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Unipotent group actions on del Pezzo cones

Takashi Kishimoto, Yuri Prokhorov and Mikhail Zaidenberg

Abstract

In [KPZ11b] we showed that for any del Pezzo surface Y of degree $d \geqq 4$ and for any $r \geqq 1$, the affine cone $X = \mathrm{cone}_{r(-K_Y)}(Y)$ admits an effective $\mathbb{G}_a$-action. In particular, the group $\mathrm{Aut}(X)$ is infinite-dimensional. In this note we prove that for a del Pezzo surface Y of degree $\leqslant 2$, the generalized cones X as above do not admit any nontrivial action of a unipotent affine algebraic group.

1. Introduction

We are working over an algebraically closed field $\Bbbk$ of characteristic 0. Let Y be a smooth projective variety with a polarization H, where H is an ample Cartier divisor. A *generalized affine cone* over (Y, H) is the normal affine variety

$$\mathrm{cone}_H(Y) = \mathrm{Spec} \bigoplus_{\nu \geqslant 0} H^0(Y, \nu H)\,.$$

This variety $\mathrm{cone}_H(Y)$ is the usual affine cone over Y embedded in a projective space $\mathbb{P}^n$ by the linear system $|H|$ provided that H is very ample and that the image of Y in $\mathbb{P}^n$ is projectively normal.

In this paper we deal with a smooth del Pezzo surface Y of degree d and a pluri-anticanonical divisor $H = -rK_Y$ on Y, where $r \geqslant 1$; we then call $\mathrm{cone}_H(Y)$ a *del Pezzo cone*. This is a usual cone if $r \geqslant 4 - d$ (see, for example, [Dol12, Theorem 8.3.4]) and a generalized cone otherwise.

It is known [KPZ11b, 3.1.13] that for any smooth rational surface there is an ample polarization such that the associated affine cone admits an effective $\mathbb{G}_a$-action. Furthermore, for any del Pezzo surface of degree $\geqslant 4$ and for any $r \geqslant 1$, the corresponding del Pezzo cone $\mathrm{cone}_{-rK_Y}(Y)$ admits such an action (*loc.cit*), and the group generated by all these $\mathbb{G}_a$-actions is infinitely transitive off the vertex of the cone [Per11]. An effective $\mathbb{G}_a$-action exists also on affine cones over certain smooth rational Fano threefolds with Picard number 1 [KPZ11b, KPZ11a]. However, for del Pezzo surfaces of small degrees the consideration turns out to be more complicated. In this paper we investigate the cases $d = 1$ and $d = 2$. Our main result can be stated as follows.

Theorem 1.1. *Let Y be a del Pezzo surface of degree $d = {K_Y}^2 \leqslant 2$. Then for any $r \geqslant 1$, there*

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is no nontrivial action of a unipotent affine algebraic group on the del Pezzo cone

$$X_r = \mathrm{cone}_{-rK_Y}(Y) = \operatorname{Spec} A, \quad \textit{where} \quad A = \bigoplus_{\nu \geqslant 0} H^0(Y, -\nu r K_Y)\,.$$

As in [KPZ11a, KPZ11b], we use in the proof a geometric criterion for the existence of an effective $\mathbb{G}_a$-action on the affine cone $\mathrm{cone}_H(Y)$ (see [KPZ12] and Theorem 2.1 below). Recently, using this criterion, I. Cheltsov, J. Park and J. Won succeeded in proving [CPW13, Theorem 1.7] that the affine cone over a smooth cubic surface in $\mathbb{P}^3$ does not admit any effective $\mathbb{C}_+$-action. This answers a question of H. Flenner and the third author [FZ03, Question 2.22] and confirms a conjecture that arises naturally from results of Section 4 in our previous paper [KPZ11b]. Summarizing, a del Pezzo cone of degree d comports an effective $\mathbb{C}_+$-action if and only if $d \geqslant 4$.

From Theorem 1.1 and [CPW13, Theorem 1.7] we deduce the following corollary.

Corollary 1.2. *In the same notation as before, assume that $d \leqslant 3$ and $r \geqslant 4-d$, so that $X_r = \mathrm{cone}_{-rK_Y}(Y)$ is a usual del Pezzo cone. Then any algebraic subgroup $G \subset \mathrm{Aut}(X_r)$ is isomorphic to a subgroup of $\mathbb{G}_m \times \mathrm{Aut}(Y)$, where $\mathrm{Aut}(Y)$ is finite.*

Proof. As follows from Theorem 1.1, G is a reductive affine algebraic group (in fact, a finite extension of an algebraic torus). Now Lemma 2.3.1 and Proposition 2.2.6 in [KPZ11b] yield the relations

$$G \hookrightarrow \mathrm{Lin}(X_r) \simeq \mathbb{G}_m \times \mathrm{Lin}(Y) \subset \mathbb{G}_m \times \mathrm{Aut}(Y)\,,$$

where the group $\mathrm{Aut}(Y)$ is finite, see [Dol12]. □

We suggest the following conjecture:

