Algebraic geometry

A symplectic analog of the Quot scheme

Un analogue symplectique du schéma Quot

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A B S T R A C T

We construct a symplectic analog of the Quot scheme that parameterizes the torsion quotients of a trivial vector bundle over a compact Riemann surface. Some of its properties are investigated.

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R É S U M É

Nous construisons un analogue symplectique du schéma Quot, qui paramètre les modules quotients de torsion d’un fibré vectoriel trivial sur une surface de Riemann compacte, et nous examinons certaines de ses propriétés.

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1. Introduction

Let \( X \) be a compact connected Riemann surface. For fixed integers \( n \) and \( d \), let \( \mathcal{Q}(\mathbb{O}_X^{dR}, d) \) denote the Quot scheme that parameterizes the torsion quotients of \( \mathbb{O}_X^{dR} \) of degree \( d \) (see [8] for construction and properties of a general Quot schemes). This particular Quot scheme \( \mathcal{Q}(\mathbb{O}_X^{dR}, d) \) arises in the study of moduli space of vector bundles of rank \( n \) on \( X \) [4,7,3]. Being a moduli space of vortices, it is also studied in mathematical physics (see [1] and references therein).

Here we consider a symplectic analog of the Quot scheme. Let \( \mathbb{O}_X^{2r} \) be the trivial vector bundle on \( X \) equipped with a symplectic structure given by the standard symplectic form on \( \mathbb{C}^{2r} \). Take torsion quotients of it of degree \( dr \) that are compatible with the symplectic structure (this is explained in Section 2.1). Fixing \( X, r \) and \( d \), let \( \mathcal{Q} \) denote the associated symplectic Quot scheme. The projective symplectic group \( \text{PSp}(2r, \mathbb{C}) \) has a natural action on \( \mathcal{Q} \). We show that the connected component, containing the identity element, of the group of all automorphisms of \( \mathcal{Q} \) coincides with \( \text{PSp}(2r, \mathbb{C}) \).

In [4], Bifet, Ghione and Letizia used the usual Quot schemes \( \mathcal{Q}(\mathbb{O}_X^{dR}, d) \) associated with \( X \) to compute the cohomologies of the moduli spaces of semistable vector bundles of rank \( n \) on \( X \). Our hope is to be able to compute the cohomologies of the moduli space of semistable \( \text{Sp}(2r, \mathbb{C}) \)-bundles on \( X \) using the symplectic Quot scheme \( \mathcal{Q} \).

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2. The symplectic Quot scheme

2.1. Construction of the symplectic Quot scheme

Let

$$\omega' := \sum_{i=1}^{r} (e_i^* \otimes e_{i+r}^* - e_{i+r}^* \otimes e_i^*)$$

be the standard symplectic form on \(\mathbb{C}^r\). Let \(X\) be a compact connected Riemann surface. The sheaf of holomorphic functions on \(X\) will be denoted by \(\mathcal{O}_X\). Let

$$E_0 := \mathcal{O}_X^{\oplus 2r}$$

be the trivial holomorphic vector bundle on \(X\) of rank \(2r\). The above symplectic form \(\omega'\) defines a symplectic structure on \(E_0\), because the fibers of \(E_0\) are identified with \(\mathbb{C}^{2r}\). This symplectic structure on \(E_0\) will be denoted by \(\omega_0\).

Fix an integer \(d \geq 1\). Let

$$Q := Q(\omega_0, d)$$

be the symplectic Quot scheme parameterizing all torsion quotients

$$\tau_Q : E_0 \longrightarrow Q$$

of degree \(dr\) satisfying the following condition: there is an effective divisor \(D_Q\) on \(X\) of degree \(d\) such that the restricted form \(\omega_0|_{\text{kernel}(\tau_Q)}\) factors as

$$\text{kernel}(\tau_Q) \otimes \text{kernel}(\tau_Q) \longrightarrow O_X(-D_Q) \hookrightarrow O_X;$$

it should be clarified that \(D_Q\) depends on \(Q\). Equivalently, the symplectic Quot scheme \(Q\) parameterizes all coherent analytic subsheaves \(F \subset E_0\) of rank \(2r\) and degree \(-dr\) such that the form \(\omega_0|_F\) factors as

$$F \otimes F \longrightarrow O_X(-D) \hookrightarrow O_X,$$

where \(D\) is some effective divisor on \(X\) of degree \(d\) that depends on \(F\). This description of \(Q\) sends any subsheaf \(F\) to the quotient sheaf \(E_0/F\).

