

ON THE IITAKA FIBRATION OF VARIETIES OF MAXIMAL ALBANESE DIMENSION

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ABSTRACT. We prove that the tetracanonical map of a variety X of maximal Albanese dimension induces the Iitaka fibration. Moreover, if X is of general type, then the tricanonical map is birational.

1. INTRODUCTION

In the study of smooth complex algebraic varieties, the natural maps defined by differential forms are of special importance. In particular pluricanonical maps have been extensively studied.

When X is of maximal Albanese dimension, the study was started by Chen and Hacon [CH2, CH3]. Their results were improved by Jiang [J2], who showed that the 5-th canonical map induces the Iitaka fibration. Recently, Tirabassi [Ti], showed that if X is of general type then the 4-th pluricanonical is birational.

Combining Theorems 4.1 and 5.1, we obtain the following statement.

Theorem A. *Let X be a smooth projective variety of maximal Albanese dimension. Then,*

- (1) *the linear system $|4K_X|$ induces the Iitaka fibration of X ,*
- (2) *if X is of general type, then the linear system $|3K_X|$ induces a birational map.*

This bound is optimal for varieties of maximal Albanese dimension. On the one hand, if X is a curve of genus 2, then $|2K_X|$ is not birational (Varieties of general type whose bicanonical map is not birational have been studied in [BLNP, L].) On the other hand, we produce varieties of dimension at least 4, whose tricanonical map does not induce the Iitaka fibration (see Example 5.6).

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We observe that when $\chi(X, \omega_X) > 0$, the birationality of the tricanonical map was proved by Chen and Hacon [CH3, Thm. 5.4]. Hence, we restrict ourselves to the case $\chi(X, \omega_X) = 0$. In this situation we have a special fibration where the m -th pluricanonical linear system restricts surjectively to the general fiber for $m \geq 3$ (see Lemma 3.5). On the base of this fibration, we construct two positive line bundles (see Lemmas 3.3 and 3.4). One of them induces a birational map on the base φ . The other one is used to prove the effectiveness that shows that the fibration followed by φ factors through the pluricanonical map. We use these line bundles to apply Lemma 2.1, which allows us to proceed by induction on the dimension of X . When, X is of general type it is enough to consider the tricanonical map to get the effectivity mentioned above. The lack of this effectiveness is what forces us to consider the tetra-canonical map for non-general type varieties (as we note in Remark 5.5), i.e. when X is not of general type, the tricanonical map does not necessarily respect the fibration arising from the Albanese morphism.

Notation. In the sequel, X will always be a smooth complex projective variety of maximal Albanese dimension. We denote by $a_X : X \rightarrow A_X$ the Albanese morphism. Given an abelian variety A , let \widehat{A} be its dual. For a morphism $t : X \rightarrow A$ to an abelian variety and a coherent sheaf \mathcal{F} on X , we denote by $V^i(\mathcal{F}, t)$ the i -th cohomological support loci:

$$\{P \in \text{Pic}^0(A) \mid H^i(X, \mathcal{F} \otimes t^*P) \neq 0\}.$$

We will use the terms M -regular, I.T.-index j (IT^j for short) and continuously globally generated (cgg for short) as they are defined in [PP1]. Given two divisors E, F , we will write $E \preceq F$ if $F - E$ is effective.

2. PRELIMINARIES

We begin with some easy lemmas.

Lemma 2.1. *Let $f : X \xrightarrow{g} Z \xrightarrow{h} Y$ be fibrations between smooth projective varieties. Let L be a line bundle on X . If the following two conditions hold:*

- 1) *The image of $H^0(X, L) \rightarrow H^0(X_y, L|_{X_y})$ induces a map birationally equivalent to $g|_{X_y} : X_y \rightarrow Z_y$ for a general fiber X_y of f ;*

- 2) There are line bundles H_i , $1 \leq i \leq M$, on Y such that $L - f^*H_i$ is effective and the multiple evaluation map

$$\varphi_Y : Y \rightarrow \mathbf{P}(H^0(Y, H_1)^*) \times \cdots \times \mathbf{P}(H^0(Y, H_M)^*)$$

is birational.

Then, the linear system $|L|$ induces a map birationally equivalent to $g : X \rightarrow Z$.

Proof. Since the $L - f^*H_i$ are effective we have a map π that induces the following diagram

$$\begin{array}{ccc} X & \xrightarrow{\varphi_{|L|}} & \mathbf{P}(H^0(X, L)^*) \\ \downarrow g & \nearrow \varphi_Z & \downarrow \pi \\ Z & & \\ \downarrow h & & \\ Y & \xrightarrow{\varphi_Y} & \mathbf{P}(H^0(Y, H_1)^*) \times \cdots \times \mathbf{P}(H^0(Y, H_M)^*) \end{array}$$

(Note: A curved arrow labeled 'f' points from X to Y, and a dotted arrow labeled 'phi_Z' points from Z to the product space.)

Condition 2) guarantees that $\varphi_{|L|}$ separates generic fibers of f and condition 1) shows that the map $\varphi_{|L|}$ factorizes as $\varphi_Z \circ g$ and a general fiber of h is mapped birationally via φ_Z . \square

We will need the following lemma to ensure the birationality of φ_Y in the previous lemma.

Lemma 2.2. *Let $\hat{\pi} : \hat{Y} \rightarrow Y$ be an abelian cover with Galois group G of smooth projective varieties of maximal Albanese dimensions. We denote $b_{\hat{Y}} = a_Y \circ \hat{\pi} : \hat{Y} \rightarrow A_Y$. Assume that $V^0(\omega_{\hat{Y}}, b_{\hat{Y}}) = \text{Pic}^0(Y)$ and*

$$\hat{\pi}_* \omega_{\hat{Y}}^2 = \bigoplus_{\chi \in G^*} \mathcal{H}_{\chi},$$

where \mathcal{H}_{χ} is the line bundle corresponding to the character $\chi \in G^*$.

Then, there exists \mathcal{H}_{χ_0} such that the multiple evaluation map

$$\varphi_{P_1 \dots P_M} : Y \rightarrow \mathbf{P}(H^0(Y, \mathcal{H}_{\chi_0} \otimes P_1)^*) \times \cdots \times \mathbf{P}(H^0(Y, \mathcal{H}_{\chi_0} \otimes P_M)^*)$$

is birational for some $P_i \in \text{Pic}^0(Y)$, $1 \leq i \leq M$.

