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THE FAMILY OF LINES ON THE FANO THREEFOLD V_5

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Introduction

A smooth projective algebraic 3-fold V over the field $\boldsymbol{C}$ is called a Fano 3-fold if the anticanonical divisor $-K_V$ is ample. The integer $g = g(V) = \frac{1}{2}(-K_V)^3$ is called the genus of the Fano 3-fold V. The maximal integer $r \geqq 1$ such that $\mathcal{O}(-K_V) \cong \mathcal{H}^r$ for some (ample) invertible sheaf $\mathcal{H} \in \operatorname{Pic} V$ is called the index of the Fano 3-fold V. Let V be a Fano 3-fold of the index $r = 2$ and the genus $g = 21$ which has the second Betti number $b_2(V) = 1$. Then V can be embedded in $\boldsymbol{P}^6$ with degree 5, by the linear system $|\mathcal{H}|$, where $\mathcal{O}(-K_V) \cong \mathcal{H}^2$ (see Iskovskih [5]). We denote this Fano 3-fold V by V_5.

V_5 can be also obtained as the section of the Grassmannian $G(2, 5) \hookrightarrow \boldsymbol{P}^9$ of lines in $\boldsymbol{P}^4$ by 3 hyperplanes in general position.

There are some other constructions of the Fano 3-fold V_5 (cf. Fujita [1], Mukai-Umemura [9] and Furushima-Nakayama [3]). But so obtained V_5's are all projectively equivalent (cf. [5]).

The remarkable fact on V_5 is that V_5 is a complex analytic compactification of $\boldsymbol{C}^3$ which has the second Betti number one (see Problem 28 in Hirzebruch [4]).

Now, in this paper, we will analyze in detail the universal family of lines on V_5 and determine the hyperplane sections which can be the boundary of $\boldsymbol{C}^3$ in V_5.

In § 1, we will summarize some basic results about V_5 obtained by Iskovskih [5], Fujita [1] and Peternell-Schneider [6]. In § 2, we will construct a $\boldsymbol{P}^1$-bundle $\boldsymbol{P}(\mathcal{E})$ over $\boldsymbol{P}^2$, where $\mathcal{E}$ is a locally free sheaf of rank 2 on $\boldsymbol{P}^2$, and a finite morphism $\psi: \boldsymbol{P}(\mathcal{E}) \to V_5 \hookrightarrow \boldsymbol{P}^6$ of $\boldsymbol{P}(\mathcal{E})$ onto V_5 applying the results by Mukai-Umemura [9]. Further, we will show that the $\boldsymbol{P}^1$-bundle $\boldsymbol{P}(\mathcal{E})$ in fact the universal family of lines on V_5. In § 3, we will study the boundary of $\boldsymbol{C}^3$ in V_5 and the set $\{H \in |\mathcal{O}_V(1)|;\ V_5 \backslash H \cong \boldsymbol{C}^3\}$.

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§1. Basic facts on V_5

Let $V := V_5$ be a Fano 3-fold of degree 5 in P^6 (see Introduction) and $\ell \cong P^1$ is a line on V. Then the normal bundle $N_{\ell|V}$ of ℓ in V can be written as follows:

(a) $N_{\ell|V} \cong \mathcal{O}_\ell \oplus \mathcal{O}_\ell$, or

(b) $N_{\ell|V} \cong \mathcal{O}_\ell(-1) \oplus \mathcal{O}_\ell(1)$

We will call a line ℓ of the type $(0, 0)$ (resp. $(-1, 1)$) if $N_{\ell|V}$ is of the type (a) (resp. type (b)) above.

Let $\sigma\colon V' \to V$ be the blowing up of V along the line ℓ, and put $L' := \sigma^{-1}(\ell)$. Then $L' \cong P^1 \times P^1$ if ℓ is of type $(0, 0)$, and $L' \cong F_2$ if ℓ is of type $(-1, 1)$. Let f_1, f_2 be respectively fibers of the first and second projection of $P^1 \times P^1$ onto P^1, and let s, f be respectively the negative section and a fiber of F_2. Let H be a hyperplane section of V. Since the linear system $|\sigma^*H - L'|$ on V' has no fixed component and no base point and since $h^0(\mathcal{O}(\sigma^*H - L')) = 5$ and $(\sigma^*H - L')^3 = (\sigma^*H - L')^2 \cdot L' = 2$, the linear system $|\sigma^*H - L'|$ defines a birational morphism $\varphi := \varphi_{|\sigma^*H - L'|}\colon V' \to W \hookrightarrow P^4$ of V' onto a quadric hypersurface W in P^4, in particular, $Q := \varphi(L')$ is a hyperplane section of W. Let $E := E_\ell$ be the ruled surface swept out by lines which intersect the line ℓ and E' the proper transform of E in V'.

