**

THEOREM: Let M be a simple hyperkähler manifold, and Γ its mapping class group. Then
(i) $\Gamma\Big|_{H^2(M,\mathbb{Z})}$ **is a finite index subgroup of $O(H^2(M,\mathbb{Z}),q)$.**
(ii) The map $\Gamma \longrightarrow O(H^2(M,\mathbb{Z}),q)$ **has finite kernel.**

REMARK: Sullivan's theorem implies that the mapping class group for compact Kähler M with $\dim_{\mathbb{C}} M \geqslant 3$, $\pi_1(M) = 0$, **is an arithmetic lattice**. Very much unlike the Teichmüller group!

The period map

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

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

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

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

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

THEOREM: (Bogomolov) For any hyperkähler manifold, **period map is locally a diffeomorphism.**

Period space as a Grassmannian of positive 2-planes

PROPOSITION: The period space

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

is identified with $SO(b_2-3,3)/SO(2)\times SO(b_2-3,1)$**,** which is a Grassmannian of positive oriented 2-planes in $H^2(M, \mathbb{R})$.

Proof. Step 1: Given $l \in \mathbb{P}H^2(M, \mathbb{C})$, **the space generated by** $\operatorname{Im} l, \operatorname{Re} l$ **is 2-dimensional,** because $q(l,l) = 0, q(l, \bar{l})$ implies that $l \cap H^2(M, \mathbb{R}) = 0$.

Step 2: This 2-dimensional plane is positive, because $q(\operatorname{Re} l, \operatorname{Re} l) = q(l + \bar{l}, l + \bar{l}) = 2q(l, \bar{l}) > 0$.

Step 3: Conversely, for any 2-dimensional positive plane $V \in H^2(M, \mathbb{R})$, **the quadric** $\{l \in V \otimes_{\mathbb{R}} \mathbb{C} \ \mid \ q(l,l) = 0\}$ **consists of two lines;** a choice of a line is determined by orientation. ■

General hyperkähler manifolds are non-algebraic

REMARK: Let $W \subset H^2(M,\mathbb{R})$ be a 2-plane associated with a manifold (M,I). Then $W^\perp = H^{1,1}_I(M,\mathbb{R})$. Since Per is locally a diffeomorphism, $H^{1,1}_I(M) \cap H^2(M,\mathbb{Z})$ **is generally empty.**

COROLLARY: A general deformation of a given hyperkähler manifold **has no complex curves and no divisors.**

Proof: The corresponding cohomology groups $H^{1,1}_I(M) \cap H^2(M,\mathbb{Z})$ and $H^{2n-1,2n-1}_I(M) \cap H^2(M,\mathbb{Z})$ are trivial. ∎

Birational Teichmüller moduli space

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: (Huybrechts) Two points $I, I' \in$ Teich **are non-separable if and only if there exists a bimeromorphism $(M, I) \longrightarrow (M, I')$ which is non-singular in codimension 2 and acts as identity on $H^2(M)$.**

REMARK: This is possible only if (M, I) and (M, I') contain a rational curve. **General hyperkähler manifold has no curves;** ones which have curves belong to a countable union of divisors in Teich.

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

THEOREM: (Torelli theorem for hyperkähler manifolds)
The period map $\text{Teich}_b \xrightarrow{\text{Per}} \mathbb{P}\text{er}$ is a diffeomorphism, for each connected component of Teich_b.

Ergodic complex structures

DEFINITION: Let (M,μ) be a space with measure, and G a group acting on M preserving measure. This action is **ergodic** if all G-invariant measurable subsets $M' \subset M$ satisfy $\mu(M') = 0$ or $\mu(M\backslash M') = 0$.

CLAIM: Let M be a manifold, μ a Lebesgue measure, and G a group acting on M ergodically. **Then the set of non-dense orbits has measure 0.**

Proof. Step 1: Consider a non-empty open subset $U \subset M$. Then $\mu(U) > 0$, hence $M' := G \cdot U$ satisfies $\mu(M\backslash M') = 0$. For any orbit $G \cdot x$ not intersecting U, $x \in M\backslash M'$. Therefore, the set Z_U of such orbits has measure 0.