1.3. **Conjecture.** *If $d \leqslant 3$, then for any $r \geqslant 4-d$, the full automorphism group $\mathrm{Aut}(X_r)$ of the del Pezzo cone X_r of degree d is a finite extension of the multiplicative group $\mathbb{G}_m$.*

Sections 2, 3, and 4 contain necessary preliminaries. Theorem 1.1 is proven in Section 5. The proof proceeds as follows. Assuming to the contrary that there exists a nontrivial unipotent group action on $X_r = \mathrm{cone}_{(-rK_Y)}(Y)$, there also exists an effective $\mathbb{G}_a$-action on X_r. By Theorem 2.1 there is an effective $\mathbb{Q}$-divisor D on Y such that $D \sim_{\mathbb{Q}} -K_Y$ and $U = Y \setminus D \cong Z \times \mathbb{A}^1$, where Z is a smooth rational affine curve. Such a principal open subset U is called a $(-K_Y)$-*polar cylinder* in [KPZ11b]. One of the key points consists in an estimate for the singularities of the pair (Y, D). More precisely, we consider the linear pencil $\mathscr{L}$ on Y generated by the closures of the fibers of the projection $U \cong Z \times \mathbb{A}^1 \to Z$. Letting S be the last exceptional divisor appearing in the process of the minimal resolution of the base locus of $\mathscr{L}$, we compute the discrepancy $a(S; D)$. Using this and some subtle geometric properties of the pair (Y, D), we finally come to a contradiction.

2. Criterion

Let Y be a projective variety and let H be an ample Cartier divisor on Y. Recall [KPZ11b] that an H-*polar cylinder* in Y is an open subset $U = Y \setminus \mathrm{supp}(D)$ isomorphic to $Z \times \mathbb{A}^1$ for some affine variety Z, where D is an effective $\mathbb{Q}$-divisor on Y such that $D \sim_{\mathbb{Q}} H$, that is, qD and qH are linearly equivalent integral divisors for some $q \in \mathbb{N}$. Corollary 3.2 in [KPZ12] provides the following useful criterion for the existence of an effective $\mathbb{G}_a$-action on the affine cone (cf. also [KPZ11b, 3.1.9]).

Theorem 2.1. *Let Y be a normal projective algebraic variety with an ample polarization $H \in \operatorname{Div}(Y)$, and let $X = \operatorname{cone}_H(Y)$ be the corresponding generalized affine cone. If X is normal, then X admits an effective $\mathbb{G}_a$-action if and only if Y contains an H-polar cylinder.*

We apply this criterion to a del Pezzo surface Y of degree $d \leqslant 2$ and a generalized cone

$$X_r = \operatorname{Spec} \bigoplus_{\nu \geqslant 0} H^0(Y, -\nu r K_Y)$$

associated with $H = -rK_Y$, where $r \geqslant 1$. It follows, in particular, that if the cone X_r admits an effective $\mathbb{G}_a$-action, then Y contains a cylinder $Y \setminus \operatorname{supp} D$ with $D \sim_{\mathbb{Q}} -K_Y$. This assumption finally leads to a contradiction, which proves Theorem 1.1.

Remark 2.2. In [KPZ11a, KPZ11b, KPZ12] we used different notions of an H-polar cylinder. In fact, in our setting these definitions are equivalent.

Indeed, let Y, H be as in Theorem 2.1, and let $U = Y \setminus \operatorname{supp} D_i$, where D_i for $i = 1, 2, 3$, are effective $\mathbb{Q}$-divisors on Y. Consider the following conditions:

(1) $D_1 \in |dH|$ for some $d \in \mathbb{N}$;

(2) $[D_2] \in \mathbb{Q}_+[H]$ in $\operatorname{Pic}_{\mathbb{Q}}(Y)$;

(3) $D_3 \sim_{\mathbb{Q}} H$.

Obviously, if for some $i \in \{1, 2, 3\}$, there exists a D_i satisfying (i), then for the remaining $j \in \{1, 2, 3\}$, $j \neq i$, there also exist D_j satisfying (j).

3. Preliminaries on weak del Pezzo surfaces

A smooth projective surface Y is called a *del Pezzo surface* if the anticanonical divisor $-K_Y$ is ample, and a *weak del Pezzo surface* if $-K_Y$ is big and nef. The *degree* of such a surface is $\deg Y = K_Y^2 \in \{1, \ldots, 9\}$.

Lemma 3.1 (see, for example, [Dol12, Proposition 8.1.23]). *Blowing up a point on a del Pezzo surface of degree $d \geqslant 2$ yields a weak del Pezzo surface of degree $d - 1$.*

Theorem 3.2 (see, for example, [Dol12, Thm. 8.3.2]). *Let Y be a del Pezzo surface of degree d. Then the following hold.*

(i) *If $d \geqslant 3$, then $|-K_Y|$ defines an embedding $Y \hookrightarrow \mathbb{P}^d$.*

(ii) *If $d = 2$, then $|-K_Y|$ defines a double cover $\Phi : Y \to \mathbb{P}^2$ branched along a smooth curve $B \subset \mathbb{P}^2$ of degree 4.*

(iii) *If $d = 1$, then $|-K_X|$ is a pencil with a single base point, say O. The linear system $|-2K_Y|$ defines a double cover $\Phi : Y \to Q' \subset \mathbb{P}^3$, where Q' is a quadric cone with vertex at $\Phi(O)$. Furthermore, Φ is branched along a smooth curve $B \subset Q'$ cut out on Q' by a cubic surface.*

The Galois involution $\tau : Y \to Y$ associated with the double cover Φ is a regular morphism. It is called a *Geiser involution* in the case $d = 2$ and a *Bertini involution* in the case $d = 1$.