LEMMA 1.1 (Iskovskih [5], Fujita [1]). *W is a smooth quadric hypersurface in P^4 and $Y := \varphi(E)$ is a twisted cubic curve contained in Q. In particular, $\varphi\colon V' \to W$ is the blowing up of W along the curve Y. Further, we have the following.*

(a) *If ℓ is of type $(0, 0)$, then $\varphi|_{L'}\colon L' \xrightarrow{\sim} Q \cong P^1 \times P^1$, and $\overline{Y} \sim f_1 + 2f_2$ in L'.*

(b) *If ℓ is of type $(-1, 1)$, then $\varphi|_{L'}\colon L' \to Q \cong Q_0^2$ (a quadric cone) is the contraction of the negative section s of $L' \cong F_2$, and $\overline{Y} \sim s + 3f$ in L'.*

In (a) and (b), we denote the proper transform of $Y \hookrightarrow Q$ in L' by $\overline{Y}$.

COROLLARY 1.1. (a) *If ℓ is of type $(0, 0)$, then $E' \cong F_1$.*

(b) *If ℓ is of type $(-1, 1)$, then $E' \cong F_3$.*

Proof. Let $N_{Y|W}$ be the normal bundle of Y in W. Then $N_{Y|W} \cong \mathcal{O}_Y(3) \oplus \mathcal{O}_Y(4)$ if ℓ is of the type $(0, 0)$, and $N_{Y|W} \cong \mathcal{O}_Y(2) \oplus \mathcal{O}_Y(5)$ if Y is of type $(-1, 1)$. Q.E.D.

COROLLARY 1.2. (a) *If ℓ is of type $(0, 0)$, then there are two points $q_1 \neq q_2$ of ℓ such that* (i) *there are two lines in V through the point q_i* $(i = 1, 2)$, *and* (ii) *there are three lines in V through every point q of $\ell \setminus \{q_1, q_2\}$.*

(b) *If ℓ is of type $(-1, 1)$, there is exactly one point q_0 of ℓ such that* (i) *ℓ is the unique line in V through the point q_0, and* (ii) *there are two lines in V through every point q of $\ell \setminus \{q_0\}$.*

Proof. (a) Let p_2: $Q \cong \boldsymbol{P}^1 \times \boldsymbol{P}^1 \rightarrow \boldsymbol{P}^1$ be the projection onto the second component. Since $\bar{Y} \sim f_1 + 2f_2$, $p_2|_Y$: $Y \rightarrow \boldsymbol{P}^1$ is a double cover over $\boldsymbol{P}^1$. Thus there are two branched point $b_1 \neq b_2$ in $\boldsymbol{P}^1$. We put $q_i := \sigma \circ (\varphi|_{L'})^{-1}((p_2|_Y)^{-1}(b_i))$ $(i = 1, 2)$. Then $\ell = \sigma(\bar{Y})$ and $\ell_i := \sigma(\varphi^{-1}(p_2^{-1}(b_i))$ $(i = 1, 2)$ are two lines through the point q_i for each i. For $b \in \boldsymbol{P}^1 \setminus \{b_1, b_2\}$, $\ell = \sigma(\bar{Y})$ and $\sigma(\varphi^{-1}(p_2^{-1}(b)))$ are three lines through the point $q \in \ell \setminus \{q_1, q_2\}$, since $p_2^{-1}(b)$ consists of two different points. This proves (a).

(b) We put $q_0 := \sigma(\bar{Y} \cap s) \in \ell$. Then $\ell = \sigma(\bar{Y}) = \sigma(s)$ is the unique line through the point $q_0 \in \ell$. For $y \in Y \setminus \varphi(s)$, $\ell = \sigma(\bar{Y})$ and $\sigma(\varphi^{-1}(y))$ are two lines through a point of $\ell \setminus \{q_0\}$. This proves (b). Q.E.D.

