On surfaces of general type with maximal Albanese dimension

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Abstract

Given a minimal surface $S$ equipped with a generically finite map to an Abelian variety and $C \subset S$ a rational or an elliptic curve, we show that the canonical degree of $C$ is bounded by four times the self-intersection of the canonical divisor of $S$. As a corollary, we obtain the finiteness of rational and elliptic curves with an optimal uniform bound on their canonical degrees on any surface of general type with two linearly independent regular one forms.

1 Introduction

The object of this paper is to give an effective bound on the canonical degrees of rational and elliptic curves on a minimal surface of general type with generically finite Albanese map linearly in terms of the canonical volume of the surface. Here, the canonical degree is the degree with respect to the canonical polarization of the surface and the self-intersection of this polarization is the canonical volume.

We will work in the complex analytic setting so that all varieties are complex analytic. We will assume the rudiments from the the theory of classification of complex projective surfaces as found for example in [3]. We call a smooth projective surface to be of maximal Albanese dimension if its Albanese map is generically finite (N.B. This terminology is different from that introduced in [21]). We recall that any smooth projective surface $S$ of maximal Albanese dimension admits a morphism to a minimal one whose canonical divisor pulls back to the positive part $P$ of the Zariski decomposition of the canonical divisor $K$ of $S$ and the canonical volume of $S$ is by definition $\text{vol}(K) := P^2$. Our main theorem is as follows.

**Theorem 1.1** Let $S$ be a smooth projective surface with maximal Albanese dimension and $C$ a rational or an elliptic curve in $S$. Let $P$ be the positive part in the Zariski decomposition of the canonical divisor $K$ of $S$. Then

$$PC \leq 4 \text{vol}(K).$$

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We remark that Y. Miyaoka has recently given an effective canonical bound for surfaces with positive Segre class \([16]\) generalizing the same given by him and the author for surfaces with positive topological index \([12]\). It is easy to construct examples of surfaces with maximal Albanese dimension which do not have positive Segre class. Prior to the present article, all such canonical bounds were obtained via the powerful but highly nontrivial log-orbifold Miyaoka-Yau inequality on surfaces, for which we cite \([4, 15, 22, 20, 12, 13, 11, 16]\). But the bounds so obtained are neither simple nor are optimal. In this article, we introduce an elementary approach that relates geometrically the canonical degree of curves directly with the canonical class of the surface. In view of the simplicity and aptitude of the idea, the method introduced and the resulting bound, we expect it to have significance and applicability to arbitrary algebraic curves and even to holomorphic curves as well as to arithmetic objects as it seems to relate to the standard conjectures in these subjects; its generalizations to arbitrary curves would have strong implications, for example, for the abc-conjecture over function field for an abelian variety.

We also remark that a weakened version of our theorem has already been given by Noguchi-Winkelmann-Yamanoi \([19]\) where the Albanese map is assumed to be finite and surjective, that is they exclude the possibility of exceptional fibers in their hypothesis although they do deal with the quasi-projective case at the same time. In that case, they bound the canonical degree of elliptic curves in terms of the degree of Gauss map of the canonical divisor of the surface, which they do not bound. Our bound gives a sharp effective bound for the degree of this Gauss map and we expect it to be sharp also for the canonical degree of elliptic curves on such a surface, if not extremely close to it, being by its very nature the best bound allowed by this approach.

We finally remark that it is possible to obtain less effective (noneffective) bounds more simply. But as all the details presented here are quite general in nature and has much wider applicability, we believe that they are worth the trouble for the optimal bound given.

Since a surface of general type cannot support a nontrivial family of rational or elliptic curves and a bound on the canonical degree of such curves puts them in a bounded family, our result implies that that there are only a finite number of rational and elliptic curves on a surface of general type with generically finite Albanese map. In fact, our result is strictly stronger as it implies a global bound on such finiteness, in a smooth family of such surfaces for example. More generally, for a surface with irregularity at least two, if its Albanese map is not generically finite, then it admits a map to a hyperbolic curve by the structure theorem of Kawamata and Ueno \([7]\). Hence rational and elliptic curves lie on the fibers of such a map and are thus finite in number if the surface is of general type. It follows that there are only a finite number of rational and elliptic curves on any surface of general type with irregularity at least two. The following is an immediate corollary of this and of the main theorem of Noguchi-Winkelmann-Yamanoi in \([18]\) giving the algebraic degeneracy of holomorphic curves in the remaining case of such surfaces.

**COROLLARY 1.2** Let \(S\) be a smooth projective surface of general type with irregularity two or more. Then \(S\) admits a proper Zariski subset that contains all nontrivial holomorphic images of \(\mathbb{C}\).
In general we have the following sweeping conjecture concerning the algebraic pseudo-hyperbolicity of varieties of general type. The conjecture is at least well indicated from the works of F. Bogomolov, B. Mazur, M. Green and P. Griffiths in the seventies and that of Y. Kawamata in the early eighties and made explicit by Serge Lang in 1986 [10]:

**CONJECTURE 1.3** An algebraic variety of general type admits a proper Zariski subset that contains all subvarieties not of general type.