Remark 3.3. Recall the following facts (see, for example, [Dol12]). For an irreducible curve C on Y we have $C^2 \geqslant -1$ if Y is a del Pezzo surface and $C^2 \geqslant -2$ if Y is a weak del Pezzo surface. In both cases $C^2 = -1$ if and only if C is a (-1)-curve, that is, if and only if $-K_Y \cdot C = 1$, and $C^2 = -2$ if and only if C is a (-2)-curve, that is, if and only if $-K_Y \cdot C = 0$. A weak del Pezzo surface is del Pezzo if and only if it has no (-2)-curve.

If $d \geqslant 2$, then any curve C on Y with $-K_Y \cdot C = 1$ is an irreducible smooth rational curve by statements (i) and (ii). By the adjunction formula such a C must be a (-1)-curve.

Lemma 3.4. *Let Y be a del Pezzo surface of degree $d \leqslant 2$. Then any member $R \in |-K_Y|$ is reduced and $p_a(R) = 1$. Moreover, R is irreducible except in the case where*

– *$d = 2$; $R = R_1 + R_2$; $R_i^2 = -1$ for $i = 1, 2$; $R_1 \cdot R_2 = 2$; and $R_2 = \tau(R_1)$.*

Furthermore, $\mathrm{Sing}(R) \subset \Phi^{-1}(B)$ and for any $P \in \Phi^{-1}(B)$, there is a unique member $R \in |-K_Y|$ that is singular at P.

Proof. We have $p_a(R) = 1$ by adjunction. Let $R_1 \subsetneq R$ be a reduced irreducible component. Then $(-K_Y) \cdot R_1 < (-K_Y) \cdot R = d$ and so $d = 2$ and R_1 is a (-1)-curve by Remark 3.3. Since $R^2 = d = 2$, we have $R \neq 2R_1$. Therefore $R = R_1 + R_2$, where the R_i $(i = 1, 2)$ are (-1)-curves and $R_1 \cdot R_2 = \frac{1}{2}(R^2 - R_1^2 - R_2^2) = 2$. Finally, in both cases we have $R = \Phi^{-1}(L)$, where L is a line in $\mathbb{P}^2$. Thus R is singular at P if and only if $\Phi(P) \in B$ and L is tangent to B at $\Phi(P)$. □

Remark 3.5. Let R_1 and R_2 be (-1)-curves on a del Pezzo surface Y of degree 2 such that $R_1 \cdot R_2 \geqslant 2$. Then $R_2 = \tau(R_1)$, $R_1 \cdot R_2 = 2$, and $R_1 + R_2 \in |-K_Y|$. Indeed, $R_1 + \tau(R_1) \sim -K_Y$. Hence $\tau(R_1) \cdot R_2 = -1$ and so $\tau(R_1) = R_2$.

4. $(-K)$-polar cylinders on del Pezzo surfaces

Here we adjust some lemmas of [KPZ11b, § 4] to our setting.

Notation 4.1. Let Y be a del Pezzo surface of degree d. Suppose that Y admits a $(-K_Y)$-polar cylinder

$$U = Y \setminus \mathrm{supp}(D) \cong Z \times \mathbb{A}^1 \quad \text{with} \quad D = \sum_{i=1}^{n} \delta_i \Delta_i \sim_{\mathbb{Q}} -K_Y \,, \tag{4.1}$$

where the Δ_i are prime divisors, the $\delta_i > 0$ are rational numbers, and Z is a smooth rational affine curve. We let $\mathscr{L}$ be the linear pencil on Y defined by the rational map $\Psi : Y \dashrightarrow \mathbb{P}^1$ which extends the projection $\mathrm{pr}_1 : U \cong Z \times \mathbb{A}^1 \to Z$.

Resolving, if necessary, the base locus of the pencil $\mathscr{L}$, we obtain a diagram

$$\begin{array}{ccc} & W & \\ {}^{p}\swarrow & & \searrow^{q} \\ Y & \overset{\Psi}{\dashrightarrow} & \mathbb{P}^1 \end{array} \tag{4.2}$$

where we let $p : W \to Y$ be the shortest succession of blowups such that the proper transform $\mathscr{L}_W := p_*^{-1}\mathscr{L}$ is base point free. Let S be the last exceptional curve of the modification p unless p is the identity map, that is, $\mathrm{Bs}\,\mathscr{L} = \emptyset$. Notice that S is a unique (-1)-curve in the exceptional locus $p^{-1}(P)$ and a section of q. The restriction $\Phi_{\mathscr{L}_W}|_U$ is an $\mathbb{A}^1$-fibration and its fibers are reduced, irreducible affine curves with one place at infinity, situated on S.