COROLLARY 1.3 (Peternell-Schneider [6]). *Let E be a non-normal hyperplane section of V_5. Then the singular locus of E is a line ℓ on V, in particular, E is a ruled surface swept out by lines which intersect the line ℓ. Further $V - E \cong \boldsymbol{C}^3$ if and only if the line ℓ is of type $(-1, 1)$.*

Proof. By Lemma (3.35) in Mori [8], the non-normal locus of E is a line ℓ on V. Since $h^0(\mathcal{O}_V(1) \oplus \mathcal{I}_\ell^2) = 1$ and Pic $V \cong \boldsymbol{Z}$, the linear system $|\mathcal{O}_V(1) \oplus \mathcal{I}_\ell^2|$ consists of E, where $\mathcal{I}_\ell$ is the ideal sheaf of ℓ. By Lemma 1, ℓ must be the singular locus of E. Assume ℓ is of type $(0, 0)$. Then, by Lemma 1, $V - E \cong \{(x, y, z, u) \in \boldsymbol{C}^4;\ x^2 + y^2 + z^2 + u^2 = 1\} \not\cong \boldsymbol{C}^3$.

Q.E.D.

§ 2. Construction of the universal family

1. Let $(x: y)$, $(u: v)$ be respectively homogeneous coordinates of the first factor and the second factor of $S := \boldsymbol{P}^1 \times \boldsymbol{P}^1$. Let us consider the diagonal $SL(2; \boldsymbol{C})$-action on S, namely, for $\sigma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL_2 := SL(2; \boldsymbol{C})$,

$$\begin{cases} x^\sigma = ax + by \\ y^\sigma = cx + dy\,, \end{cases} \qquad \begin{cases} u^\sigma = au + bv \\ v^\sigma = cu + dv\,. \end{cases}$$

Let $\tau\colon S \to \boldsymbol{P}^2$ be the double covering of $\boldsymbol{P}^2$ given by

$$\begin{cases} \tau^* X_0 = x \otimes u \\ \tau^* X_1 = \frac{1}{2}(x \otimes v + y \otimes u) \\ \tau^* X_2 = y \otimes v \end{cases}$$

where $(X_0\colon X_1\colon X_2)$ be a homogeneous coordinate on $\boldsymbol{P}^2$. We can also define SL_2-action on $\boldsymbol{P}^2$ as follows:

$$\begin{cases} X_0^\sigma = a^2 X_0 + 2ab X_1 + b^2 X_2 \\ X_1^\sigma = ac X_0 + (ad + bc) X_1 + bd X_2 \\ X_2^\sigma = c^2 X_0 + 2cd X_1 + d^2 X_2 \end{cases}$$

for $\sigma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL_2$.

Then, the morphism τ is SL_2-linear, that is, $\tau(p^\sigma) = \tau(p)^\sigma$ for $p \in S$ and $\sigma \in SL_2$. Further, τ is branched along the smooth conic $C := \{X_1^2 = X_0 X_2\} = \tau(\varDelta)$, where $\varDelta := \varDelta_{\boldsymbol{P}^1}$ is the diagonal in $\boldsymbol{P}^1 \times \boldsymbol{P}^1 = S$. Let f_i be a fiber of the projection $P_i\colon S \to \boldsymbol{P}^1$ onto i-th factor ($i = 1, 2$). Let $\pi\colon M := \boldsymbol{P}(\mathscr{E}) \to \boldsymbol{P}^2$ be the $\boldsymbol{P}^1$-bundle over $\boldsymbol{P}^2$ associated with the vector bundle $\mathscr{E} := \tau_* \mathscr{O}_S(4f_1)$ of rank 2 on $\boldsymbol{P}^2$.

LEMMA 2.1. (1) *$\det(\tau_* \mathscr{O}_S(kf_1)) \cong \mathscr{O}_{\boldsymbol{P}^2}(k-1)$ and $c_2(\tau_* \mathscr{O}_S(kf_1)) = \frac{1}{2}k(k-1)$ for all $k \geqq 0$.*

(2) *$\mathscr{E} \otimes \mathscr{O}_C \cong \mathscr{O}_{\boldsymbol{P}^1}(3) \oplus \mathscr{O}_{\boldsymbol{P}^1}(3)$, where $C = \tau(\varDelta)$.*

(3) *The natural morphism $S \to M$ corresponding to the homomorphism $\tau^* \mathscr{E} \to \mathscr{O}_S(4f_1)$ is a closed embedding, hence, S can be considered as a divisor on M.*

(4) *$\mathscr{O}_M(S) \cong \mathscr{O}_{\mathscr{E}}(2) \otimes \pi^* \mathscr{O}_{\boldsymbol{P}^2}(-2)$, where $\mathscr{O}_{\mathscr{E}}(1)$ is the tautological line bundle on M with respect to $\mathscr{E}$.*

(5) *$\mathscr{O}_{\mathscr{E}}(1)$ is nef,* i.e., *$\mathscr{E}$ is a semi-positive vector bundle*