Aside from Bogomolov’s result validating the conjecture for surfaces of positive Segre class [4], the best general evidence for such a conjecture up till now was given by Kawamata [8] validating the conjecture for subvarieties of Abelian varieties in characteristic zero. This result was later generalized to the case of semi-Abelian varieties by Noguchi [17] and to the case when the field of definition is an algebraically closed field of arbitrary characteristic [1]. However, none of these results is effective and, besides the above mentioned result of Noguchi-Winkelmann-Yamanoi, the conjecture seemed unknown in general for a variety with maximal Albanese dimension. Our method here applies directly to this latter case for its affirmative resolution [14].

A short but already quite telling description of the proof of this main theorem is as follows. The theorem reduces easily to the case when $S$ is minimal (so that $P = K$) and admits a surjective morphism $\alpha$ to an abelian surface $A$ and to the case $C$ is neither $\alpha$-exceptional, so that $C_0 = \alpha(C)$ is an elliptic curve in $A$, nor contained in the ramification locus of $\alpha$. In this case, $(\det d\alpha)$ is a canonical choice for $K$ and, outside its common divisorial locus with $\hat{C} = \alpha^*(C_0)$, $K$ intersects properly with $\hat{C}$ and the relevant local intersection numbers with $C$ are dominated by the local intersection numbers of $\hat{C}$ with each such component of $K$. These local intersection numbers along a horizontal component of $D = K_{\text{red}}$ can be interpreted in terms of the vanishing degree of the natural section of $K + D$ along $D$ given by $(\alpha^*w_0) \wedge ds/s$ where $w_0$ is the nonzero holomorphic one form on $A$ such that $TC_0 \in \ker w_0$. Since the intersection number of $\hat{C}$ with any vertical component of $D$ or with any horizontal component of $D$ in $\hat{C}$ is zero, finding a decomposition of $K$ into parts having nonnegative intersection number with $K + D$ and summing yield the result.

As for the plan of the paper, section two deals with this decomposition of $K$ while section three gives the key lemmas for the proof of the main theorem in section 4.

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## 2 A decomposition of divisors on surfaces

We will let $S$ be a smooth projective surface and $K$ a canonical divisor for $S$ throughout. Let $D, D'$ be two divisors in $S$. We will denote $D \leq D'$ to mean that $D' - D$ is effective (possibly zero). By a component of a divisor, we will mean a prime component as opposed to a connected component of a divisor, so that it is reduced and irreducible.
LEMMA 2.1 Let $D$ be a reduced divisor in $S$ and $C$ a connected divisor contained in $D$, i.e. $C \leq D$. If $(K + D)C < 0$, then either $(K + D)C = -2$ or $(K + D)C = -1$. These two cases, which we will call case 1 and case 2, imply respectively:

1. $(K + C)C = -2$ and $(D - C)C = 0$. The latter means that $C$ is isolated in $D$, i.e. $C$ is not connected to the rest of $D$.

2. $(K + C)C = -2$ and $(D - C)C = 1$. The latter means that $C$ intersect the rest of $D$ at one point (and transversely).

Proof: Since $C$ is connected, its arithmetic genus $g$ is given by $1 - (h^0(\mathcal{O}_C) - h^1(\mathcal{O}_C)) = h^1(\mathcal{O}_C) \geq 0$. Hence by adjunction, $(K + C)C = 2g - 2$ is an even number that is at least $-2$. The rest follows from $(K + D)C = (K + C)C + (D - C)C$. ■

Recall that a tree of curves is a connected reduced curve $C$ which is disconnected by removing any of its component curves. Any component of such a tree is connected to any other component by a unique path. A rooted tree of curves is a tree with a component curve singled out, called the root. Such a tree becomes directed by the partial ordering given by $C_i \leq C_j$ if the unique path from the root to the component $C_j$ passes through $C_i$, in which case we also say that $C_j$ is a descendant of $C_i$. Note in particular that every component curve is a descendant of itself in a directed tree. A component curve $C_j$ without a descendant beside itself is called a leaf. In a rooted tree of curves, the union of a component curve with all its descendant is called a branch. A tree without a root specified is called a free tree and such a tree becomes directed by either choosing a root curve or by choosing the unique transversal intersection of a pair of curves if exists, with the obvious ordering given as before. A disjoint collection of trees is called a forest.

LEMMA 2.2 In the previous lemma, a curve $C$ in case 1 consists of an isolated (free) tree of rational curves intersecting transversally and a curve $C$ in case 2 consists of a rooted tree of rational curves intersecting transversally. If we direct the tree of case 1 by choosing a transversal intersection point of two curves if it exists, then every branch of the tree in either case satisfies the conditions of case 2.