If $\hat{\pi}$ is an isomorphism, then Lemma 2.2 is contained in the proof of [CH3, Thm. 4.4].

Proof. We first write

$$\hat{\pi}_* \omega_{\hat{Y}} = \bigoplus_{\chi \in G^*} \mathcal{L}_{\chi}.$$

Since $V^0(\omega_{\widehat{Y}}, b_{\widehat{Y}}) = \text{Pic}^0(Y)$, we conclude that there exists χ_1 such that $V^0(\mathcal{L}_{\chi_1}, a_Y) = \text{Pic}^0(Y)$. Then, for any $P \in \text{Pic}^0(Y)$, the line bundle $\mathcal{L}_{\chi_1}^{\otimes 2} \otimes P$ is globally generated on the open dense subset

$$Y - \cap_{P \in \text{Pic}^0(Y)} \text{Bs}(|\mathcal{L}_{\chi_1} \otimes P|).$$

Since there is the natural G -map of vector bundles on Y ,

$$(\widehat{\pi}_* \omega_{\widehat{Y}})^{\otimes 2} \rightarrow \widehat{\pi}_* \omega_{\widehat{Y}}^2,$$

if we take $\chi_0 = \chi_1^2$, then we have an inclusion $\mathcal{L}_{\chi_1}^2 \hookrightarrow \mathcal{H}_{\chi_0}$. Hence, there is an open dense subset U of Y such that for any $P \in \text{Pic}^0(Y)$, the line bundle $\mathcal{H}_{\chi_0} \otimes P$ is globally generated on U , i.e. $\varphi_P|_U$ is a morphism.

On the other hand, we consider $\widehat{\pi}_*(\omega_{\widehat{Y}}^2 \otimes \mathcal{I}(|\omega_{\widehat{Y}}|))$. Since $\mathcal{I}(|\omega_{\widehat{Y}}|) \hookrightarrow \mathcal{O}_{\widehat{Y}}$ is G -invariant, we can write

$$\widehat{\pi}_*(\omega_{\widehat{Y}}^2 \otimes \mathcal{I}(|\omega_{\widehat{Y}}|)) = \bigoplus_{\chi \in G^*} \mathcal{H}_{\chi} \otimes \mathcal{I}_{\chi},$$

where \mathcal{I}_{χ} is an ideal sheaf on Y . Moreover, we have

$$H^0(Y, \mathcal{H}_{\chi} \otimes \mathcal{I}_{\chi}) \simeq H^0(Y, \mathcal{H}_{\chi}),$$

and

$$H^i(Y, \mathcal{H}_{\chi} \otimes \mathcal{I}_{\chi} \otimes P) = 0,$$

for any $P \in \text{Pic}^0(Y)$ and $i \geq 1$.

Therefore, $\mathcal{H}_{\chi_0} \otimes \mathcal{I}_{\chi_0} \otimes P$ is globally generated on the open subset U , so $\text{Supp}(\mathcal{O}_Y/\mathcal{I}_{\chi_0})$ is contained in $Y - U$. Now, let $V = U - \text{Exc}(a_Y)$ and for any point $y \in V$, from the exact sequence

$$0 \rightarrow \mathcal{I}_y \otimes \mathcal{H}_{\chi_0} \otimes \mathcal{I}_{\chi_0} \rightarrow \mathcal{H}_{\chi_0} \otimes \mathcal{I}_{\chi_0} \rightarrow \mathbf{C}_y \rightarrow 0,$$

we see that $a_{Y*}(\mathcal{I}_y \otimes \mathcal{H}_{\chi_0} \otimes \mathcal{I}_{\chi_0})$ is a M -regular sheaf, so it is *cgg* (see [PP1, Prop. 2.13]). Hence for any $z \in V$ different from y , there exists $P \in \text{Pic}^0(Y)$ such that $\mathcal{I}_y \otimes \mathcal{H}_{\chi_0} \otimes \mathcal{I}_{\chi_0} \otimes P$ is globally generated on z .

This shows that for any two different points $y, z \in V$ there exists $P \in \text{Pic}^0(Y)$ and a divisor D_P in $|\mathcal{H}_{\chi_0} \otimes P|$ such that $y \in D_P$ but $z \notin D_P$. Therefore $\varphi_P(y) \neq \varphi_P(z)$.

We take P_1, \dots, P_M such that $\varphi_{P_1 \dots P_M}$ becomes stable, namely $\varphi_{P_1 \dots P_M}$ is birational equivalent to $\varphi_{P_1 \dots P_M P}$ for any $P \in \text{Pic}^0(Y)$. Then, $\varphi_{P_1 \dots P_M}$ is birational. \square

The following lemma should be compared to [CH1, Lem. 3.1].

Lemma 2.3. *Let $f : X \rightarrow Y$ be a surjective morphism between smooth projective varieties. Assume that X is of maximal Albanese dimension. Then, $K_{X/Y}$ is effective.*

Proof. We have the natural inclusion $f^*\Omega_Y^1 \xrightarrow{i} \Omega_X^1$. Denote by \mathcal{F} the saturation of $i(f^*\Omega_Y^1)$. Then, $\det(\mathcal{F}) - f^*K_Y$ is an effective divisor on X . We then consider the exact sequence

$$0 \rightarrow \mathcal{F} \rightarrow \Omega_X^1 \rightarrow \mathcal{Q} \rightarrow 0.$$

Since X is of maximal Albanese dimension, Ω_X^1 is generically globally generated and hence so is \mathcal{Q} .

Hence $\det(\mathcal{Q})$ is also an effective divisor. Hence $K_{X/Y} = \det(\mathcal{F}) - f^*K_Y + \det(\mathcal{Q})$ is effective. \square

The following lemma is used in [J1, Lem. 2.3] under the assumption that the plurigena are positive (since X is of maximal Albanese dimension, this condition is automatically satisfied). We recall it here for easy reference.

Lemma 2.4. *Suppose that $f : X \rightarrow Y$ is an algebraic fiber space between smooth projective varieties. Assume that Y is of general type. Then, the Iitaka model of $(X, K_X + (m - 2)K_{X/Y})$ dominates Y , for any $m \geq 2$.*

3. POSITIVE BUNDLES ON THE BASE AND SURJECTIVITY OF THE RESTRICTION MAP TO A FIBER

We will use the following definition that it is strongly related to Hypotheses 4.7 in [BLNP].