Step 2: Choose a countable base $\{U_i\}$ of topology on M. Then the set of points in dense orbits is $M \backslash \bigcup_i Z_{U_i}$. ■

DEFINITION: Let M be a complex manifold, Teich its Techmüller space, and Γ the mapping group acting on Teich **An ergodic complex structure** is a complex structure with dense Γ-orbit.

CLAIM: Let (M,I) be a manifold with ergodic complex structure, and I' another complex structure. **Then there exists a sequence of diffeomorphisms ν_i such that $\nu_i^*(I)$ converges to I'.**

Ergodicity of the mapping class group action

DEFINITION: A lattice in a Lie group is a discrete subgroup $\Gamma \subset G$ such that G/Γ has finite volume with respect to Haar measure.

THEOREM: (Calvin C. Moore, 1966) Let Γ be a lattice in a non-compact simple Lie group G with finite center, and $H \subset G$ a non-compact subgroup. **Then the left action of Γ on G/H is ergodic.**

THEOREM: Let $\mathbb{P}\mathrm{er}$ be a component of a birational Teichmüller space, and Γ its monodromy group. Let $\mathbb{P}\mathrm{er}_e$ be a set of all points $L \subset \mathbb{P}\mathrm{er}$ such that the orbit $\Gamma \cdot L$ is dense (such points are called **ergodic**). **Then $Z := \mathbb{P}\mathrm{er} \setminus \mathbb{P}\mathrm{er}_e$ has measure 0.**

Proof. Step 1: Let $G = SO(b_2 - 3, 3)$, $H = SO(2) \times SO(b_2 - 3, 1)$. **Then Γ-action on G/H is ergodic,** by Moore's theorem.

Step 2: Ergodic orbits are dense, becuse the union of non-ergodic orbits has measure 0. ■

REMARK: Generic deformation of M has no rational curves, and no non-trivial birational models. Therefore, **outside of a measure zero subset,** $\mathrm{Teich} = \mathrm{Teich}_b$. This implies that **almost all complex structures on M are ergodic.**

Ratner's theorem

EXAMPLE: By Borel and Harish-Chandra theorem, **any integer lattice in a simple Lie group has finite covolume.**

DEFINITION: **Unipotent element** in a Lie group $G \subset GL(V)$ is an exponent of a nilpotent element in its Lie algebra.

THEOREM: Let $H \subset G$ be a Lie subroup generated by unipotents, and $\Gamma \subset G$ an arithmetic lattice. Then **the closure of any Γ-orbit in G/H is an orbit of a Lie subgroup $S \subset G$, such that $S \cap \Gamma \subset S$ is a lattice.**

EXAMPLE: Let V be a real vector space with a non-degenerate bilinear symmetric form of signature $(3, k)$, $k > 0$, $G := SO^+(V)$ a connected component of the isometry group, $H \subset G$ a subgroup acting trivially on a given positive 2-dimensional plane, $H \cong SO^+(1, k)$, and $\Gamma \subset G$ an arithmetic lattice. Consider the quotient $\mathbb{P}\mathrm{er} := G/H$. **Then a closure of $\Gamma \cdot J$ in G/H is an orbit of a closed Lie subgroup $S \subset G$ containing H.**

Classification of Γ-orbits on $\mathbb{P}\mathrm{er}$

CLAIM: Let $G = SO(3,k)$ be a group of oriented isometries of $V = \mathbb{R}^{3,k}$, and $H \cong SO(1,k) \subset G$. Denote by $\mathfrak{h}$, $\mathfrak{g}$ their ie algebras. Then **any Lie algebra $\mathfrak{s}$ such that $\mathfrak{h} \subsetneq \mathfrak{s} \subsetneq \mathfrak{g}$ is isomorphic to $\mathfrak{so}(2,k)$.** This is the Lie algebra of the Lie group $S = SO(2,k)$ fixing a positive vector $v \in V$.

COROLLARY: Let $J \in \mathbb{P}\mathrm{er} = G/H$, and $\Gamma \subset G$ be an arithmetic lattice. **Then one of three things happens.**

(i) ether J has dense orbit,

(ii) or the closure of Γ-orbit of J is an orbit of S or its connected component S^+,

(iii) or the orbit $\Gamma \cdot J$ is closed.