Proof: We will only show the lemma in case 2 since case 1 follows similarly. In this case, $(K + D)C = -1$ and $C$ intersects the rest of $D$ at one point $p$. Let $C_0$ be the component of $C$ containing $p$ and let $C_{01}, \ldots, C_{0k}$ be the connected components of $C - C_0$. Let $D' = D - \sum_i C_{0i}$. By construction, $(K + D)C_{0i} \geq -1$ and $C_{0i}(C - C_{0i}) \geq 1$ for all $i$ and since $C_0$ is a connected nonisolated component of $D'$, we have by the previous lemma that

$$-1 \leq (K + D')C_0 = (K + D)C_0 - \sum_i C_{0i}C_0$$

$$= (K + D)C - \sum_i [(K + D)C_{0i} + C_{0i}(C - C_{0i})] \leq (K + D)C = -1.$$

This forces equality everywhere and so $(K + D)C_{0i} = -1$ for all $i$ and $(K + D')C_0 = -1$. This means that the $C_{0i}$’s are all curves belonging to case 1 connected to $C_0$ and that $C_0$ is
a smooth rational curve as \((K + C_0)C_0 = -2\) by the previous lemma. Hence we see that \(C\) is a rooted tree of rational curves by induction, with \(C_0\) as a root.

We now set

\[
F(D) = \{ C \leq D \mid C \text{ is connected and } (K + D)C < 0 \}.
\]

It follows that the union of the elements in \(F(D)\) form a subset of \(D\) that is a forest. We will call this forest \(F_D\). It is a disjoint union of maximal elements in \(F(D)\) and the leaves in this forest are exactly the prime components of \(D\) belonging to \(F(D)\).

We apply our result to the case \(D = K_{\text{red}}\), the reduced canonical divisor, to obtain a positive partial decomposition of \(K\). The following lemma is the key to this decomposition.

Recall that a curve \(C\) is called a Hirzebruch-Jung string if it is a rooted tree of curves with exactly one leave so that we have actually a total ordering on \(C\). In this case, we may write the prime decomposition of \(C\) as \(C_0 + C_1 + \cdots + C_r\) where \(C_iC_j\) is one or zero according to whether \(j = i + 1\) or not and \(C_0, C_r\) are the root and leave of the string respectively. We will denote the subset of \(F(D)\) consisting of elements that are not isolated in \(D\) and that are Hirzebruch-Jung strings by \(F_{\text{HJ}}(D)\).

**LEMMA 2.3** Let notation be as above but with \(D = K_{\text{red}}\). Let \(C \in F_{\text{HJ}}(D)\) with the prime decomposition \(C_0 + C_1 + \cdots + C_r\) as given above. Let \(C_{-1}\) be the unique component of \(D - C\) connected to \(C\). Let \(m_i > 0\) be the multiplicity of \(K\) on \(C_i\). If \(S\) is minimal, then for \(i = -1, 0, \ldots, r - 1\), we have

\[
m_i \geq 2m_r.
\]

**Proof:** Since each component \(C_i\) of \(C\) is a rational curve and \(S\) is minimal, we have, for each \(i \geq 0\),

\[
C_i^2 = -2 - KC_i \leq -2.
\]

Let \(\hat{C} = C_{-1} + C\). Then

\[
(m_{r-1} + 1) + (m_r + 1)C_r^2 = (K + D)C_r = -1,
\]

and we obtain \(m_{r-1} + 2 = -(m_r + 1)C_r^2 \geq 2(m_r + 1)\). Hence \(m_{r-1} \geq 2m_r\) and our lemma is true for \(i = r - 1\). We now establish the lemma by showing that \(m_{i-1} > m_i\) for all \(i \geq 0\). This being already established for \(i = r\), we assume by induction that \(m_i > m_{i+1}\) for an \(i\) strictly between \(-1\) and \(r\). For such an \(i\), we have by lemma 2.2 that

\[
0 = (K + D)C_i = (m_{i-1} + 1) + (m_i + 1)C_i^2 + (m_{i+1} + 1) < m_{i-1} + 1 + (m_i + 1)(C_i^2 + 1),
\]

and so \(m_{i-1} > m_i\) and the result follows by induction.

We remark that if \(S\) is not minimal, the lemma would still hold with a weaker inequality.
**LEMMA 2.4** With the notations as before and $D = K_{\text{red}}$, let $C \in F(D)$ be a maximal element non-isolated in $D$. Let $C = \sum_{i \in I} C_i$ be the prime decomposition of $C$ and let $K_C = \sum_{i \in I} m_i C_i$ where $m_i > 0$ is the multiplicity of $K$ on $C_i$. If $S$ is minimal and $C$ is not a Hirzebruch-Jung string, then $(K + D)K_C \geq 0$.