Definition 3.1. Let \mathcal{F} be a coherent sheaf on an abelian variety A . We say that \mathcal{F} is almost M -regular if $V^0(\mathcal{F}) = \widehat{A}$, $\text{codim}_{\widehat{A}} V^i(\mathcal{F}) \geq i + 1$, for $1 \leq i \leq \dim A - 1$, and $\dim V^{\dim A}(\mathcal{F}) = 0$.

Let X be a smooth projective variety of dimension n and maximal Albanese dimension. We know that the pushforward of the canonical bundle $a_{X*}\omega_X$ is a GV -sheaf but it often fails to be M -regular, which makes the tricanonical map difficult to study. Hence we consider the set

$$\mathcal{S}_X := \{0 < j < n \mid V^j(\omega_X, a_X) \text{ has a component of codimension } j\},$$

which measures how far $a_{X*}\omega_X$ is from being almost M -regular.

Setting 3.2. Assume that \mathcal{S}_X is not empty. We denote by k the maximal number of \mathcal{S}_X and $Q + \widehat{B} \subseteq V^k(\omega_X, a_X)$ a codimension- k component, where Q is zero or a torsion element of $\text{Pic}^0(X) - \widehat{B}$. Let

the following commutative diagram

$$\begin{array}{ccc} X & \xrightarrow{a_X} & A_X \\ f \downarrow & & \downarrow \text{pr} \\ Y & \xrightarrow{a_Y} & B \end{array}$$

be a suitable birational modification of the Stein factorization of the composition $\text{pr} \circ a_X$, such that Y is smooth.

Lemma 3.3. *Assume \mathcal{S}_X is not empty, so we are in Setting 3.2. Then, for some birational model of $f : X \rightarrow Y$, there exists a line bundle \mathcal{L} on Y such that $a_{Y*}\mathcal{L}$ is almost M -regular, $V^0(\mathcal{L}, a_Y) = \widehat{B}$, and $\mathcal{O}_X(K_X + jQ) \otimes f^*\mathcal{L}^{-1}$ has a non-trivial section for some $j \in \mathbf{Z}$. Moreover,*

- 1) *if Q is trivial, we can take \mathcal{L} to be ω_Y and $j = 0$;*
- 2) *if $Q \in \text{Pic}^0(X) - \widehat{B}$, then we can take \mathcal{L} such that $a_{Y*}\mathcal{L}$ is M -regular.*

Proof. We know by [GL, Theorem 0.1] that the dimension of a general fiber of f is k .

Assume first that Q is trivial. For $P_B \in \widehat{B} - \cup_j V^1(R^j f_* \omega_X) \neq \emptyset$ (e.g. [PP2, Thm. 5.8]),

$$\begin{aligned} 0 &< h^k(X, \omega_X \otimes a_X^* P_B) = h^k(X, \omega_X \otimes f^* P_B) \\ &= h^0(Y, R^k f_* \omega_X \otimes a_Y^* P_B) && \text{e.g. [PP2, Prop. 3.14]} \\ &= h^0(Y, \omega_Y \otimes a_Y^* P_B) && \text{[K1, Prop. 7.6]}. \end{aligned}$$

By generic vanishing $\chi(Y, \omega_Y) = h^0(Y, \omega_Y \otimes a_Y^* P_B)$ for a general $P_B \in \widehat{B}$. Hence $\chi(Y, \omega_Y) > 0$ and $V^0(\omega_Y, a_Y) = \text{Pic}^0(Y)$.

Moreover, the pull-back by pr of any codimension- j component of $V^j(\omega_Y, a_Y)$ is a codimension- $(j+k)$ component of $V^{j+k}(\omega_X, a_X)$ (by [K2, Thm. 3.1]). Hence by the maximality of k , we know that $\text{codim}_{\widehat{B}} V^i(\omega_Y, a_Y) \geq i+1$ for all $0 < i < \dim Y$ and $a_{Y*}\omega_Y$ is almost M -regular. By Lemma 2.3, $\mathcal{O}_X(K_X - f^*K_Y)$ is effective.

Now, assume that $Q \in \text{Pic}^0(X) - \widehat{B}$. We may choose Q such that $\langle Q \rangle \cap \widehat{B} = 0$, where $G := \langle Q \rangle$ is the subgroup generated by Q . We then consider the étale cover $\pi : \widetilde{X} \rightarrow X$ induced by G and, after

modifications, we have the following diagram

$$(1) \quad \begin{array}{ccccc} & & \overset{b_{\tilde{X}}}{\curvearrowright} & & \\ \tilde{X} & \xrightarrow{\pi} & X & \xrightarrow{a_X} & A_X \\ \downarrow \tilde{f} & & \downarrow f & & \downarrow \text{pr} \\ \hat{Y} & \xrightarrow{\hat{\pi}} & Y & \xrightarrow{a_Y} & B \\ & & \underset{b_{\hat{Y}}}{\curvearrowleft} & & \end{array}$$

where all varieties are smooth and the vertical morphisms are fibrations (in particular, \hat{Y} is a modification of the Stein factorization of $f \circ \pi$).

The same arguments as in the previous case show that $V^0(\hat{Y}, b_{\hat{Y}}) = \hat{B}$ and $\text{codim}_{\hat{B}} V^i(\omega_{\hat{Y}}, b_{\hat{Y}}) \geq i + 1$ for all $0 < i < \dim \hat{Y}$.