Lemma 4.2. *One of the following holds.*

(i) *$\mathrm{Bs}\,\mathscr{L}$ consists of a single point, say P;*

(ii) *$\mathrm{Bs}\,\mathscr{L} = \emptyset$ and $5 \leqslant d \leqslant 8$.*

Proof. Since the general members of $\mathscr{L}$ are disjoint in U and each one meets the cylinder U along an $\mathbb{A}^1$-curve, $\mathrm{Bs}\,\mathscr{L}$ consists of at most one point, which we denote by P. Suppose that

$\operatorname{Bs}\mathscr{L} = \emptyset$. Then the pencil $\mathscr{L}$ yields a conic bundle $\Psi : Y \to \mathbb{P}^1$ with a section, which is a component of D, say Δ_0. In particular, $d \leqslant 8$. For a general fiber L of Ψ we have

$$L^2 = 0, \quad -K_Y \cdot L = 2 = D \cdot L = \delta_0 .$$

Note that Ψ has exactly $8-d$ degenerate fibers $L_1, \dots, L_{8-d}$. Each of these fibers is reduced and consists of two (-1)-curves meeting transversally at a point. Let C_i be the component of L_i that meets Δ_0. We claim that each C_i is a component of D. Indeed, otherwise

$$1 = -K_Y \cdot C_i = D \cdot C_i \geqslant \delta_0 \Delta_0 \cdot C_i = \delta_0 = 2 ,$$

which is a contradiction. Therefore we may assume that $C_i = \Delta_i$ and so

$$1 = D \cdot C_i \geqslant \delta_0 \Delta_0 \cdot C_i + \delta_i C_i^2 = 2 - \delta_i .$$

Hence $\delta_i \geqslant 1$ for $i = 1, \dots, 8-d$. We obtain

$$d = -K_Y \cdot D \geqslant \sum \delta_i \geqslant \delta_0 + \sum_{i=1}^{8-d} \delta_i \geqslant 2 + 8 - d = 10 - d .$$

Thus $d \geqslant 5$ as stated. □

Remark 4.3. If $\operatorname{Bs}\mathscr{L} = \{P\}$ ($\operatorname{Bs}\mathscr{L} = \emptyset$, respectively), then all the components Δ_i of D (all the components Δ_i of D except for Δ_0, respectively) are contained in the fibers of Ψ. Indeed, otherwise not all the fibers of $\Psi|U$ were $\mathbb{A}^1$-curves, contrary to the definition of a cylinder.

Lemma 4.4. *For the number n of irreducible components of the curve* $\operatorname{supp}(D)$ *we have* $n \geqslant 10-d$.

Proof. Consider the exact sequence

$$\bigoplus_{i=1}^{n} \mathbb{Z}[\Delta_i] \longrightarrow \operatorname{Pic}(Y) \longrightarrow \operatorname{Pic}(U) \longrightarrow 0 .$$

Since $\operatorname{Pic}(Z) = 0$ and $U \cong Z \times \mathbb{A}^1$, we have $\operatorname{Pic}(U) = 0$. Hence $n \geqslant \rho(Y) = 10 - d$, as stated. □

Lemma 4.5. *Assume that* $\operatorname{Bs}\mathscr{L} = \{P\}$. *Let L be a member of $\mathscr{L}$ and let C be an irreducible component of L. Then the following hold:*

(i) $\operatorname{supp}(L)$ *is simply connected and* $\operatorname{supp}(L) \setminus \{P\}$ *is an SNC divisor;*

(ii) *C is rational and smooth outside P;*

(iii) *if $P \in C$, then $C \setminus \{P\} \simeq \mathbb{A}^1$.*

Proof. All the assertions follow from the fact that q in (4.2) is a rational curve fibration and the fact that the exceptional locus of p coincides with $p^{-1}(P)$. □

In the next lemma we study the singularities of the pair (Y, D). We refer to [Kol97] or to [KM98, Chapter 2] for the standard terminology on singularities of pairs.

Lemma 4.6 (Key Lemma). *Assume that* $\operatorname{Bs}\mathscr{L} = \{P\}$. *Then the pair (Y, D) is not log canonical at P. More precisely, using the notation introduced in 4.1, the discrepancy $a(S; D)$ of S with respect to $K_Y + D$ is equal to -2.*

Proof. We write

$$K_W + D_W \sim_{\mathbb{Q}} p^*(K_Y + D) + a(S; D)S + \sum a(E; D)E, \tag{4.3}$$

where the summation on the right-hand side ranges over the components of the exceptional divisor of p except for S, and D_W is the proper transform of D on W. Letting l be a general fiber of q, by (4.3) we obtain

$$-2 = (K_W + D_W)\cdot l = a(S; D)\,.$$

Indeed, $K_Y + D \sim_{\mathbb{Q}} 0$ and l does not meet the curve $\operatorname{supp}(D_W + p^*(P) - S)$. This proves the assertion. □

Corollary 4.7. *If* $\operatorname{Bs}\mathscr{L} = \{P\}$, *then* $\operatorname{mult}_P(D) > 1$.