The above pairing

$$F \otimes F \longrightarrow O_X(-D)$$

produces an injective homomorphism

$$\mu : F \longrightarrow O_X(-D) \otimes F^*$$

between coherent analytic sheaves of rank \(2r\); the homomorphism \(\mu\) is injective because it is injective over the complement of the support of \(E_0/F\). Since

$$\text{degree}(F) = -dr = \text{degree}(O_X(-D) \otimes F^*),$$

the homomorphism \(\mu\) in (3) is an isomorphism. This means that the pairing \(F_x \otimes F_x \longrightarrow O_X(-D)_x\) is nondegenerate for every \(x \in X\). The divisor \(D\) is uniquely determined by \(F\) because \(\mu\) is an isomorphism. More precisely, consider the homomorphism of coherent analytic sheaves

$$\tilde{\mu} : F \longrightarrow F^*$$

given by the restriction \(\omega_0|_F\). The divisor \(D\) is the scheme theoretic support of the quotient sheaf \(F^*/\tilde{\mu}(F)\).

The group of all permutations of \(\{1, \cdots, d\}\) will be denoted by \(S_d\). The quotient

$$X^d/S_d$$

of \(X^d\) for the natural action of \(S_d\) is the symmetric product \(\text{Sym}^d(X)\). Let

$$\varphi : Q \longrightarrow \text{Sym}^d(X)$$

be the morphism that sends any quotient \(Q\) to the divisor \(D_Q\) (see (2)).

Let

$$\tilde{Q} := Q(O_X^{\oplus 2r}, rd)$$

(6)
be the Quot scheme that parameterizes all torsion quotients of $\mathcal{O}_{X}^{\otimes 2r} = E_0$ of degree $rd$. It is an irreducible smooth complex projective variety of dimension $2r^2d$. For any subsheaf $F$ of $E_0$ with $E_0/F \in \bar{Q}$, we have

$$T_{E_0/F} \bar{Q} = H^0(X, (E_0/F) \otimes F^*).$$

(7)

Now assume that $E_0/F \in \bar{Q}$. First consider the homomorphism $F \otimes E_0 \xrightarrow{\alpha_0} \mathcal{O}_X$ obtained by restricting $\omega_0$. Note that $\omega_0(F \otimes F) \subset \mathcal{O}_X(-\varphi(E_0/F))$, where $\varphi$ is the morphism in (5) (see (2)). Therefore, $\omega_0$ produces a homomorphism

$$\theta : F \otimes (E_0/F) \rightarrow \mathcal{O}_X/(\mathcal{O}_X(-\varphi(E_0/F))).$$

The subspace

$$T_{E_0/F} \bar{Q} \subset T_{E_0/F} \bar{Q}$$

consists of all homomorphisms $\alpha : F \rightarrow E_0/F$ (see (7)) such that

$$\theta(v \otimes \alpha(w)) = \theta(w \otimes \alpha(v)).$$

Clearly $\bar{Q}$ is a closed subscheme of $\bar{Q}$.

**Lemma 1.** The scheme $Q$ is an irreducible projective variety of dimension $d(r^2 + r + 2)/2$.

**Proof.** The morphism $\varphi$ in (5) is clearly surjective. Also, each fiber of $\varphi$ is irreducible. Since $\text{Sym}^d(X)$ is irreducible, we conclude that $Q$ is also irreducible.

Take a point $\bar{x} := (x_1, \ldots, x_d) \in \text{Sym}^d(X)$ such that all $x_i \in X$, $1 \leq i \leq d$, are distinct. Let

$$\mathbb{L} \subset \text{Gr}(\mathbb{C}^{2r}, r)$$

be the variety parameterizing all Lagrangian subspaces of $\mathbb{C}^{2r}$ for the standard symplectic form $\omega'$. We have a map $\mathbb{L} \rightarrow \varphi^{-1}(\bar{x})$ that sends any $(V_1, \ldots, V_d) \in \mathbb{L}^d$ to the composition

$$\mathcal{O}_{X}^{\otimes 2r} \rightarrow \mathcal{O}_{X}^{\otimes 2r} \mid_{V_1,\ldots,V_d} = \bigoplus_{i=1}^{d} C_{x_i}^{2r} \rightarrow \bigoplus_{i=1}^{d} C_{x_i}^{2r}/V_i,$$

where $C_{x_i}^{2r}$ is the sheaf supported at $x_i$ with stalk $\mathbb{C}^{2r}$; note that this composition is surjective and hence it defines an element of $\varphi^{-1}(\bar{x})$. This map $\mathbb{L}^d \rightarrow \varphi^{-1}(\bar{x})$ is clearly an isomorphism. Since $\dim \mathbb{L} = (r + 1)/2$, it follows that $\dim Q = d(r^2 + r + 2)/2$. □

2.2. Vortex equation and stability

Fix a Hermitian metric $\omega_X$ on $X$; note that $\omega_X$ is Kähler.