Characterization of ergodic complex structures

REMARK: By Ratner's theorem, the S^+-orbit of J in (ii) and the H-orbit of J in (iii) has finite volume in G/Γ. Therefore, **its intersection with Γ is a lattice in H.** This brings

COROLLARY: Consider the action of the mapping class group Γ of a hyperkähler manifold on its period space $\mathbb{P}\mathrm{er}$. Let $J \in \mathbb{P}\mathrm{er}$ be a point such that its Γ-orbit is closed in $\mathbb{P}\mathrm{er}$. Consider its stabilizer $\mathrm{St}(J) \cong H \subset G$. **Then $\mathrm{St}(J) \cap \Gamma$ is a lattice in $\mathrm{St}(J)$.**

COROLLARY: Let J be a complex structure with closed Γ-orbit on a hyperkähler manifold, Ω its holomorphic symplectic form, and $W \subset H^2(M,\mathbb{R})$ a plane generated by $\operatorname{Re}\Omega, \operatorname{Im}\Omega$. **Then W is rational.**

Similarly, one has

COROLLARY: Let J be a non-ergodic complex structure on a hyperkähler manifold, and $W \subset H^2(M,\mathbb{R})$ be a plane generated by $\operatorname{Re}\Omega, \operatorname{Im}\Omega$. **Then W contains a rational vector.**

Non-hyperbolic manifolds

DEFINITION: **An entire curve** in a complex manifold is an image of $\mathbb{C}$ under a non-constant holomorphic map.

REMARK: Let (M, I_k) be a sequence of complex structures on M converging to I. Assume that all (M, I_k) contain an entire curve. **Then (M, I) contains an entire curve.** This result follows from Brody lemma.

DEFINITION: A complex manifold containing no entire curves is called **Kobayashi hyperbolic**. A complex manifold containing an entire curve is called **non-hyperbolic**.

Ergodicity implies the following result.

THEOREM: **Hyperkähler manifolds are never Kobayashi hyperbolic.**

Twistor spaces and hyperkähler geometry

DEFINITION: A **hyperkähler structure** on a manifold M is a Riemannian structure g and a triple of complex structures I, J, K, satisfying quaternionic relations $I \circ J = -J \circ I = K$, such that g is Kähler for I, J, K.

DEFINITION: **Induced complex structures** on a hyperkähler manifold are complex structures of form $S^2 \cong \{L := aI + bJ + cK, \quad a^2 + b^2 + c^2 = 1.\}$

DEFINITION: A **twistor space** $\mathrm{Tw}(M)$ of a hyperkähler manifold is **a complex manifold obtained by gluing these complex structures into a holomorphic family over $\mathbb{C}P^1$.** More formally:

Let $\mathrm{Tw}(M) := M \times S^2$. Consider the complex structure $I_m : T_m M \to T_m M$ on M induced by $J \in S^2 \subset \mathbb{H}$. Let I_J denote the complex structure on $S^2 = \mathbb{C}P^1$.

The operator $I_{\mathrm{Tw}} = I_m \oplus I_J : T_x \mathrm{Tw}(M) \to T_x \mathrm{Tw}(M)$ satisfies $I_{\mathrm{Tw}}^2 = -\operatorname{Id}$. **It defines an almost complex structure on $\mathrm{Tw}(M)$.** This almost complex structure is known to be integrable (Obata).

Entire curves in twistor fibers

THEOREM: (F. Campana, 1992)
Let M be a hyperkähler manifold, and $\mathrm{Tw}(M) \xrightarrow{\pi} \mathbb{C}P^1$ its twistor projection. **Then there exists an entire curve in some fiber of π.**

CLAIM: There exists a twistor family which has only ergodic fibers.

Proof: A twistor curve $\mathbb{C}P^1 \subset \mathbb{P}\mathrm{er}$ associated with a 3-plane $W \subset H^2(M, \mathbb{R})$ without rational vectors does not contain any non-ergodic complex structures.
■

THEOREM: All hyperkähler manifolds are non-hyperbolic.

Proof: Let $\mathrm{Tw}(M) \longrightarrow \mathbb{C}P^1$ be a twistor family with all fibers ergodic. **By Campana's theorem, one of these fibers, denoted (M, I), is non-hyperbolic.** Since any complex structure $I' \in$ Teich lies in the closure of $\mathrm{Diff}(M) \cdot I$, all complex structures $I' \in$ Teich are non-hyperbolic. ■