Proof. Indeed, otherwise the pair (Y, D) would be canonical by [Kol97, Ex. 3.14.1], and in particular, log canonical at P, which contradicts Lemma 4.6. □

Corollary 4.8. *If* $\operatorname{Bs}\mathscr{L} = \{P\}$, *then every* (-1)*-curve* C *on* Y *passing through* P *is contained in* $\operatorname{supp}(D)$.

Proof. Assume to the contrary that C is not a component of D. Then

$$\operatorname{mult}_P D \leqslant C\cdot D = -K_Y\cdot C = 1\,,$$

which contradicts Corollary 4.7. □

Convention 4.9. From now on we assume that $d \leqslant 3$. By Lemma 4.2 we have $\operatorname{Bs}\mathscr{L} = \{P\}$.

Lemma 4.10. *We have* $\lfloor D\rfloor = 0$, *that is,* $\delta_i < 1$ *for all* $i = 1, \ldots, n$.

Proof. For the case $d = 3$, see [KPZ11b, Lemma 4.1.5]. Consider the case $d = 1$. By Lemma 4.4, $n \geqslant 9$. For any $i = 1, \ldots, n$, we have

$$1 = -K_Y\cdot D = \sum_{j=1}^{n}\delta_j(-K_Y)\cdot\Delta_j > \delta_i(-K_Y)\cdot\Delta_i\,.$$

Since the anticanonical divisor $-K_Y$ is ample, it follows that $\delta_i < 1$, as required.

Now let $d = 2$. Assuming that $\delta_1 \geqslant 1$, we obtain

$$2 = -K_Y\cdot D = \sum_{i=1}^{n}\delta_i(-K_Y)\cdot\Delta_i > \delta_1(-K_Y)\cdot\Delta_1 \geqslant -K_Y\cdot\Delta_1\,, \tag{4.4}$$

where $n \geqslant 8$ by Lemma 4.4. It follows that $-K_Y\cdot\Delta_1 = 1$, that is, Δ_1 is a (-1)-curve. Then $C := \tau(\Delta_1)$ is also a (-1)-curve, where τ is the Geiser involution, and $\Delta_1 + C \sim -K_Y$. If $C \subset \operatorname{supp}(D)$, for example, $C = \Delta_2$, then by (4.4) we obtain that $\delta_2 < 1$. Now $\Delta_1 + \Delta_2 \sim_{\mathbb{Q}} D$ yields a relation with positive coefficients

$$(1-\delta_2)\Delta_2 \sim_{\mathbb{Q}} (\delta_1 - 1)\Delta_1 + \sum_{i=3}^{n}\delta_i\Delta_i\,.$$

This implies that $C^2 = \Delta_2^2 \geqslant 0$, which is a contradiction.

Hence $C \not\subset \operatorname{supp}(D)$. Thus $C \sim_{\mathbb{Q}} D - \Delta_1$, where the right-hand side is effective. This leads to a contradiction as before. □

Lemma 4.11 (cf. [KPZ11b, Lemma 4.1.6]). *For a member* L *of* $\mathscr{L}$, *any irreducible component of* L *passes through the base point* P *of* $\mathscr{L}$.

Proof. Assume to the contrary that there exists a component C of L such that $P \notin C$. Then $C^2 < 0$ (see the proof of Lemma 4.2). Since we also have $-K_Y \cdot C > 0$, C is a (-1)-curve. Let C' be a component of L meeting C. If $P \notin C'$, then C and C' are both (-1)-curves and so $L = C+C'$. Thus $\mathscr{L} = |C+C'|$ is base point free, which contradicts Lemma 4.2. Hence C' passes through P. Since P is a unique base point of $\mathscr{L}$, C does not meet any member $L' \in \mathscr{L}$ different from L. By Lemma 4.5, L is simply connected, so C' is the only component of L meeting C. Note that $\operatorname{supp}(D)$ is connected because D is ample. Hence C' must be contained in $\operatorname{supp}(D)$. In fact, supposing to the contrary that C' is not contained in $\operatorname{supp}(D)$, the curve C must be contained in $\operatorname{supp}(D)$. Indeed, the affine surface $U = Y \setminus \operatorname{supp}(D)$ does not contain any complete curve. Since $\operatorname{supp}(D)$ is connected, there is an irreducible component of $\operatorname{supp}(D)$ intersecting C and passing through P. This contradicts Lemma 4.5. Thus we may suppose that $C' = \Delta_1$.

If $C \subset \operatorname{supp}(D)$, say, $C = \Delta_2$, then

$$1 = -K_Y \cdot C = \left(\sum_{i=1}^{n} \delta_i \Delta_i\right) \cdot \Delta_2 = \delta_1 - \delta_2 \,.$$

Hence $\delta_1 = \delta_2 + 1 > 1$, which contradicts Lemma 4.10.

