CONSTRAINTS ON AUTOMORPHISM GROUPS OF HIGHER DIMENSIONAL MANIFOLDS

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Abstract. In this note, we prove, for instance, that the automorphism group of a rational manifold $X$ which is obtained from $\mathbb{P}^k(\mathbb{C})$ by a finite sequence of blow-ups along smooth centers of dimension at most $r$ with $k > 2r + 2$ has finite image in $GL(H^*(X, \mathbb{Z}))$. In particular, every holomorphic automorphism $f : X \to X$ has zero topological entropy.

1. Introduction

1.1. Dimensions of indeterminacy loci. Recall that a rational map admitting a rational inverse is called birational. Birational transformations are, in general, not defined everywhere. The domain of definition of a birational map $f : M \to N$ is the largest Zariski-open subset on which $f$ is locally a well defined morphism. Its complement is the indeterminacy set $\text{Ind}(f)$; its codimension is always larger than, or equal to, 2. The following statement shows that the dimension of $\text{Ind}(f)$ and $\text{Ind}(f^{-1})$ can not be too small simultaneously unless $f$ is an automorphism. The proof of this result follows a nice argument of Nessim Sibony concerning the degrees of regular automorphisms of the complex space $\mathbb{C}^k$ (see [Sib99]); this idea was explained to us by an anonymous referee (compare [BC12]). It may be considered as an extension of a theorem due to Matsusaka and Mumford (see [MaMu64], and [KSC04], Exercise 5.6).

Theorem 1.1. Let $k$ be a field. Let $M$ be a smooth connected projective variety defined over $k$. Let $f$ be a birational transformation of $M$. Assume that the following two properties are satisfied.

(i) the Picard number of $M$ is equal to 1;
(ii) the indeterminacy sets of $f$ and its inverse satisfy

$$\dim(\text{Ind}(f)) + \dim(\text{Ind}(f^{-1})) < \dim(M) - 2.$$  

Then $f$ is an automorphism of $M$.

Moreover, $\text{Aut}(M)$ is an algebraic group because the Picard number of $M$ is equal to 1. As explained below, this statement provides a direct proof of the following corollary, which was our initial motivation.

Corollary 1.2. Let $M_0$ be a smooth, connected, projective variety with Picard number 1. Let $m$ be a positive integer, and $\pi_i : M_{i+1} \to M_i$, $i = 0, \ldots, m-1$, be a sequence of blow-ups of smooth irreducible subvarieties of dimension at most $r$. If $\dim(M_0) > 2r + 2$ then the number of connected components of $\text{Aut}(M_m)$ is finite;

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moreover, the projection $\pi : M_m \to M_0$ conjugates $\text{Aut}(M_m)$ to a subgroup of the algebraic group $\text{Aut}(M_0)$.

For instance, if $M_0$ is the projective space (respectively a cubic hypersurface of $\mathbb{P}^4_k$) and if one modifies $M_0$ by a finite sequence of blow-ups of points, then $\text{Aut}(M_0)$ is isomorphic to a linear algebraic subgroup of $\text{PGL}_4(k)$ (respectively is finite). This provides a sharp (and strong) answer to a question of Eric Bedford. In Section 3, we provide a second, simpler proof of this last statement.

**Remark 1.3.** The initial question of E. Bedford concerned the existence of automorphisms of compact Kähler manifolds with positive topological entropy in dimension $> 2$. This link with dynamical systems is described, for instance, in [Can11]. If a compact complex surface $S$ admits an automorphism with positive entropy, then $S$ is Kähler and is obtained from the projective plane $\mathbb{P}^2(C)$, a torus, a $K3$ surface or an Enriques surface, by a finite sequence of blow-ups (see [Can01, Can99] and [Nag61]). Examples of automorphisms with positive entropy are easily constructed on tori, $K3$ surfaces, or Enriques surfaces. Examples of automorphisms with positive entropy on rational surfaces are given in [BK06, BK10, McM07]; these examples are obtained from birational transformations $f$ of the plane by a finite sequence of blow-ups that resolves all indeterminacies of $f$ and its iterates simultaneously. These results suggest to look for birational transformations of $\mathbb{P}^n_C$, $n \geq 3$, that can be lifted to automorphisms with a nice dynamical behavior after a finite sequence of blow-ups; the above result shows that at least one center of the blow-ups must have dimension $\geq n/2 - 1$.

**Remark 1.4.** Recently, Tuyen Truong obtained results which are similar to Corollary 1.2, but with hypothesis on the Hodge structure and nef classes of $M_0$ that replace our strong hypothesis on the Picard number (see [Tru12, Tru13]).