By [PP2, Thm. 5.8 and Prop. 3.14], $R^j f_*(\omega_X \otimes Q)$ are GV -sheaves for all $j \geq 0$. Then by [K2, Thm. 3.1], for $P_B \in \hat{B}$ general $h^k(\omega_X \otimes Q \otimes a_Y^* P_B) = h^0(Y, R^k f_*(\omega_X \otimes Q) \otimes a_Y^* P_B)$. Since $Q + \hat{B} \subset V^k(\omega_X, a_X)$, $R^k f_*(\omega_X \otimes Q) \neq 0$. If we denote by X_y a general fiber of f , then we know that $Q|_{X_y}$ is \mathcal{O}_{X_y} . Hence

$$(2) \quad \hat{\pi}_* \omega_{\hat{Y}} = R^k (f \circ \pi)_* \omega_{\tilde{X}} = \oplus_i (R^k f_*(\omega_X \otimes Q^i)) = \oplus_i \mathcal{L}_i,$$

where $\mathcal{L}_0 = \omega_Y$ and after modifications, we may assume that all \mathcal{L}_i are line bundles on Y . Moreover, we have

$$\begin{aligned} \ker(\hat{B} \rightarrow \text{Pic}^0(\hat{Y})) &= \hat{B} \cap \ker(\hat{A}_X \rightarrow \hat{A}_{\tilde{X}}) \\ &= \hat{B} \cap \langle Q \rangle = 0. \end{aligned}$$

Hence for $i \neq 0$, $V^{\dim Y}(\mathcal{L}_i, a_Y) = \emptyset$ and $a_{Y*} \mathcal{L}_i$ is M -regular (in particular, $\chi(Y, \mathcal{L}_i) > 0$).

We know $K_{\tilde{X}/\hat{Y}}$ is effective by Lemma 2.3 and we have a nonzero map $\hat{\pi}^* \mathcal{L}_i \rightarrow \omega_{\hat{Y}}$ for every i . Hence,

$$\begin{aligned} 0 &< h^0(\tilde{X}, \omega_{\tilde{X}} \otimes \tilde{f}^* \omega_{\hat{Y}}^{-1}) \leq h^0(\tilde{X}, \omega_{\tilde{X}} \otimes \tilde{f}^* \hat{\pi}^* \mathcal{L}_i^{-1}) \\ &= \sum_j h^0(X, \omega_X \otimes Q^j \otimes f^* \mathcal{L}_i^{-1}). \end{aligned}$$

So there exists j such that $\omega_X \otimes Q^j \otimes f^* \mathcal{L}_i^{-1}$ is effective. Thus in 2), we can take \mathcal{L} to be any \mathcal{L}_i for $i \neq 0$. \square

Lemma 3.4. *Assume \mathcal{S}_X is not empty, so we are in Setting 3.2. Let \mathcal{L} be the line bundle obtained in Lemma 3.3. Then, after modifying Y , there exists a line bundle \mathcal{H} on Y and $i \in \mathbf{Z}$ such that $\mathcal{H} \otimes \mathcal{L}^{-2}$ and $\mathcal{O}_X(2K_X + iQ) \otimes f^* \mathcal{H}^{-1}$ have non-trivial sections. Moreover we*

can take $P_i \in \text{Pic}^0(Y)$, $1 \leq i \leq M$ such that the multiple evaluation map

$$\varphi_Y : Y \rightarrow \mathbf{P}(H^0(Y, \mathcal{H} \otimes P_1)^*) \times \cdots \times \mathbf{P}(H^0(Y, \mathcal{H} \otimes P_M)^*)$$

is birational.

Proof. If Q is trivial, we just take \mathcal{H} to be ω_Y^2 . By Lemma 2.2, we conclude.

If $Q \in \text{Pic}^0(X) - \widehat{B}$, then we use the same notations as in the proof of Lemma 3.3. Notice that in diagram (1) we have $Q|_{X_y}$ is the trivial line bundle. Hence, a general fiber of \tilde{f} is birational via π to a general fiber of f . So G is also the Galois group of the field extension $k(\widehat{Y})/k(Y)$. After modifications of $\tilde{f} : \widehat{X} \rightarrow \widehat{Y}$, we may assume that G acts also on \widehat{Y} , \tilde{f} is a G -equivariant morphism, and $\widehat{\pi} : \widehat{Y} \rightarrow Y$ is a G -cover of smooth projective varieties.

Now, we apply Lemma 2.2 to $\widehat{\pi}$. Take \mathcal{H} to be the direct summand of $\widehat{\pi}_* \omega_{\widehat{Y}}^2$ which contains \mathcal{L}^2 .

As in the proof of Lemma 3.3, since $\widehat{\pi}^* \mathcal{H} \hookrightarrow \omega_{\widehat{Y}}^2$ and $K_{\widehat{X}/\widehat{Y}}$ is effective, we conclude that there exists $i \in \mathbf{Z}$ such that $\mathcal{O}_X(2K_X + iQ) \otimes f^* \mathcal{H}^{-1}$ is effective. \square

Lemma 3.5. *Assume \mathcal{S}_X is not empty, so we are in Setting 3.2. Let \mathcal{L} be the line bundle obtained in Lemma 3.3. Then, for y a general point of Y , the restriction map*

$$H^0(X, \mathcal{O}_X(mK_X - (m-3)f^* \mathcal{L}) \otimes P) \rightarrow H^0(X_y, \mathcal{O}_{X_y}(mK_{X_y}) \otimes P)$$

is surjective, for any $m \geq 2$ and $P \in V^0(\omega_X^m, a_X)$.

Proof. We just prove the statement for $P = \mathcal{O}_X$, the same arguments works for any $P \in V^0(\omega_X^m, a_X)$.

There are two distinguished cases, whether Q is trivial or not, which we address with slightly different techniques.

Case A. Assume that Q is trivial.

We have seen in the proof of Lemma 3.3 that $\chi(Y, \omega_Y) > 0$, so Y is of general type. By Lemma 2.4, the Iitaka model of $(X, K_X + (m-2)K_{X/Y})$ dominates Y and by [J1, Lem. 2.1] there exists an asymptotic multiplier ideal sheaf $\mathcal{I} := \mathcal{I}(\|K_X + (m-2)K_{X/Y}\|)$ on X such that $a_{Y*} f_*(\mathcal{O}_X(2K_X + (m-2)K_{X/Y}) \otimes \mathcal{I})$ is an IT^0 sheaf. Hence, by [PP1, Prop. 2.13],

$$\mathcal{F} := f_*(\mathcal{O}_X(2K_X + (m-2)K_{X/Y}) \otimes \mathcal{I})$$

is *egg* outside the exceptional locus of a_Y .