Therefore $C \not\subset \operatorname{supp}(D)$ and so

$$1 = -K_Y \cdot C = \left(\sum_{i=1}^{n} \delta_i \Delta_i\right) \cdot C = \delta_1 \,,$$

which again gives a contradiction by Lemma 4.10. □

5. Proof of Theorem 1.1

Below, we freely use the notation of the previous section. According to our geometric criterion (see Theorem 2.1), Theorem 1.1 is a consequence of the following proposition.

Proposition 5.1. *Let Y be a del Pezzo surface of degree $d \leqslant 2$. Then Y does not admit any $(-K_Y)$-polar cylinder.*

Convention 5.2. We let Y be a del Pezzo surface of degree $d \leqslant 2$. We assume to the contrary that Y possesses a $(-K_Y)$-polar cylinder U as in (4.1). By Lemma 4.2, we have $\operatorname{Bs}\mathscr{L} = \{P\}$.

Lemma 5.3. *For any $R \in |-K_Y|$, we have $\operatorname{supp}(R) \not\subset \operatorname{supp}(D)$.*

Proof. Suppose to the contrary that $\operatorname{supp}(R) \subset \operatorname{supp}(D)$. Let $\lambda \in \mathbb{Q}_{>0}$ be maximal such that $D - \lambda R$ is effective. We can write

$$D = \lambda R + D_{\mathrm{res}} \,,$$

where D_{res} is an effective $\mathbb{Q}$-divisor such that $\operatorname{supp}(R) \not\subset \operatorname{supp}(D_{\mathrm{res}})$. For $t \in \mathbb{Q}_{\geqslant 0}$, we consider the following linear combination:

$$D_t := D - tR + \frac{t}{1-\lambda} D_{\mathrm{res}} \sim_{\mathbb{Q}} -K_Y.$$

We have $D_0 = D$ and $D_\lambda = \frac{1}{1-\lambda} D_{\mathrm{res}}$. For $t < \lambda$, the $\mathbb{Q}$-divisor D_t is effective with $\operatorname{supp}(D_t) = \operatorname{supp}(D)$. By Lemma 4.6 applied to D_t instead of D, for any $t < \lambda$, the pair (Y, D_t) is not log canonical at P, with discrepancy $a(S; D_t) = -2$. Since the function $t \mapsto a(S; D_t)$ is continuous, passing to the limit, we obtain $a(S; D_\lambda) = -2$. Hence the pair (Y, D_λ) is not log canonical at P either and so $\operatorname{mult}_P(D_\lambda) > 1$.

Assume that R is irreducible. Since $R \subset \operatorname{supp}(D)$, R is a component of a member of $\mathscr{L}$. Hence the curve R is smooth outside P and rational (see Lemma 4.5(ii)). Since $p_a(R) = 1$, R is singular at P and $\operatorname{mult}_P(R) = 2$. Since R is different from the components of D_λ and $\operatorname{mult}_P(D_\lambda) > 1$, we obtain

$$2 \geqslant K_Y^2 = D_\lambda \cdot R \geqslant \operatorname{mult}_P(D_\lambda)\operatorname{mult}_P(R) > 2\,, \tag{5.1}$$

which is a contradiction.

Now let R be reducible. By Lemma 3.4, we have $d = 2$ and $R = R_1 + R_2$, where, say, $R_i = \Delta_i$ for $i = 1, 2$ are (-1)-curves passing through P (see Lemma 4.11). We may assume that $\delta_1 \leqslant \delta_2$ and so $\lambda = \delta_1$. Since Δ_1 is not a component of D_λ, we obtain

$$1 = -K_Y \cdot R_1 = D_\lambda \cdot \Delta_1 \geqslant \operatorname{mult}_P(D_\lambda) > 1\,,$$

which is a contradiction. This finishes the proof. □

Proof of Proposition 5.1 in the case $d = 1$. Since $\dim|-K_Y| = 1$, there is a $C \in |-K_Y|$ passing through P. Furthermore, by Lemma 3.4, C is irreducible. By Lemma 5.3, C is not contained in $\operatorname{supp}(D)$. As in (5.1), we get a contradiction. Indeed, by Corollary 4.7, we have

$$1 = C^2 = D \cdot C \geqslant \operatorname{mult}_P D \cdot \operatorname{mult}_P C > 1\,.$$

□

Convention 5.4. From now on, we assume that $d = 2$.

Lemma 5.5. *A member $R \in |-K_Y|$ cannot be singular at P.*

Proof. Assume that $P \in \operatorname{Sing}(R)$. By Lemma 3.4, we have two possibilities for R. Suppose first that R is irreducible. By Lemma 5.3, $R \not\subset \operatorname{supp}(D)$, and we get a contradiction as in (5.1). In the second case, $R = R_1 + R_2$, where R_1 and R_2 are (-1)-curves passing through P. Hence $R_1, R_2 \subset \operatorname{supp}(D)$ by Corollary 4.8. The latter contradicts Lemma 5.3. □

Notation 5.6. We let $f : Y' \to Y$ be the blowup of P and let $E' \subset Y'$ be the exceptional divisor. By Lemma 3.1, Y' is a weak del Pezzo surface of degree 1.