**Proof:** We first introduce some terminology. Let $C \in F(D)$ be non-isolated in $D$. Let $C_i$ be a component of $C$. Recall that $\tilde{C}_i$ is the union of all the descendant of $C_i$. A component $C_i$ of $C$ is called split if $\tilde{C}_i - C_i$ contains more than one connected components, at least one of which lies in $F^{HJ}(D)$. In this case, we let $K_i = m_i C_i + \sum_j m_{ij} C_{ij}$ where the $C_{ij}$'s are the connected components of $\tilde{C}_i - C_i$ lying in $F^{HJ}(D)$, $m_i$ is the multiplicity of $K$ on $C_i$ and $m_{ij}$ is the multiplicity of $K$ on the leave of $C_{ij}$. Since $(K + D)\tilde{C}_i = -1$, $(K + D)C_{ij} = -1$ for all $j$ and $(K + D)(\tilde{C}_i - C_{i1}) = -1$ by Lemma 2.2 in this case, we obtain easily from Lemma 2.3 that

$$(K + D)K_i \geq 0.$$ 

By assumption, $C$ is not a Hirzebruch-Jung string. So every leave of $C$ is the descendant of a split component of $C$. Let $C_i, i \in I'$ be the collection of split components of $C$ and $K_i$ be as above. Now $K' = \sum_{i \in I'} K_i \leq K_C$ by lemma 2.3 and $K'' = K_C - K'$ has zero multiplicity on the leaves by construction. Hence $K''$ has only support on the $C_j$'s which are not leaves and as $(K + D)C_j \geq 0$ for such $C_j$'s, $(K + D)K'' \geq 0$. It follows that

$$(K + D)K_C = (K + D)K'' + \sum_{i \in I'} (K + D)K_i \geq 0. \quad \blacksquare$$

3 The key proposition

Let $G$ be a reduced irreducible divisor on a smooth projective surface $S$ and defined by the section $s \in H^0(S, \mathcal{O}(G))$, i.e., $(s) = G$. The key point to our approach is that $ds/s$ gives a well defined holomorphic section of $\Omega_S(G)$ over $G$. We will only need this fact in the following situation.

**LEMMA 3.1** With the data as given above, let $w$ be a holomorphic one-form on $S$. Then $w \wedge ds/s$ gives a well defined holomorphic section of $\mathcal{O}(K + G)|_G$, i.e.,

$$u = w \wedge ds \in H^0(G, \mathcal{O}(K + G)).$$

If $w$ does not pull back to the zero one-form on any component of $G$, then $u$ is nowhere identically vanishing.

**Proof:** Given two local trivializations for $\mathcal{O}_G(G)$ on $G \cap U$ where $U$ is a Stein neighborhood of a point $p \in G$, consider two trivializations of $\mathcal{O}_U(G)$ that extend them. Let $s_1$ and $s_2$ be the respective holomorphic functions on $U$ representing $s$ with respect to the trivializations. Then $t = s_1/s_2$ is a nonvanishing holomorphic function on $U$. Since $ds_1 = tds_2 + s_2 dt$ on $U$, we have $w \wedge ds_1 = tw \wedge ds_2$ on $G \cap U$. It follows that $w \wedge ds$ transforms as a holomorphic section of $\Omega^2_S(G) = \mathcal{O}(K + G)$ over $G$ under different local trivializations of $\mathcal{O}_G(G)$. The last part of the lemma is clear. \blacksquare
An important remark for the application in general is that if $s$ is only required to satisfy $G = (s)_{\text{red}}$, then $ds/s$ would give a nowhere-vanishing section of $\Omega_S(G)$ over $G$ thereby effectively reducing the multiplicities of $(s)$ to one.

We now apply this lemma to obtain the key proposition for the proof of our theorem.

**PROPOSITION 3.2** Let $S$ be a smooth non-Abelian surface, $A$ a complex Abelian surface and $\alpha : S \to A$ a surjective morphism. We consider the following data on $S$:

- $K = (\det d\alpha)$ the canonical divisor of $S$ determined by $\alpha$
- $D = K_{\text{red}}$ the reduced canonical divisor
- $G$ a horizontal component of $D$, i.e., $G$ is not $\alpha$-exceptional
- $C_0$ an elliptic curve in $A$ considered as a reduced divisor
- $\hat{C} = \alpha^*(C_0)$ the total transform of $C_0$
- $C''$ the sum of non-elliptic horizontal components of $\hat{C}$ on which $\hat{C}$ has multiplicity one
- $\bar{C} = \hat{C} - C' - C''$ where $C''$ is some vertical part of $\hat{C}$, i.e., $C'' \leq \hat{C}$ is $\alpha$-exceptional

Assume that $G$ is not a component of $\bar{C}$. Then we have

$$(G, \bar{C}) \leq 2(G, P + D) - n_G,$$

where $n_G$ is the intersection number of $D - G$ with the smooth part of $G$.