We conclude, similarly to [BLNP, Prop. 4.4. and Cor. 4.11] that, $\mathcal{F} \otimes \omega_Y$ is globally generated in an open dense subset of Y . Indeed, we first notice that $|\omega_Y \otimes P|$ is not empty for all $P \in \widehat{B}$. Take P_i , $1 \leq i \leq N$ such that the evaluation map

$$\bigoplus_{i=1}^N H^0(Y, \mathcal{F} \otimes P_i) \otimes P_i^{-1} \rightarrow \mathcal{F}$$

is surjective. Then

$$\bigoplus_{i=1}^N H^0(Y, \mathcal{F} \otimes P_i) \otimes H^0(Y, \omega_Y \otimes P_i^{-1}) \otimes \mathcal{O}_Y \rightarrow \mathcal{F} \otimes \omega_Y$$

is surjective over $Y - \bigcup_{1 \leq i \leq N} \text{Bs}(|\omega_Y \otimes P_i|)$. Finally this evaluation map factors through $H^0(Y, \mathcal{F} \otimes \omega_Y) \otimes \mathcal{O}_Y \rightarrow \mathcal{F} \otimes \omega_Y$.

Moreover, by [J1, Lem. 3.5], \mathcal{F} is a non-zero sheaf on Y of rank $P_m(X_y)$. Hence, over a general point $y \in Y$, $\mathcal{F} \otimes k(y)$ is isomorphic to $H^0(X_y, \mathcal{O}_{X_y}(mK_{X_y}))$. Since

$$\mathcal{F} \otimes \omega_Y \subset f_*(\mathcal{O}_X(mK_X - (m-3)f^*K_Y))$$

and they have the same rank $P_m(X_y)$, we conclude the proof of the lemma when Q is trivial.

Case B. If Q is non-trivial, we use the same commutative diagram as in the proof of Lemma 3.3:

$$\begin{array}{ccccc} & & \xrightarrow{b_{\tilde{X}}} & & \\ \tilde{X} & \xrightarrow{\pi} & X & \xrightarrow{a_X} & A_X \\ & \downarrow \tilde{f} & \downarrow f & & \downarrow \text{pr} \\ \widehat{Y} & \xrightarrow{\widehat{\pi}} & Y & \xrightarrow{a_Y} & B \\ & & \xrightarrow{b_{\widehat{Y}}} & & \end{array}$$

We claim that the Iitaka model of $(X, (m-1)K_X - (m-2)f^*\mathcal{L}_i)$ dominates Y . Indeed, by Lemma 2.4, the Iitaka model of $(\tilde{X}, (m-1)K_{\tilde{X}/\widehat{Y}} + \tilde{f}^*K_{\widehat{Y}})$ dominates \widehat{Y} . By definition of \mathcal{L}_i (see (2)), we have $\widehat{\pi}^*\mathcal{L}_i \preceq K_{\widehat{Y}}$, which implies that $\pi^*f^*\mathcal{L}_i \preceq f^*K_{\widehat{Y}}$. This is equivalent to $(m-1)K_{\tilde{X}/\widehat{Y}} + \tilde{f}^*K_{\widehat{Y}} \preceq \pi^*((m-1)K_X - (m-2)f^*\mathcal{L}_i)$. Since π is birational to an étale cover, the claim is clear.

Then, by [J1, Lem. 2.1] there is an ideal \mathcal{I}_i of X such that

$$a_{Y*}(f_*\mathcal{O}_X(mK_X) \otimes \mathcal{I}_i \otimes \mathcal{L}_i^{-(m-2)})$$

is an IT^0 sheaf and by [J1, Proof of Lem. 3.9] $f_*\mathcal{O}_X(mK_X) \otimes \mathcal{I}_i \otimes \mathcal{L}_i^{-(m-2)}$ has rank $P_m(X_y)$. We conclude as before, that for $i \neq 0$, $f_*(\mathcal{O}_X(mK_X - (m-3)f^*\mathcal{L}_i))$ is globally generated over an open dense subset of Y . \square

4. GENERAL TYPE CASE

In this section X will be a variety of general type.

Theorem 4.1. *Let X be a smooth projective variety, of maximal Albanese dimension and general type. Then, the linear system $|3K_X + P|$ induces a birational map, for any $P \in \text{Pic}^0(X)$.*

Proof. We reason by induction on the dimension of X , that we will denote by n . Note that for $n = 1$ the result is well known. So we assume that for any $P_Y \in \text{Pic}^0(Y)$, $|3K_Y + P_Y|$ induces birational map for any smooth projective variety Y of maximal Albanese dimension, general type, and $\dim Y \leq n - 1$.

Observe that \mathcal{S}_X is empty if and only if $a_{X*}\omega_X$ is almost M -regular. Since X is of general type, if \mathcal{S}_X is empty, then $\chi(X, \omega_X) > 0$ (e.g. [BLNP, Prop. 4.10]). We notice that Chen and Hacon have proved that $|3K_X + P|$ induces a birational map in this situation (see [CH3, Thm. 5.4]).

From now on, we will assume \mathcal{S}_X is not empty. As in the last section, we are in Setting 3.2. So, let k be the maximal number of \mathcal{S}_X and let $Q + \widehat{B}$ be an irreducible component of $V^k(\omega_X, a_X)$. Note that we can choose Q such that $\langle Q \rangle \cap \widehat{B} = 0$. Taking the étale cover induced by $G := \langle Q \rangle$, we get the same commutative diagram as in the proof of Lemma 3.5 (see (1))

$$(3) \quad \begin{array}{ccccc} & & \xrightarrow{b_{\widehat{X}}} & & \\ \widetilde{X} & \xrightarrow{\pi} & X & \xrightarrow{a_X} & A_X \\ & \downarrow \widetilde{f} & \downarrow f & & \downarrow \text{pr} \\ \widehat{Y} & \xrightarrow{\widehat{\pi}} & Y & \xrightarrow{a_Y} & B, \\ & & \xrightarrow{b_{\widehat{Y}}} & & \end{array}$$

where \widetilde{f} is obtained by taking the Stein factorization of $\text{pr} \circ b_{\widehat{X}}$ and after modifications, we may assume $\widehat{\pi}$ is a G -cover of smooth varieties.

Let $y \in Y$ be a general point and denote by X_y a general fiber of f .