5.7. Applying Proposition 5.1 with $d = 1$, we can conclude that Y' is not del Pezzo because it contains a $(-K_Y)$-polar cylinder. Indeed, let D' be the crepant pull-back of D on Y', that is,

$$K_{Y'} + D' = f^*(K_Y + D) \qquad \text{and} \qquad f_*D' = D\,.$$

Then we have

$$D' = \sum_{i=1}^{6} \delta_i \Delta_i' + \delta_0 E'\,, \quad \text{where} \quad \delta_0 = \operatorname{mult}_P(D) - 1 > 0 \tag{5.2}$$

(see Lemma 4.7) and Δ_i' is the proper transform of Δ_i on Y'. Thus D' is an effective $\mathbb{Q}$-divisor on Y' such that $D' \sim_{\mathbb{Q}} -K_{Y'}$ and $Y' \setminus \operatorname{supp} D' \simeq U \simeq Z \times \mathbb{A}^1$ is a $(-K_Y)$-polar cylinder.

Lemma 5.8. *We have $\operatorname{mult}_P(D) < 2$ and $\lfloor D' \rfloor = 0$.*

Proof. Suppose first that all components of D are (-1)-curves. Then $\Delta_i \cdot \Delta_j = 1$ for $i \neq j$ by Remark 3.5 and Lemma 5.3. Hence f is a log resolution of the pair (Y, D). Therefore $1 - \sum \delta_i = a(Y, E') < -1$ by Lemma 4.6, so $\sum \delta_i > 2$. On the other hand, $2 = -K_Y \cdot D = \sum \delta_i$, which is a contradiction. This shows that there exists a component Δ_i of D which is not a (-1)-curve. By the dimension count there exists an effective divisor $R \in |-K_Y|$ passing through P and a general point $Q \in \Delta_i$. On the other hand, there is no (-1)-curve in Y passing through Q. So by Lemma 3.4, we may assume that R is reduced and irreducible. By Lemma 5.3, R is different from the components of D. Assuming that $\mathrm{mult}_P(D) \geqslant 2$, we obtain

$$2 = R \cdot D \geqslant \mathrm{mult}_P(D) + \delta_i > 2\,,$$

which is a contradiction. This proves the first assertion. The second assertion follows because $\delta_0 > 0$ in (5.2). ☐

Corollary 5.9. *The pair (Y', D') is Kawamata log terminal in codimension one and is not log canonical at some point $P' \in E'$.*

Proof. This follows from Lemma 5.8 taking into account that D' is the crepant pull-back of D, see [Kol97, L. 3.10]. ☐

Since $\dim |-K_{Y'}| = 1$, there exists an element $C' \in |-K_{Y'}|$ passing through the point P' as in Corollary 5.9.

Lemma 5.10. *The point $P \in Y$ is a smooth point of the image $C = f_*C'$.*

Proof. This follows by Lemma 5.5 because $C \in |-K_Y|$ passes through P. ☐

Corollary 5.11. *E' is not a component of C'.*

Proof. We can write $f^*C = C' + kE'$ for some $k \in \mathbb{Z}$. Then $k = -kE'^2 = C' \cdot E' = 1$. By Lemma 5.10, the coefficient of E' in f^*C is equal to 1 as well. The assertion now follows. ☐

Lemma 5.12. *C is reducible.*

Proof. Indeed, otherwise C' is irreducible by Corollary 5.11. Since $\mathrm{mult}_{P'} D' > 1$ by Corollary 5.9 and $D' \cdot C' = K_{Y'}^2 = 1$, C' is a component of D'. Hence C is a component of D. This contradicts Lemma 5.3. ☐

Lemma 5.13. *We have $C' = C_1' + C_2'$, where C_1 is a (-1)-curve, C_2' is a (-2)-curve, and $C_1' \cdot C_2' = 2$. Furthermore, $P' \in C_2' \setminus C_1'$ and $C_2 = f(C_2')$ is a (-1)-curve.*

Proof. Since C is reducible and $C \in |-K_Y|$, by Lemma 3.4, $C = C_1 + C_2$, where C_1, C_2 are (-1)-curves with $C_1 \cdot C_2 = 2$. By Lemma 5.10, $P \notin C_1 \cap C_2$, where C_2 is a component of D by Corollary 4.8, while by Lemma 5.3, C_1 is not. So we may assume that $P \in C_2 \setminus C_1$. The lemma now follows from Corollary 5.9. ☐

5.14. Letting $C_2 = \Delta_1$ from now on, we can write $D = \delta_1 C_2 + D_{\mathrm{res}}$, where $\delta_1 > 0$, D_{res} is an effective $\mathbb{Q}$-divisor, and C_2 is not a component of D_{res}. Similarly,

$$D' = \delta_1 C_2' + D'_{\mathrm{res}} + \delta_0 E'\,,$$

where D'_{res} is the proper transform of D_{res} and $\delta_0 = \mathrm{mult}_P(D) - 1$ (cf. (5.2)).