**Proof:** Our assumption on $S$ implies easily that $\alpha$ must be ramified somewhere and so $\det d\alpha$ gives a well defined divisor on $S$. We note also that, since $\hat{C}$ cannot be reduced on any vertical component of the ramification divisor, our assumption on $G$ implies that it is not a component of $\hat{C}$ so that $G \cap (\hat{C})_{\text{red}}$ is a finite set containing $Q = G \cap (\hat{C})_{\text{red}}$. We first assume that $G$ is smooth for the proof.

Let $w_0$ be the constant holomorphic one-form that defines the direction of $C_0$, i.e., locally we can write $w_0 = df_0$ with $(f_0) = C_0$. By definition,

$$(G, \hat{C}) = \sum_{x \in Q} (G, \hat{C})_x \leq \sum_{x \in Q} (G, \hat{C})_x.$$

Let $x \in Q$ and $U$ a Stein neighborhood of $\alpha(x)$. Then $w_0|_U = df_0$ for a holomorphic function $f_0$ on $U$ with $(f_0) = C_0|_U$. Let $V = \alpha^{-1}(U)$ and $f = \alpha^*f_0 = f_0 \circ \alpha \in \mathcal{O}_V$. Then $(G, \hat{C})_x$ is by definition the vanishing order at $x$ of $f|_G$, i.e.,

$$(G, \hat{C})_x = \text{ord}_x(f|_G).$$

Let $w = \alpha^*w_0$ and $\gamma_1 = w \wedge ds|_G \in H^0(G, K + G)$. Then $w|_V = df$ and so

$$\text{ord}_x(\gamma_1) = \text{ord}_x(df|_G) = (G, \hat{C})_x - 1.$$
Let $G'$ be the reduced divisor $D - G$ considered also as a subset of $S$. Let $r$ be a section of $O(G')$ with $(r) = G'$ and let $\gamma = \gamma_1 \otimes r$. Then $\gamma$ is a section of $O(K + D)$ over $G$ and

$$\text{ord}_x(\gamma) = \text{ord}_x(\gamma_1) + (G, G')_x \geq (G, D - G)_x.$$ (3.1)

We observe that if $x \notin G'$, then $(G, G')_x = 0$ and $x$ lies in some horizontal component(s) of $\hat{C}$ away from any intersection point with vertical components of $\hat{C}$. In this case, either $\hat{C}$ is not reduced at $x$, in which case $(G, \hat{C})_x \geq (G, C)_x \geq 2$, or the components of $\hat{C}$ through $x$ are horizontal elliptic curves. In the latter case, since the tangent directions of these elliptic curves cannot lie in the kernel of $d\alpha$ as no elliptic curve can ramify over an elliptic curve, $d\alpha$ has rank one at $x$ and maps the tangent "directors" of $C$ at $x$, and therefore also $T_x S$, to $T_{\alpha(x)} C_0 = \ker w_0(\alpha(x))$. Hence, in this case, $w = \alpha^* w_0$ is identically zero on $T_x S$ and so $\text{ord}_x(\gamma_1) \geq 1$. It follows that if $x \notin G'$, then $\text{ord}_x(\gamma) = \text{ord}_x(\gamma_1) \geq 1$ and so

$$(G, \hat{C})_x = \text{ord}_x(\gamma_1) + 1 \leq 2 \text{ord}_x(\gamma_1) = 2 \text{ord}_x(\gamma) - (G, D - G)_x.$$

On the other hand, if $x \in G'$, then $1 \leq (G, G')_x$, and so we have again

$$(G, \hat{C})_x = \text{ord}_x(\gamma_1) + 1 \leq \text{ord}_x(\gamma) \leq 2 \text{ord}_x(\gamma) - (G, D - G)_x.$$

Since the inequality (3.1) is actually true for all $x \in G$ by the construction of $\gamma$, we have $2 \text{ord}_x(\gamma) - (G, D - G)_x \geq 0$ for all $x \in G$. It follows that

$$(G, \hat{C}) \leq \sum_{x \in G} (2 \text{ord}_x(\gamma) - (G, D - G)_x) = 2(G, K + D) - (G, D - G).$$

This proves the proposition in the case $G$ is smooth.

In the case $G$ is not smooth, let $\pi : \tilde{S} \to S$ be a minimal resolution of $G$. By replacing $G$ with its strict transform $\tilde{G}$, $\hat{C}$ with its total transform $\pi^* \hat{C}$, $K$ with the canonical divisor $\tilde{K} = (\det d(\alpha \circ \pi))$ of $\tilde{S}$ and $D$ with $(\tilde{K})_{\text{red}} = (\pi^* D)_{\text{red}}$ we find that all the assumptions of the proposition still hold and therefore

$$(G, \hat{C}) = (\tilde{G}, \pi^* \hat{C}) \leq 2(\tilde{G}, \tilde{K} + \tilde{D}) - (\tilde{G}, \tilde{D} - \tilde{G}) \leq 2(\tilde{G}, \tilde{K} + \tilde{D}) - n_G,$$