By Lemma 3.5, the restriction map

$$(4) \quad H^0(X, \mathcal{O}_X(3K_X) \otimes P) \rightarrow H^0(X_y, \mathcal{O}_{X_y}(3K_{X_y}) \otimes P)$$

is surjective for any $P \in \text{Pic}^0(X)$ and, by the induction hypothesis,

$$|3K_{X_y} + P|_{X_y}|$$

induces a birational map.

We have also produced interesting line bundles on Y in Lemma 3.3 and Lemma 3.4. Let \mathcal{H} be the line bundle on Y constructed in Lemma

3.4. According to Lemma 2.1, in order to conclude the proof of the theorem, we just need to prove the following claim.

Claim †. For every $P \in \widehat{A}_X$ and every $P' \in \widehat{B}$, the line bundle

$$3K_X + P - f^*(\mathcal{H} + P')$$

has a non-trivial section.

Let be $\mathcal{I} := \mathcal{I}(\|2K_X - f^*\mathcal{H} + \frac{1}{N}f^*H\|)$, where N is an integer large enough and H is an ample divisor on Y . For any $P \in \widehat{A}_X$, we define

$$\mathcal{F}_P := f_*(\mathcal{O}_X(3K_X - f^*\mathcal{H}) \otimes \mathcal{I} \otimes P).$$

Observe that to conclude the proof of the claim it is enough to see that $V^0(\mathcal{F}_P, a_Y) = \widehat{B}$.

For any ample divisor H' on Y , we have that

$$(\dagger) \quad H^i(X, \mathcal{O}_X(3K_X - f^*\mathcal{H}) \otimes \mathcal{I} \otimes P \otimes f^*\mathcal{O}_Y(H')) = 0,$$

for any $i > 0$. We postpone the proof of (\dagger) to the end of the proof of this theorem. From (\dagger) we deduce that

$$R^i f_*(\mathcal{O}_X(3K_X - f^*\mathcal{H}) \otimes \mathcal{I} \otimes P) = 0,$$

for any $i > 0$ (see e.g. [La, Lemma 4.3.10]). Therefore,

$$\chi(Y, \mathcal{F}_P) = \chi(X, \mathcal{O}_X(3K_X - f^*\mathcal{H}) \otimes \mathcal{I} \otimes P)$$

is constant for $P \in \widehat{A}_X$.

By Lemma 3.3 and Lemma 3.4, there exist integers i and j and effective divisors $D_1 \in |K_X + iQ - f^*\mathcal{L}|$ and $D_2 \in |2K_X + jQ - f^*\mathcal{H}|$. Let $m = i + j$ and write $D = D_1 + D_2 \in |3K_X + mQ - f^*\mathcal{H} - f^*\mathcal{L}|$, i.e.

$$H^0(X, \mathcal{O}_X(3K_X + mQ - f^*\mathcal{H} - f^*\mathcal{L})) = H^0(X, \mathcal{O}_X(D)) \neq 0.$$

Since

$$\begin{aligned} \mathcal{I} &= \mathcal{I}(\|2K_X - f^*\mathcal{H} + \frac{1}{N}f^*H\|) \\ &\supset \mathcal{I}(\|2K_X - f^*\mathcal{H}\|) && H \text{ is ample on } Y \\ &= \mathcal{I}(\|2K_X + jQ - f^*\mathcal{H}\|) && Q \text{ is torsion} \\ &\supset \mathcal{O}_X(-D_2) && \text{by [La, Thm. 11.1.8],} \end{aligned}$$

we have

$$\begin{aligned} H^0(Y, \mathcal{F}_{mQ} \otimes \mathcal{L}^{-1}) &= H^0(X, \mathcal{O}_X(3K_X + mQ - f^*\mathcal{H} - f^*\mathcal{L}) \otimes \mathcal{I}) \\ (5) \quad &\supset H^0(X, \mathcal{O}_X(D_1)) \neq 0. \end{aligned}$$

Therefore, since $V^0(\mathcal{L}, a_Y) = \widehat{B}$, we have $h^0(Y, \mathcal{F}_{mQ} \otimes P') > 0$ for all $P' \in \widehat{B}$.

On the other hand, we see by [J1, Lem. 2.5] that \mathcal{F}_P is a GV -sheaf for any $P \in \widehat{A}_X$. Therefore, for $P' \in \widehat{B}$ general and any $P \in \widehat{A}_X$,

$$h^0(Y, \mathcal{F}_P \otimes P') = \chi(B, \mathcal{F}_P) = \chi(B, \mathcal{F}_{mQ}) = h^0(B, \mathcal{F}_{mQ} \otimes P') > 0.$$

Hence, by semicontinuity, for any $P \in \widehat{A}_X$, $V^0(\mathcal{F}_P, a_Y) = \widehat{B}$.

Proof of (†) Notice that $2K_{\widetilde{X}/\widehat{Y}} \preceq \pi^*(2K_X - f^*\mathcal{H})$ and $K_{\widetilde{X}/\widehat{Y}} + \frac{1}{N}\widetilde{f}^*\widehat{\pi}^*H$ is a big \mathbf{Q} -divisor on \widetilde{X} . Hence, $2K_X - f^*\mathcal{H} + \frac{1}{N}f^*H$ is a big \mathbf{Q} -divisor on X . So (†) is a consequence of Nadel vanishing theorem (see [La, Thm. 11.2.12]). \square

5. IITAKA FIBRATION

In this section X will not necessarily be a variety of general type.

Theorem 5.1. *Let X be a smooth projective variety, of maximal Albanese dimension. Then, the linear system $|4K_X + P|$ induces a model of the Iitaka fibration of X , for any $P \in V^0(\omega_X^2, a_X)$.*

Before starting the proof the Theorem 5.1, which is parallel to the proof of Theorem 4.1, let us fix the notation.

Setting 5.2. Consider the following diagram:

$$\begin{array}{ccc} X & \xrightarrow{a_X} & A_X \\ \downarrow g & & \downarrow \text{pr}_Z \\ Z & \xrightarrow{a_Z} & A_Z \end{array}$$

where $g : X \rightarrow Z$ is a model of the Iitaka fibration of X such that Z is smooth. Let K be the kernel of pr_Z . We denote by X_z a general fiber of g , which is birational to its Albanese variety \widetilde{K} , and the natural map $\widetilde{K} \rightarrow K$ is an isogeny. We know that $\text{pr}_Z^* \widehat{A}_Z$ is an irreducible component of

$$\mathcal{H} := \ker(\widehat{A}_X \rightarrow \text{Pic}^0(X_z))$$

and denote by $\mathcal{Q} := \mathcal{H} / \text{pr}_Z^* \widehat{A}_Z$. Observe that \mathcal{Q} can be also identified with $\ker(\widehat{K} \rightarrow \widetilde{K})$.