Lemma 5.15. *We have $2\delta_1 \leqslant 1$.*

Proof. This follows from

$$0 \leqslant D_{\mathrm{res}} \cdot C_1 = (D - \delta_1 C_2) \cdot C_1 = 1 - 2\delta_1\,.$$

☐

Lemma 5.16. *In the same notation as before, $\delta_0 + D'_{\mathrm{res}} \cdot C_2' > 1$.*

Proof. Let us show first that $\{P'\} = C'_2 \cap E' = C'_2 \cap \mathrm{supp}(D'_{\mathrm{res}})$. Indeed, $P' \in E'$ by construction, $P' \in C'_2$ by Lemma 5.13, and $P' \in \mathrm{supp}(D'_{\mathrm{res}})$ because otherwise P' would be a node of D' (indeed, E' meets C'_2 transversally at P') and so the pair (Y', D') would be log canonical at P', contrary to Corollary 5.9. On the other hand, the curves C'_2 and D'_{res} have only one point in common, by Lemma 4.5(i).

Since $\delta_1 < 1$, the pair $(Y', C'_2 + D'_{\mathrm{res}} + \delta_0 E')$ is not log canonical at P'. By applying [KM98, Corollary 5.57], we now obtain

$$1 < (D'_{\mathrm{res}} + \delta_0 E') \cdot C'_2 = \delta_0 + D'_{\mathrm{res}} \cdot C'_2\,,$$

as stated. □

Proof of Proposition 5.1 in the case $d = 2$. We use the same notation as above. Since C'_2 is a (-2)-curve, by virtue of Lemmas 5.15 and 5.16, we have

$$1 - \delta_0 < D'_{\mathrm{res}} \cdot C'_2 = (D' - \delta_1 C'_2 - \delta_0 E') \cdot C'_2 = 2\delta_1 - \delta_0 \leqslant 1 - \delta_0\,,$$

which is a contradiction. Now the proof of Proposition 5.1 is completed. □

Remark 5.17. Our proof of Proposition 5.1 goes along the lines of that of Lemmas 3.1 and 3.5 in [Chel08]. [1] However, this proposition does not follow immediately from the results in [Chel08]. Indeed, in the notation of [Chel08], by Lemma 4.6, we have $\mathrm{lct}(Y, D) < 1$. This is not sufficient to get a contradiction with [Chel08, Theorem 1.7]. The point is that our boundary D is not arbitrary, on the contrary, it is rather special (see Lemma 4.5).

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REFERENCES

Chel08 I. Cheltsov, *Log canonical thresholds of del Pezzo surfaces*, Geom. Funct. Anal. **18** (2008), no. 4, 1118–1144. http://dx.doi.org/10.1007/s00039-008-0687-2

CPW13 I. Cheltsov, J. Park and J. Won, *Affine cones over smooth cubic surfaces*, arXiv:1303.2648 (2013).

Dol12 I. Dolgachev, *Classical Algebraic Geometry: A Modern View*, Cambridge University Press, Cambridge, 2012.

FZ03 H. Flenner and M. Zaidenberg, *Rational curves and rational singularities*, Math. Z. **244** (2003), no. 3, 549–575.

KM98 J. Kollár and S. Mori, *Birational geometry of algebraic varieties*, With the collaboration of C. H. Clemens and A. Corti, Translated from the 1998 Japanese original, Cambridge Tracts in Mathematics **134**, Cambridge University Press, Cambridge, 1998.

Kol97 J. Kollár, *Singularities of pairs*, In Algebraic geometry—Santa Cruz 1995, Proc. Sympos. Pure Math. **62**, 221–287, Amer. Math. Soc. Providence, RI, 1997.

KPZ11a T. Kishimoto, Yu. Prokhorov and M. Zaidenberg, *Affine cones over Fano threefolds and additive group actions*, Osaka J. Math. (to appear), arXiv:1106.1312 (2011).

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KPZ11b T. Kishimoto, Yu. Prokhorov and M. Zaidenberg, *Group actions on affine cones*, In Affine algebraic geometry, 123–163. Peter Russell's Festschrift, CRM Proc. Lecture Notes, **54**, Amer. Math. Soc. Providence, RI, 2011.

KPZ12 T. Kishimoto, Yu. Prokhorov and M. Zaidenberg, $\mathbf{G}_a$*-actions on affine cones*, Transf. Groups (to appear), arXiv:1212.4249 (2012).

Per11 A. Perepechko, *Flexibility of affine cones over del Pezzo surfaces of degree 4 and 5*, Funct. Anal. Appl. (to appear), arXiv:1108.5841 (2011).

Takashi Kishimoto tkishimo@rimath.saitama-u.ac.jp
Department of Mathematics, Faculty of Science, Saitama University, Saitama 338-8570, Japan

Yuri Prokhorov prokhoro@gmail.com
Steklov Institute of Mathematics, 8 Gubkina street, Moscow 119991, Russia
and
Laboratory of Algebraic Geometry, GU-HSE, 7 Vavilova street, Moscow 117312, Russia

Mikhail Zaidenberg zaidenbe@ujf-grenoble.fr
Université Grenoble I, Institute Fourier, UMR 5582 CNRS-UJF, BP 74, 38402 Saint Martin d'Heres cedex, France