the last inequality owing to the fact that the intersection number $n_G$ of $D - G$ with the smooth part of $G$ is unaffected by $\pi$ and so can be no greater than $(\tilde{G}, \tilde{D} - \tilde{G})$. The proposition now follows from the claim that $(\tilde{G}, \tilde{K} + \tilde{D}) \leq (\tilde{G}, \tilde{K} + \tilde{D})$ for which it is sufficient via induction to verify for the case $\pi$ is a single blow-up. But this case follows directly from $\tilde{K} = \pi^* (K) + E$ and $\tilde{D} = \pi^* (D) - (m - 1)E$ where the multiplicity $m$ of the point of $D$ blown up is necessarily no less than two as $D$ is singular there. ■

### 4 Proof of the main theorem

We first reduce the main theorem, Theorem 1.1, to the case when the surface $S$ is minimal of general type admitting a surjective morphism to an Abelian surface.
Recall that the Albanese map of a smooth projective variety $X$ is a morphism $\alpha_X : X \to A$ where $A$ is an Abelian variety (i.e., $A$ is a projective variety whose universal covering is $\mathbb{C}^n$ for some $n > 0$) and where the pair $(\alpha_X, A)$ is characterized by the following universal property: Any morphism $\beta : X \to A'$ where $A'$ is an Abelian variety admits a unique factorization $\beta = j \circ \alpha_X$ where $j : A \to A'$ is a morphism of Abelian varieties. The pair $(\alpha, A)$ exists and is unique up to isomorphism for any smooth projective variety $X$. The Abelian variety $A$ is called the Albanese torus of $X$, denoted by $\text{Alb}(X)$. The universal property implies that $\alpha(X)$ generates $A$ in the sense that it is not contained in any subabelian variety and, in particular, $\alpha$ induces an inclusion $H^0(\Omega_A) \subset H^0(\Omega_X)$.

Let $S_0$ be the minimal model of $S$ and $\pi : S \to S_0$ the projection. Since $\pi$ is a composition of blowups, its exceptional fibers consist of rational curves that are necessarily exceptional with respect to $\alpha$. Hence $\alpha = \alpha_0 \circ \pi$ where $\alpha_0$ is the Albanese map of $S_0$ and $\text{Alb}(S) = \text{Alb}(S_0)$ by the universal property of the Albanese. Since $P^2 = K_{S_0}^2 \geq 0$ as $S_0$ is minimal and since the $\pi$-exceptional curves have zero degree with respect to $\tilde{P} = \pi^*K_{S_0}$ and all other irreducible curves in $S$ are strict transforms of those in $S_0$, we see that it suffices to prove the theorem for $S = S_0$. So we may set $K = \tilde{P} = (\text{det } \text{d}\alpha)$.

Now let $A$ be an Abelian variety, and $\alpha : S \to A$ a generically finite morphism, i.e., $\dim \alpha(S) = 2$. Since $S$ has maximal Albanese dimension, such a morphism exists. Hence, there is a nonvanishing holomorphic two form $v$ on $S$ such that $\alpha(S)$ is not contained in the codimensional two foliation defined by $v$ and we may set the canonical divisor of $S$ to be $K = (\alpha^*v)$. Now $K$ is nef and contains all the exceptional divisors of $\alpha$ by construction. So any exceptional divisor of $\alpha$ satisfies the inequality given in the theorem. So it remains to prove the inequality of the theorem for elliptic curves $C$ that are not $\alpha$-exceptional as rational curves are necessarily $\alpha$-exceptional. If $C$ is such a curve and $\dim A > 2$, then $\alpha(C)$ is an elliptic curve in $A$ and hence a translate of a one dimensional subgroup $E$ of $A$. Let $\alpha_1$ be the composition of $\alpha$ with the projection $p_1$ from $A$ to the quotient abelian variety $A_1 = A/E$. If $\dim \alpha_1(S) = 2$, then $C$ is $\alpha_1$-exceptional and so, as all previous hypothesis on $\alpha$ are satisfied for $\alpha_1$, $C$ satisfies the conclusion of our theorem. Hence we may assume by induction that $\dim \alpha_1(S) = 1$. By the Poincaré reducibility theorem, see for example Chap. 6 of [3] or Theorem 5.3.5 of [2], there is an étale base change (i.e., an unramified covering map) $z : \tilde{A}_1 \to A_1$ for an Abelian variety such that $z^{-1}(A) = \tilde{A}_1 \times E$ and $z_1^{-1}(p_1) : \tilde{A}_1 \times E \to A_1$ is the projection $\pi_1$ to the first factor. This means that we have an étale covering $z : \tilde{A}_1 \times E \to A$ such that $p_1 \circ z = z_1 \circ \pi_1$. As our problem is unchanged by such an étale base change, we may assume that $\tilde{A}_1 = A_1$ and that $A = A_1 \times E$ so that $\pi_1$ is the quotient map of $B$ by $E$. Let $\tilde{C}_1$ be the normalization of $C_1 = \alpha_1(S)$. Then the smooth surface $S' = \tilde{C}_1 \times E$ is the normalization of $\alpha(S)$ and, as $S$ is smooth, $\alpha$ factors through $S'$ by the Stein factorization theorem. So replacing $A_1$ by the Albanese torus of $\tilde{C}_1$, we may assume that $C_1$ is smooth. By construction, $C$ lies in the pre-image of a point $p \in C_1$. Suppose $\dim A_1 > 1$. Then one can find a nonzero holomorphic one form $u_1$ on $A_1$ such that $T_pC = \ker u_1(p)$. It follows that $\alpha_1^*u_1$ vanishes at every point of $C$ and therefore $C$ lies in the zero locus of the section $s$ of $\mathcal{O}_S(K) = \Omega_S^2$ defined by the wedge product of $\alpha_1^*u_1$ with the pull back of a one-form $u_2$ on $E$. Now the pull back of $u_1$ to $C_1$ is not identically vanishing as $C_1$ generates $A_1$ and so $s$ is not identically vanishing. Hence the nef canonical
divisor $K = (s)$ contains $C$ giving again