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2. Dimensions of Indeterminacy loci

In this section, we prove Theorem 1.1 under a slightly more general assumption. Indeed, we replace assumption (i) with the following assumption

(i’) There exists an ample line bundle $L$ such that $f^*(L) \cong L^{\otimes d}$ for some $d > 1$.

This property is implied by (i). Indeed, if $M$ has Picard number 1, the torsion-free part of the Néron-Severi group of $M$ is isomorphic to $\mathbb{Z}$, and is generated by the class $[H]$ of an ample divisor $H$. Thus, $[f^*H]$ must be a multiple of $[H]$.

In what follows, we assume that $f$ satisfies property (i’) and property (ii). Replacing $H$ by a large enough multiple, we may and do assume that $H$ is very ample. Thus, the complete linear system $|H|$ provides an embedding of $M$ into some projective space $\mathbb{P}^m_k$, and we identify $M$ with its image in $\mathbb{P}^m_k$. With such a convention, members of $|H|$ correspond to hyperplane sections of $M$.
2.1. Degrees. Denote by $k$ the dimension of $M$, and by $\deg(M)$ its degree, i.e. the number of intersections of $M$ with a generic subspace of dimension $n - k$.

If $H_1, \ldots, H_k$ are hyperplane sections of $M$, and if $f^*(H_1)$ denotes the total transform of $H_1$ under the action of $f$, one defines the degree of $f$ by the following intersection of divisors of $M$

$$\deg(f) = \frac{1}{\deg(M)} f^*(H_1) \cdot H_2 \cdots H_k.$$ 

Since $M$ has Picard number 1, we know that divisor class $[f^*(H_1)]$ is proportional to $[H]$. Our definition of $\deg(f)$ implies that $f^*[H_1] = \deg(f)[H_1]$. As a consequence,

$$f^*(H_1) \cdot f^*(H_2) \cdots f^*(H_j) \cdot H_{j+1} \cdots H_k = \deg(f)^j \deg(M)$$

for all $0 \leq j \leq k$.

2.2. Degree bounds. Assume that the sum of the dimension of $\text{Ind}(f)$ and of $\text{Ind}(f^{-1})$ is at most $k - 3$. Then there exist at least two integers $l \geq 1$ such that

$$\dim(\text{Ind}(f)) \leq k - l - 1;$$

$$\dim(\text{Ind}(f^{-1})) \leq l - 1.$$

Let $H_1, \ldots, H_l$ and $H'_1, \ldots, H'_{k-l}$ be generic hyperplane sections of $M$; by Bertini’s theorem,

(a) $H_1, \ldots, H_l$ intersect transversally the algebraic variety $\text{Ind}(f^{-1})$ (in particular, $H_1 \cap \ldots \cap H_l$ does not intersect $\text{Ind}(f^{-1})$ because $\dim(\text{Ind}(f^{-1})) < l$);

(b) $H'_1, \ldots, H'_{k-l}$ intersect transversally the algebraic variety $\text{Ind}(f)$ (in particular, $H'_1 \cap \ldots \cap H'_{k-l}$ does not intersect $\text{Ind}(f)$ because $\dim(\text{Ind}(f)) < k - l$).

For $j \leq l$, consider the variety $V_j = f^*(H_1 \cap \ldots \cap H_j)$. In the complement of $\text{Ind}(f)$, $V_j$ is smooth, of dimension $k - j$; since $j \leq l$ and $\dim(\text{Ind}(f)) < k - l$, $V_j$ extends in a unique way as a subvariety of dimension $k - j$ in $M$. The varieties $V_j$ are reduced and irreducible.

Since each $H_i$, $1 \leq i \leq l$, intersects $\text{Ind}(f^{-1})$ transversally, $f^*(H_i)$ is an irreducible hypersurface (it does not contain any component of the exceptional locus of $f$). Thus

$$V_j = f^*(H_1 \cap \ldots \cap H_j) = f^*(H_1) \cap \ldots \cap f^*(H_j)$$

is the intersection of $j$ hypersurfaces of the same degree; for $j = l$ one gets

$$\deg(f)^j \deg(M) = f^*(H_1 \cap \ldots \cap H_l) \cdot (H'_1 \cap \ldots \cap H'_{k-l}).$$

More precisely, since the $H'_i$ are generic, this intersection is transversal and $V_j$. $(H'_1 \cap \ldots \cap H'_{k-l})$ is made of $\deg(f)^j \deg(M)$ points, all of them with multiplicity 1, all of them in the complement of $\text{Ind}(f)$ (see property (b) above).