Take a subsheaf $F \subset \mathcal{O}_{X}^{\otimes 2r}$ such that the quotient $\mathcal{O}_{X}^{\otimes 2r}/F$ is a torsion sheaf of degree $dr$, so $F \in \bar{Q}$ (see (6)). Let

$$\mathcal{O}_{X}^{\otimes 2r} \hookrightarrow F^*$$

be the dual of the inclusion of $F$ in $\mathcal{O}_{X}^{\otimes 2r}$. Note that the homomorphism in (9) defines a $2r$-pair of rank $2r [2, p. 535 (3.1)].$ Therefore, each element of $Q$ defines a $2r$-pair of rank $2r$.

Take any real number $\tau$, and take an element $z_\tau \in \bar{Q}$. Let $F \subset \mathcal{O}_{X}^{\otimes 2r}$ be the subsheaf represented by $z_\tau$. We note that the subsheaf $F$ is $\tau$-stable if $\rho > \tau$ (see [2, p. 535, Definition 3.3] for the definition of $\tau$-stability).

We assume that $\tau > rd$. Therefore, all elements of $Q$ are $\tau$-stable. Hence every $F \subset \mathcal{O}_{X}^{\otimes 2r}$ lying in $Q$ admits a unique Hermitian structure that satisfies the $2r-\tau$-vortex equation [2, p. 536, Theorem 3.5].

Take any $F \subset \mathcal{O}_{X}^{\otimes 2r}$ represented by an element of $Q$. Let $h_F$ denote the unique Hermitian structure on $F$ that satisfies the $2r-\tau$-vortex equation. The isomorphism $\mu$ in (3) takes $h_F$ to the unique Hermitian structure on $\mathcal{O}_X(-D) \otimes F^*$ that satisfies the $2r-\tau$-vortex equation for $\mathcal{O}_X(-D) \otimes F^* \in \bar{Q}$. Indeed, this follows immediately from the uniqueness of the Hermitian structure satisfying the $2r-\tau$-vortex equation.

3. Automorphisms of the symplectic Quot scheme

In this section we assume that genus$(X) \geq 2$.

The group of all holomorphic automorphisms of $Q$ will be denoted by $\text{Aut}(Q)$. Let

$$\text{Aut}(Q)^0 \subset \text{Aut}(Q)$$

be the connected component of it containing the identity element. The group of linear automorphisms of the symplectic vector space $(\mathbb{C}^{2r}, \omega')$ is $\text{Sp}(2r, \mathbb{C})$. The standard action of $\text{Sp}(2r, \mathbb{C})$ on $\mathbb{C}^{2r}$ produces an action of $\text{Sp}(2r, \mathbb{C})$ on $Q$. The center $\mathbb{Z}/2\mathbb{Z}$ of $\text{Sp}(2r, \mathbb{C})$ acts trivially on $Q$. Therefore, we get a homomorphism

$$\rho : \text{PSp}(2r, \mathbb{C}) = \text{Sp}(2r, \mathbb{C})/(\mathbb{Z}/2\mathbb{Z}) \rightarrow \text{Aut}(Q)^0.$$
Theorem 2. The above homomorphism \( \rho \) is an isomorphism.

Proof. The standard action of \( \text{Sp}(2r, \mathbb{C}) \) on \( \mathbb{C}^{2r} \) produces an action of \( \text{PSp}(2r, \mathbb{C}) \) on the variety \( \mathbb{L} \) in (8). This action on \( \mathbb{L} \) is effective. From this it follows immediately that the homomorphism \( \rho \) is injective (recall that the general fiber of \( \varphi \) is \( \mathbb{L}^d \)).

For each \( 1 \leq i \leq d \), let \( p_i : X^d \to X \) be the projection to the \( i \)-th factor of the Cartesian product. For each pair \( 1 \leq i < j \leq d \), let

\[
\Delta_{i,j} \subset X^d
\]

be the divisor over which the two maps \( p_i \) and \( p_j \) coincide. Let

\[
\tilde{U} := X^d \setminus \left( \bigcup_{1 \leq i < j \leq d} \Delta_{i,j} \right)
\]

be the complement. Consider all point \( \{x_1, \ldots, x_d\} \in \text{Sym}^d(X) \) such that \( x_k \neq x_\ell \) for all \( k \neq \ell \). The complement in \( \text{Sym}^d(X) \) of the subset defined by such points will be denoted by \( U \). The quotient map \( X^d \to X^d / \mathbb{S}_d \) (see (4)) sends \( \tilde{U} \) to \( U \). The quotient map

\[
f : \tilde{U} := X^d \setminus \left( \bigcup_{1 \leq i < j \leq d} \Delta_{i,j} \right) \to U
\]

is an étale Galois covering with Galois group \( \mathbb{S}_d \).