$$KC \leq K^2 \leq 4K^2$$

and so $C$ satisfies the conclusion of the theorem in this case. We are left with the case $C_1 = A_1$ so that $\alpha$ is a surjective morphism to $A$ and so our main theorem reduces to the following proposition.

**PROPOSITION 4.1** With the setup as in proposition 3.2, assume further that $S$ is a minimal surface. If $C$ is a rational or an elliptic curve in $S$, then

$$KC \leq 4K^2.$$

**Proof:** We will classify a curve as being vertical or horizontal according whether it is $\alpha$-exceptional or not and we first note that any element of $F(D)$ for a reduced divisor $D$ in $S$ is vertical, being a tree of rational curves by lemma 2.2.

If $C$ is vertical, then $C \leq K$ and so $KC \leq K^2 \leq 4K^2$ by the nefness of $K$. As rational curves are necessarily vertical, it suffice to consider the case $C$ is a horizontal reduced elliptic curve for our proposition. In this case, $C_0 = \alpha(C)$ is an elliptic curve in $A$. We will also consider $C_0$ as a reduced divisor in $A$. Let $C'$ be the sum of the non-elliptic horizontal components of $\hat{C} = \alpha^*C_0$ on which $\hat{C}$ has multiplicity one and let $\bar{C} = \alpha^*C_0 - C'$. Then $C \leq \bar{C} \leq \alpha^*C_0$ and so

$$KC \leq K\bar{C}$$

as $K$ is nef. Let $\sum_i n_i D_i$ be the prime decomposition of $K$. We are reduced to bounding the intersection number

$$K\bar{C} = \sum_i n_i (D_i, \bar{C}).$$

Let $D_i$ be a component of $K$ that is either vertical or $D_i \leq \bar{C}$ is horizontal, then

$$(D_i, \bar{C}) \leq (D_i, \alpha^*C_0) = 0$$

by the definition of $\bar{C}$ (since $C'$ is an effective horizontal divisor not containing $D_i$).

We now set $D = K_{red}$ in what to follow and decompose $D = \sum_i D_i$ into three parts:

$$D = D^0 + D' + D'', \quad \text{where}$$

- $D^0$ consists of all the vertical components of $D$ connected via vertical curves to a part of $D$ that belongs to $F(D) \setminus F^{HZ}(D)$ or to a part that is a maximal element of $F^{HJ}(D)$ not attached to any horizontal component of $D$,
- $D'$ consists of horizontal components of $D$ not in $\bar{C}$ and of any element of $F^{HJ}(D)$ that is attached to them,
- $D''$ consists of horizontal components of $D$ in $\bar{C}$ and of any element of $F^{HJ}(D)$ that is attached to them.
We first observe that there are no maximal element of $F(D)$ that is isolated as that would lead to an isolated surface singularity $p$ sitting above a smooth surface but away from any ramification divisor, an impossibility by theorem III.5.2 of \cite{[3]}. We observe also, by our last inequality above, that $K_{D^0}$ and $K_{D'}$ have non-positive intersection with $C$.