Similarly, one defines the subvarieties $V'_j = f_*(H'_1 \cap \ldots \cap H'_j)$ with $j \leq k - l$; as above, these subvarieties have dimension $k - j$, are smooth in the complement of $\text{Ind}(f^{-1})$, and uniquely extend to varieties of dimension $k - j$ through $\text{Ind}(f^{-1})$. Each of them is equal to the intersection of the $j$ irreducible divisors $f_*(H_i)$, $1 \leq i \leq j$. Hence,

$$(H_1 \cap \ldots \cap H_l) \cdot V'_{k-l} = \deg(f^{-1})^{k-l} \deg(M).$$

If one applies the transformation $f: M \setminus \text{Ind}(f) \to M$ to $V_l$ and to $(H'_1 \cap \ldots \cap H'_{k-l})$, one deduces that $\deg(f)^j \deg(M) \leq \deg(f^{-1})^{k-l} \deg(M)$, because all points
of intersection of \( V_i \) with \((H'_1 \cap \ldots \cap H'_{k-l})\) are contained in the complement of \( \text{Ind}(f) \).

Applied to \( f^{-1} \), the same argument provides the opposite inequality. Thus,

\[
\deg(f)^l = \deg(f^{-1})^{k-l}
\]

Since there are at least two distinct values of \( l \) for which this equation is satisfied, one concludes that

\[
\deg(f) = \deg(f^{-1}) = 1.
\]

As a consequence, \( f \) has degree 1 if it satisfies assumptions (i') and (ii), .

2.3. From birational transformations to automorphisms. To conclude the proof of Theorem 1.1, one applies the following lemma.

**Lemma 2.1.** Let \( M \) be a smooth projective variety and \( f \) a birational transformation of \( M \). If there exists an ample divisor \( H \) such that \( f^*H \) and \( f_*H \) are numerically equivalent to \( H \), then \( f \) is an automorphism.

**Proof.** Taking multiples, we assume that \( H \) is very ample. Consider the graph \( Z \) of \( f \) in \( M \times M \), together with its two natural projections \( \pi_1 \) and \( \pi_2 \) onto \( M \).

The complete linear system \( |H| \) is mapped by \( f^* \) to a linear system \( |H'| \) with the same numerical class, and vice versa if one applies \( f^{-1} \) to \( |H'| \). Thus, \( |H'| \) is also a complete linear system, of the same dimension. Both of them are very ample (but they may differ if the dimension of \( \text{Pic}^0(M) \) is positive).

Assume that \( \pi_2 \) contracts a curve \( C \) to a point \( q \). Take a generic member \( H_0 \) of \( |H| \): It does not intersect \( q \), and \( \pi_2^*H_0 \) does not intersect \( C \). The projection \( (\pi_1)_\ast, (\pi_2^\ast)H_0 \) is equal to \( f^*H_0 \); since \( f^* \) maps the complete linear system \( |H| \) to the complete linear system \( |H'| \) and \( H_0 \) is generic, we may assume that \( f^*(H_0) \) is a generic member of \( |H'| \). As such, it does not intersect the finite set \( \pi_1(C) \cap \text{Ind}(f) \). Thus, there is no fiber of \( \pi_1 \) that intersects simultaneously \( C \) and \( \pi_2^*(f_\ast H_0) \), and \( (\pi_1)_\ast, (\pi_2^\ast)H_0 \) does not intersect \( C \). This contradicts the fact that \( f^*(H_0) \) is ample. \( \square \)

2.4. Conclusion, and Kähler manifolds. Under the assumptions of Theorem 1.1, Section 2.2 shows that \( f^*H \) is numerically equivalent to \( H \). Lemma 2.1 implies that \( f \) is an automorphism. This concludes the proof of Theorem 1.1.

This proof is inspired by an argument of Sibony in [Sib99] (see Proposition 2.3.2 and Remark 2.3.3); which makes use of complex analysis: the theory of closed positive current, and intersection theory. With this viewpoint, one gets the following statement.

**Theorem 2.2.** Let \( M \) be a compact Kähler manifold and \( f \) a bi-meromorphic transformation of \( M \). Assume that

(i) there exists a Kähler form \( \omega \) such that the cohomology class of \( f^*\omega \) is proportional to the cohomology class of \( \omega \);

(ii) the indeterminacy locus of \( f \) and its inverse satisfy

\[
\dim(\text{Ind}(f)) + \dim(\text{Ind}(f^{-1})) < \dim(M) - 2.
\]

Then \( f \) is an automorphism of \( M \) that fixes the cohomology class of \( \omega \).