Remark 5.3. The group \mathcal{Q} is often non-trivial and this is exactly the reason why the tricanonical map can not always induce the Iitaka fibration. In some specific cases, given information about \mathcal{Q} , we can prove that the tricanonical map or some twisted tricanonical map (the

maps induced by $|3K_X + P|$ for some $P \in \text{Pic}^0(X)$) will induce the Iitaka fibration (see Remark 5.5).

Nevertheless we will construct a variety of maximal Albanese dimension (see Example 5.6), where NONE of the twisted tricanonical maps is birationally equivalent to the Iitaka fibration.

Before proving the theorem, we start with an easy well-known observation. We add its proof for the convenience of reader.

Lemma 5.4. *The kernel \mathcal{K} defined in Setting 5.2, satisfies*

$$\mathcal{K} = V^0(\omega_X^m, a_X) \quad \text{for all } m \geq 2.$$

Proof. It is clear that $V^0(\omega_X^m, a_X) \subseteq \mathcal{K}$. If $P \in \mathcal{K}$, then $g_*(\omega_X^m \otimes P)$ is a nontrivial torsion-free sheaf. By [J1, Lem. 2.1], $g_*(\omega_X^m \otimes \mathcal{I}(\|\omega_X^{m-1}\|) \otimes P)$ is an IT^0 sheaf for any $m \geq 2$. Hence, we conclude since $0 < h^0(Z, g_*(\omega_X^m \otimes \mathcal{I}(\|\omega_X^{m-1}\|) \otimes P)) \leq h^0(X, \omega_X^m \otimes P)$. \square

Proof of Theorem 5.1. We will prove the theorem by induction on the dimension of X . We suppose the statement is true in dimension $\leq n-1$ and assume $\dim X = n$. If X is of general type, then we are back to Theorem 4.1. Hence we can assume $\kappa(X) = \dim Z = n-l$, for some number $l > 0$. In particular, \mathcal{S}_X is not empty.

Hence, we are in Setting 3.2. Let k be the maximal number of \mathcal{S}_X and let $Q + \widehat{B}$ be an irreducible component of $V^k(\omega_X, a_X)$. Since $V^k(\omega_X, a_X) \subseteq V^0(\omega_X, a_X)$, by [CH2, Lem. 2.2], $\widehat{B} \hookrightarrow \text{pr}_Z^* \widehat{A}_Z$ (recall Setting 5.2). Hence, Setting 3.2 and 5.2 combine in the following commutative diagram

$$\begin{array}{ccc} X & \xrightarrow{a_X} & A_X \\ \downarrow g & & \text{pr}_Z \downarrow \\ Z & \xrightarrow{a_Z} & A_Z \\ \downarrow h & & \downarrow \\ Y & \xrightarrow{a_Y} & B. \end{array} \quad \begin{array}{l} \left. \begin{array}{c} \downarrow \\ \downarrow \\ \downarrow \end{array} \right\} f \\ \left. \begin{array}{c} \downarrow \\ \downarrow \\ \downarrow \end{array} \right\} \text{pr} \end{array}$$

Let $y \in Y$ be a general point and denote by X_y and Z_y general fibers of f and h . By Easy Addition Formula (e.g. [Li, Thm. 10.4]), $\dim Y + \kappa(X_y) \geq \kappa(X) = \dim Z$. Hence $\kappa(X_y) \geq \dim Z_y$ and thus $g|_{X_y} : X_y \rightarrow Z_y$ is the Iitaka fibration of X_y .

By Lemma 3.5 and 5.4, the restriction map

$$H^0(X, \mathcal{O}_X(4K_X + P)) \rightarrow H^0(X_y, \mathcal{O}_{X_y}(4K_{X_y} + P|_{X_y}))$$

is surjective, for any $P \in \mathcal{K}$. Notice that $P|_{X_y} \in V^0(\omega_{X_y}^2, a_{X_y})$, so by induction hypothesis,

$$|4K_{X_y} + P|_{X_y}|$$

induces the Iitaka fibration $g|_{X_y} : X_y \rightarrow Z_y$.

Let \mathcal{H} be the line bundle on Y constructed in Lemma 3.4. Then, by Lemma 2.1, we just need to prove the following claim to finish the proof of the theorem.

Claim. For every $P \in \mathcal{K}$ and every $P' \in \widehat{B}$,

$$4K_X + P - f^*(\mathcal{H} + P')$$

has a non-trivial section.

Let be $\mathcal{J} := \mathcal{J}(\|3K_X - f^*\mathcal{H} + \frac{1}{N}f^*H\|)$, where N is an integer large enough and H is an ample divisor on Y . For any $P \in \mathcal{K}$, we define

$$\mathcal{G}_P := g_*(\mathcal{O}_X(4K_X + P - f^*\mathcal{H}) \otimes \mathcal{J}).$$

Observe that to conclude the proof of the claim it is enough to see that $V^0(h_*\mathcal{G}_P, a_Y) = \widehat{B}$.

By [J1, Lemma 2.1], we have

$$H^i(Z, \mathcal{G}_P \otimes Q'' \otimes h^*H') = 0,$$

for any $i \geq 1$, any ample divisor H' on Y , and any $Q'' \in \widehat{A}_Z$. Hence,

$$R^i h_*(\mathcal{G}_P \otimes Q'') = 0,$$

for any $i > 0$ (see e.g. [La, Lemma 4.3.10]). Therefore,

$$(6) \quad \chi(Y, h_*(\mathcal{G}_P \otimes Q'')) = \chi(Z, \mathcal{G}_P \otimes Q'')$$

is constant for $Q'' \in \widehat{A}_Z$.