The inverse image \( \varphi^{-1}(U) \subset \mathbb{Q} \) will be denoted by \( \mathcal{V} \), where \( \varphi \) is the projection in (5). Let

\[
\varphi' := \varphi|_{\mathcal{V}} : \mathcal{V} \to U
\]

be the restriction of \( \varphi \). We note that \( \mathcal{V} \) is a fiber bundle over \( U \) with fibers isomorphic to \( \mathbb{L}^d \) (see (8) for \( \mathbb{L} \)). In particular, \( \mathcal{V} \) is contained in the smooth locus of \( \mathbb{Q} \).

The Lie algebra of \( \text{Sp}(2r, \mathbb{C}) \) will be denoted by \( \text{sp}(2r, \mathbb{C}) \). The Lie algebra of \( \text{Aut}(\mathbb{Q})^0 \) is contained in the space of algebraic vector fields \( H^0(\mathcal{V}, T\mathcal{V}) \) equipped with the Lie bracket operation of vector fields. Let

\[
d\rho : \text{sp}(2r, \mathbb{C}) \to H^0(\mathcal{V}, T\mathcal{V})
\]

be the homomorphism of Lie algebras associated with the homomorphism \( \rho \) of Lie groups. To prove that \( \rho \) is surjective, it suffices to show that \( d\rho \) is surjective. We note that \( d\rho \) is injective because \( \rho \) is injective.

Take any algebraic vector field

\[
\gamma \in H^0(\mathcal{V}, T\mathcal{V}).
\]

Let

\[
d\varphi' : T\mathcal{V} \to \varphi'^* T\mathcal{V}
\]

be the differential of the projection \( \varphi' \) in (11). As noted before, the fibers of \( \varphi' \) are isomorphic to \( \mathbb{L}^d \), in particular, they are connected smooth projective varieties, so any holomorphic function on a fiber of \( \varphi' \) is a constant function. This implies that the section \( d\varphi'(\gamma) \) descends to \( U \). In other words, there is a holomorphic vector field \( \gamma' \) on \( U \) such that

\[
d\varphi'(\gamma) = \varphi'^* \gamma'.
\]

(13)

Let

\[
\gamma'' := f^* \gamma' \in H^0(\tilde{U}, T\tilde{U})
\]

(14)

be the pullback, where \( f \) is the projection in (10). Since the vector field \( \gamma \) is algebraic, the above vector field \( \gamma'' \) is meromorphic on \( X^d \), meaning

\[
\gamma'' \in H^0(X^d, (TX^d) \otimes \mathcal{O}_{X^d}(\sum_{1 \leq i < j \leq d} m \cdot \Delta_{i,j}))
\]

for some integer \( m \). It is known that there are no such nonzero sections [5, Proposition 2.3]. Therefore, we have \( \gamma'' = 0 \), and hence from (13) and (14) it follows that

\[
d\varphi'(\gamma) = 0.
\]

(15)

The standard action of \( \text{Sp}(2r, \mathbb{C}) \) on \( \mathbb{C}^{2r} \) produces an action of \( \text{Sp}(2r, \mathbb{C}) \) on \( \mathbb{L} \) defined in (8). Let

\[
\text{sp}(2r, \mathbb{C}) \to H^0(\mathbb{L}, T\mathbb{L})
\]

be the corresponding homomorphism of Lie algebras. It is known that the above homomorphism is an isomorphism. Let
$T_{\text{rel}} \longrightarrow \tilde{U} \times_U V \longrightarrow \tilde{U}$

be the relative algebraic tangent bundle for the projection $\tilde{U} \times_U V \longrightarrow \tilde{U}$. Since

$\tilde{U} \times_U V = \tilde{U} \times \mathbb{L}$,

and $H^0(\tilde{U}, \mathcal{O}_{\tilde{U}}) = \mathbb{C}$ [5, Lemma 2.2], we have

$$H^0(\tilde{U} \times_U V, T_{\text{rel}}) = H^0(\tilde{U}, T_L)^{\oplus d} = \text{sp}(2r, \mathbb{C})^{\oplus d}. \tag{16}$$

Let

$$TV \supset T\varphi' \longrightarrow V$$

be the relative algebraic tangent bundle for the projection $\varphi'$. Since $f$ in (10) is a Galois étale covering with Galois group $S_d$, from (16) we have

$$H^0(V, T\varphi') = H^0(\tilde{U} \times_U V, T_{\text{rel}})^{S_d} = (\text{sp}(2r, \mathbb{C})^{\oplus d})^{S_d} = \text{sp}(2r, \mathbb{C}).$$

Combining this with (15) we conclude that

$$H^0(V, TV) = \text{sp}(2r, \mathbb{C}).$$

In particular the homomorphism $d\rho$ in (12) is surjective. □

**Corollary 3.** The isomorphism class of the variety $Q$ uniquely determines the isomorphism class of $X$, except when $d = 2 = \text{genus}(X)$.

**Proof.** This follows from Theorem 2 and [6]. The argument is similar to the proof of Theorem 5.1 in [5]. □

**References**