Moreover, Lieberman’s theorem (see [Lie78]) implies that a positive iterate \( f^m \) of \( f \) is contained in the connected component of the identity of the complex Lie group \( \text{Aut}(M) \).
2.5. Proof of Corollary 1.2. Since $M_m$ is obtained from $M_0$ by a sequence of blow-ups of centers of dimension $< \dim(M_m)/2 - 1$, all automorphisms $f$ of $M_m$ are conjugate, through the obvious birational morphism $\pi : M_m \to M_0$, to birational transformations of $M_0$ that satisfy
\[ \dim(\text{Ind}(f)) < \dim(M_0)/2 - 1 \text{ and } \dim(\text{Ind}(f^{-1})) < \dim(M_0)/2 - 1. \]
Thus, by Theorem 1.1 $\pi$ conjugates $\text{Aut}(M)$ to a subgroup of $\text{Aut}(M_0)$. Moreover, given any polarization of $M_0$ by a very ample class, all elements of $\text{Aut}(M_0)$ have degree 1 with respect to this polarization. Hence, $\text{Aut}(M_0)$ is an algebraic group, and the kernel of the action of $\text{Aut}(M_0)$ on $\text{Pic}^0(M_0)$ is a linear algebraic group; if $\text{Pic}^0(M_0)$ is trivial, there is a projective embedding of $\Theta : M_0 \to \mathbb{P}^n_k$ that conjugates $\text{Aut}(M_0)$ to the group of linear projective transformations $G \subset \text{PGL}_{n+1}(k)$ that preserve $\Theta(M)$.

3. Constraints on automorphisms from the structure of the intersection form

Let $X$ be a smooth projective variety of dimension $k$ over a field $k$. Denote by $\text{NS}(X)$ the Néron-Severi group of $X$, i.e. the group of classes of divisors for the numerical equivalence relation. We consider the multi-linear forms
\[ Q_d : \text{NS}(X)^d \to \mathbb{Z} \]
which are defined by
\[ Q_d(u_1, u_2, \ldots, u_d) = u_1 \cdot u_2 \cdots u_d \cdot K_X^{k-d}. \]
These forms are invariant under $\text{Aut}(X)^*$ and we shall derive new constraints on the size of $\text{Aut}(X)^*$ from this invariance.

**Theorem 3.1.** Let $X$ be a smooth projective variety of dimension $k \geq 3$, defined over a field $k$. Let $d$ be an integer that satisfies $3 \leq d \leq k$. If the projective variety
\[ W_d(X) := \{ u \in \mathbb{P}(\text{NS}(X) \otimes \mathbb{Z} \mathbb{C}) \mid Q_d(u, u, \ldots, u) = 0 \} \]
is smooth, then $\text{Aut}(X)^*$ is finite.

**Proof.** The group $\text{Aut}(X)^*$ acts by linear projective transformations on the projective space $\mathbb{P}(\text{NS}(X) \otimes \mathbb{Z} \mathbb{C})$ and preserves the smooth hypersurface $W_d$. Since $d \geq 3$ it follows from [MaMo64] that the group of linear projective transformations preserving a smooth hypersurface of degree $d$ is finite. Hence, there is a finite index subgroup $A$ of $\text{Aut}(X)^*$ which is contained in the center of $\text{GL}(\text{NS}(X))$; since the later is a finite group of homotheties, this finishes the proof. \hfill \Box

As a corollary, let us state the following one, already obtained in the previous sections:

**Corollary 3.2.** Let $X$ be a smooth projective variety of dimension $k \geq 3$. Assume that there exists a birational morphism $\pi : X \to V$ such that
\begin{itemize}
  \item the Picard number of $V$ is equal to 1
  \item $\pi^{-1}$ is the blow-up of $l$ distinct points of $V$.
\end{itemize}
Then $\text{Aut}(X)^*$ is a finite group.
Proof. We identify $\text{NS}(V)$ with $\mathbb{Z}e_0$ where $e_0$ is the class of an ample divisor. Let $a := e_0$. Since $X$ is obtained from $V$ by blowing up $l$ distinct points $p_1, \ldots, p_l$ we have

$$\text{NS}(X) = \mathbb{Z}e_0 + \bigoplus_{1 \leq i \leq l} \mathbb{Z}e_i$$

where $e_i$ is the class of the exceptional divisor $E_i := \pi^{-1}(p_i)$. Then the form $Q_k$ is given by

$$Q_k(u) = a(X_0)^k + (-1)^{k+1} \sum_{i=1}^{l} (X_i)^k$$

where $u = X_0e_0 + \sum_i X_ie_i$ and $[X_0 : \ldots : X_l]$ denotes the homogeneous coordinates on $\mathbb{P}(\text{NS}(X) \otimes \mathbb{Z} \mathbb{C})$. Hence, the projective variety defined by $Q_k$ in $\mathbb{P}(\text{NS}(X) \otimes \mathbb{Z} \mathbb{C})$ is smooth and $\text{Aut}(X)^*$ is finite. \qed

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