By definition, we can write $D^0 = \sum_i C_i^M + \sum_j (C_j^H + C_j^+) + C'$ where the $C_i^M$'s are the maximal elements in $F(D)$ not in $F^H(D)$, the $C_j^H$'s are the maximal elements in $F^H(D)$ not attached to any horizontal part of $D$, $C_j^+$ the vertical component of $D$ attached to $C_j^H$ and $C'$ the rest of $D^0$. By construction, $C'$ does not contain any leave of $F_D$ so that any component $D_k$ of $C'$ satisfies $(D_k, K + D) \geq 0$. Hence $(K_{C'}, K + D) \geq 0$, where we recall that $K_{C'}$ is the part of $K$ supported on $C'$. We now note that, for all $j$, $\hat{C}_j = C_j^H + C_j^+ \notin F(D)$ so that $(\hat{C}_j, K + D) \geq 0$. Letting $m_j$ be the multiplicity of $K$ on the leave of $C_j^H$, we have $m_j \hat{C}_j \leq K$ by lemma \ref{2.3}. As $K_{\hat{C}_j} - m_j \hat{C}_j$ consists of components not belonging to $F(D)$, we obtain $(K_{\hat{C}_j}, K + D) \geq 0$ for all $j$. Finally, as $(K_{C^M}, K + D) \geq 0$ by lemma \ref{2.4} and as $K_{D^0} = \sum_i C_i^M + \sum_j \hat{C}_j + K_{C'}$, we get

\[(K_{D^0}, \hat{C}) \leq 0 \leq (K_{D^0}, K + D) \leq 2(K_{D^0}, K + D).\]

By the same token, $D'' \notin F(D)$. In fact, by definition, $D'' = \sum_l (D_l + \sum_{l'} D_{l'})$ where the $D_l$'s are the horizontal components of $D$ lying in $\hat{C}$ and, for each $l$, the $D_{l'}$'s are the elements of $F^H(D)$ attached to $D_l$ and $E_l = D_l + \sum_{l'} D_{l'} \notin F(D)$. Let $m_l$ be the multiplicity of $K$ on $D_l$. Then $m_l$ is greater than the multiplicity $m_{l'}$ of $K$ on the leave of $D_{l'}$ for every $l'$. By lemma \ref{2.3} We also have $\hat{D}_l = m_l D_l + \sum_{l'} m_{l'} D_{l'} \leq K_{D''}$ by the same lemma. As $(m_l E_l, K + D) \geq 0$ while $(D_{l'}, K + D) < 0$ for all $l'$, we see that $(\hat{D}_l, K + D) \geq 0$ for all $l$. Since $K_{D''} - \sum_l \hat{D}_l$ is an effective divisor not having any component that belongs to $F(D)$, we obtain as before

\[(K_{D''}, \hat{C}) \leq 0 \leq (K_{D''}, K + D) \leq 2(K_{D''}, K + D).\]

As for $D'$, let $\{G_n\}_{n \in I}$ be the collection of horizontal components of $D$ not lying in $\hat{C}$ and, for each $n \in I$, let $H_n = G_n + G_{nn'}$ where the $G_{nn'}$'s are the elements of $F^H(D)$ attached to $G_n$. Then $D' = \sum_n H_n$ and we are interested in bounding $(K_{H_n}, \hat{C})$ for each $n$. Fix an $n$. We have by proposition \ref{3.2} that

\[ (G_n, \hat{C}) \leq 2(G_n, K + D) - n_{G_n}, \]

where $n_{G_n}$ is the intersection number of the smooth part of $G$ with the rest of $D$. Since $(G_{nn'}, G_n) = 1 = -(G_{nn'}, K + D)$, we have $n_{G_n} \geq (\sum_{n'} G_{nn'}, G_n) = -(\sum_{n'} G_{nn'}, K + D)$ and so

\[ (G_n, \hat{C}) \leq 2(G_n, K + D) - n_{G_n} \leq 2(G_n, K + D) + (\sum_{n'} G_{nn'}, K + D). \]

Let $m_n$ be the multiplicity of $K$ on $G_n$ and $m_{nn'}$ that on the leave of $G_{nn'}$. Then lemma \ref{2.3} implies that $2m_{nn'} \leq m_n$ for all $n'$ and that $\hat{H}_n = m_n G_n + \sum_{n'} m_{nn'} G_{nn'} \leq K_{H_n}$. It follows from $(G_{nn'}, \hat{C}) \leq 0$ and $(G_{nn'}, K + D) < 0$ that

\[ (\hat{H}_n, \hat{C}) \leq (m_n G_n, \hat{C}) \leq (2m_n G_n + \sum_{n'} m_n G_{nn'}, K + D) \leq (2\hat{H}_n, K + D) = 2(\hat{H}_n, K + D). \]
Since any component $D_r$ of $K_{H_n} - \bar{H}_n$ is a vertical non-leave component of $D$, we have $(D_r, \bar{C}) \leq 0 \leq 2(D_r, K + D)$ and so $(K_{H_n}, \bar{C}) \leq 2(K_{H_n}, K + D)$. Summing over $n$ gives

$$(K_{D'}, \bar{C}) \leq 2(K_{D'}, K + D).$$

Finally, as $K = K_{D^0} + K_{D'} + K_{D''}$, we obtain

$$(K, \bar{C}) \leq 2(K, K + D) \leq 4K^2.$$  

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