By Lemma 3.3 and Lemma 3.4, we know there exists $m \in \mathbf{Z}$ such that

$$H^0(X, \mathcal{O}_X(3K_X + mQ - f^*\mathcal{H} - f^*\mathcal{L})) \neq 0.$$

Observe that $P - mQ$ is not necessarily in $\text{pr}_Z^* \widehat{A}_Z$. But, since $P - mQ \in \mathcal{K}$, we have that $a_{Z*}g_*\mathcal{O}_X(K_X + P - mQ)$ is a non-trivial GV -sheaf. In particular, $V^0(g_*\mathcal{O}_X(K_X + P - mQ), a_Z) \neq \emptyset$. Hence there exists $Q_0 \in \text{pr}_Z^* \widehat{A}_Z$ such that $P - mQ + Q_0 \in V^0(\omega_X, a_X)$.

Therefore

$$\begin{aligned} & 4K_X + P + Q_0 - f^*\mathcal{H} - f^*\mathcal{L} \\ = & (K_X + P - mQ + Q_0) + (3K_X + mQ - f^*\mathcal{H} - f^*\mathcal{L}) \end{aligned}$$

is the sum of two effective divisors. By the same argument as in (5),

$$H^0(Z, \mathcal{G}_P \otimes h^* \mathcal{L}^{-1} \otimes Q_0) \neq 0.$$

We know that $V^0(\mathcal{L}, a_Y) = \widehat{B}$ (see Lemma 3.3) and $h_*(\mathcal{G}_P \otimes Q')$ is a GV -sheaf for any $P \in \mathcal{K}$ and any $Q' \in \widehat{A}_Z$ (see [J1, Lem. 2.5]). Hence, for $P' \in \widehat{B}$ general,

$$\begin{aligned} h^0(Y, h_* \mathcal{G}_P \otimes P') &= \chi(Y, h_* \mathcal{G}_P) = \chi(Y, h_*(\mathcal{G}_P \otimes Q_0)) \quad \text{by (6)} \\ &= h^0(Y, h_*(\mathcal{G}_P \otimes Q_0) \otimes P') > 0. \end{aligned}$$

By semicontinuity, $V^0(h_* \mathcal{G}_P, a_Y) = \widehat{B}$ for any $P \in \mathcal{K}$. \square

Now, we can make more precise Remark 5.3.

Remark 5.5. In the previous proof, observe that if $P - mQ$ lies in $\text{pr}_Z^* \widehat{A}_Z$, then $3K_X + P + Q_0 - f^* \mathcal{H} - f^* \mathcal{L}$ is effective for some $Q_0 \in \text{pr}^* \widehat{A}_Z$. So, we could have improved the result to the tricanonical map (assuming the induction hypothesis). In particular, if $\mathcal{Q} := \mathcal{K} / \text{pr}_Z^* \widehat{A}_Z$ is trivial for X and the successive fibers of the induction process, then the tricanonical map twisted by an element in \mathcal{K} induces the Iitaka fibration.

Moreover, if for some $P \in \mathcal{K}$, $P + \text{pr}_Z^* \widehat{A}_Z$ is an irreducible component of $V^0(\omega_X, a_X)$, then we can again prove that the tricanonical map twisted by an element in \mathcal{K} induces the Iitaka fibration. This shows that varieties of maximal Albanese dimension, where none of the twisted tricanonical map is birational equivalent to the Iitaka fibration, are closely related to varieties of maximal Albanese dimension, of general type with vanishing holomorphic Euler characteristic.

We finish with an example of maximal Albanese dimension, whose tricanonical map does not induce the Iitaka fibration. This example is based on the famous Ein-Lazarsfeld threefold, which is constructed in [EL, Ex. 1.13] and further investigated in [CDJ].

Example 5.6. We take three bielliptic curves C_i of genus 2, $i = 1, 2, 3$. Let $\rho_i : C_i \rightarrow E_i$ be the double cover over an elliptic curve E_i and denote by τ_i the involution of fibers of ρ_i . We write

$$\rho_{i*} \mathcal{O}_{C_i} = \mathcal{O}_{E_i} \oplus \mathcal{L}_i^{-1},$$

where \mathcal{L}_i is a line bundle on E_i of degree 1.

Let Y be the threefold $(C_1 \times C_2 \times C_3) / (\tau_1, \tau_2, \tau_3)$, which has only rational singularities. We know that $a_Y : Y \rightarrow E_1 \times E_2 \times E_3$ is a $(\mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z})$ -cover.

We then take an abelian variety A and a $(\mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z})$ -étale cover $\tilde{A} \rightarrow A$. Set $\{\mathcal{O}_A, P_1, P_2, P_3\}$ to be the kernel $\hat{A} \rightarrow \tilde{A}$.

Denote $H = (\mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z})$ and let X' be the variety $(Y \times \tilde{A})/H$, where H acts diagonally on $Y \times \tilde{A}$. Notice that X' has only rational singularities and let X be a resolution of singularities of X' . The Albanese morphism

$$a_X : X \rightarrow E_1 \times E_2 \times E_3 \times A$$

is birationally a $(\mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z})$ -cover.

After permutation of $\{P_i, i = 1, 2, 3\}$, we have

$$\begin{aligned} a_{X*}\omega_X^3 &\simeq (\mathcal{L}_1^2 \boxtimes \mathcal{L}_2^2 \boxtimes \mathcal{L}_3^2 \boxtimes \mathcal{O}_A) \oplus (\mathcal{L}_1^3 \boxtimes \mathcal{L}_2^3 \boxtimes \mathcal{L}_3^2 \boxtimes P_1) \\ &\oplus (\mathcal{L}_1^3 \boxtimes \mathcal{L}_2^2 \boxtimes \mathcal{L}_3^3 \boxtimes P_2) \oplus (\mathcal{L}_1^2 \boxtimes \mathcal{L}_2^3 \boxtimes \mathcal{L}_3^3 \boxtimes P_3) \end{aligned}$$

It is easy to check that for any $P \in \text{Pic}^0(X)$, the linear series $|3K_X + P|$ can not induce the Iitaka fibration $X \rightarrow E_1 \times E_2 \times E_3$.

Using, the notation of Setting 5.2, observe that

$$\mathcal{K} = V^0(\omega_X^2, a_X) = \bigcup_{Q \in \{\mathcal{O}_A, P_1, P_2, P_3\}} E_1 \times E_2 \times E_3 \times \{Q\}$$

and $\mathcal{Q} = \mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z}$. Indeed, \mathcal{Q} can be identified with $\{\mathcal{O}_A, P_1, P_2, P_3\}$.

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