(6) *We put $\mathscr{O}_M(1) := \mathscr{O}_{\mathscr{E}}(1) \otimes \pi^* \mathscr{O}_{\boldsymbol{P}^2}(1)$. Then*

$$\begin{aligned} H^0(M, \mathscr{O}_M(1)) &\cong H^0(S, \mathscr{O}_S(5f_1 + f_2)) \\ &\cong H^0(\boldsymbol{P}^1, \mathscr{O}_{\boldsymbol{P}^1}(5)) \otimes_{\boldsymbol{C}} H^0(\boldsymbol{P}^1, \mathscr{O}_{\boldsymbol{P}^1}(1))\,. \end{aligned}$$

Proof. (1) Let us consider the exact sequence:

$$0 \longrightarrow \tau_* \mathscr{O}_S(kf_1) \longrightarrow \tau_* \mathscr{O}_S((k+1)f_1) \longrightarrow \tau_* \mathscr{O}_{f_1} \longrightarrow 0\,.$$

Now $\ell_1 = \tau(f_1)$ is a line on $\boldsymbol{P}^2$ and $\mathcal{O}_{\ell_1} \cong \tau_*\mathcal{O}_{f_1}$. Thus, $\det(\tau_*\mathcal{O}_S((k+1)f_1)) \cong \det(\tau_*\mathcal{O}_S(kf_1)) \otimes \mathcal{O}(1)$ and $c_2(\tau_*\mathcal{O}_S((k+1)f_1)) = (\det(\tau_*\mathcal{O}_S(kf_1))\cdot\mathcal{O}(1)) + c_2(\tau_*\mathcal{O}_S((kf_1))$. Since $\tau_*\mathcal{O}_S \cong \mathcal{O} \otimes \mathcal{O}(-1)$, we are done.

(2) Let us consider the following diagram:

$$\begin{tikzcd}
 & & & 0 \arrow[d] & \\
 & 0 \arrow[d] & & \mathcal{O}_\Delta(3f_1 - f_2) \arrow[d] & \\
0 \arrow[r] & \mathcal{O}_S(2f_1 - 2f_2) \arrow[r] \arrow[d] & \mathcal{O}_S(4f_1) \arrow[r] & \mathcal{O}_{2\Delta}(4f_1) \arrow[r] \arrow[d] & 0 \\
0 \arrow[r] & \mathcal{O}_S(3f_1 - f_2) \arrow[r] \arrow[d] & \mathcal{O}_S(4f_1) \arrow[r] & \mathcal{O}_\Delta(4f_1) \arrow[r] \arrow[d] & 0 \\
 & \mathcal{O}_\Delta(3f_1 - f_2) \arrow[d] & & 0 & \\
 & 0 & & &
\end{tikzcd}$$

Since $\tau^*C = 2\Delta$, we have $\tau_*\mathcal{O}_{2\Delta}(4f_1) \cong \mathscr{E} \otimes \mathcal{O}_C$ and the exact sequence:

$$\begin{tikzcd}
0 \arrow[r] & \tau_*\mathcal{O}_\Delta(3f_1 - f_2) \arrow[r] \arrow[d, phantom, "\wr\|"] & \mathscr{E} \otimes \mathcal{O}_C \arrow[r] & \tau_*\mathcal{O}_\Delta(4f_1) \arrow[r] \arrow[d, phantom, "\wr\|"] & 0 \\
 & \mathcal{O}_{\boldsymbol{P}^1}(2) & & \mathcal{O}_{\boldsymbol{P}^1}(4)\,. &
\end{tikzcd}$$

To show that $\mathscr{E} \otimes \mathcal{O}_C \cong \mathcal{O}_{\boldsymbol{P}^1}(3) \oplus \mathcal{O}_{\boldsymbol{P}^1}(3)$, it is enough to prove that

$$H^0(C, (\mathscr{E} \otimes \mathcal{O}_C) \otimes \mathcal{O}_{\boldsymbol{P}^1}(-4)) \cong H^0(\mathcal{O}_{2\Delta}(2f_1 - 2f_2)) = 0\,.$$

By the above diagram, we have the exact sequences:

$$\begin{tikzcd}
0 \arrow[r] & P_{2*}\mathcal{O}_S(-4f_2) \arrow[r, "\varphi"] \arrow[d, phantom, "\wr\|"] & P_{2*}\mathcal{O}_S(2f_1 - 2f_2) \arrow[r] \arrow[d, phantom, "\wr\|"] & P_{2*}\mathcal{O}_{2\Delta}(2f_1 - 2f_2) \arrow[r] & 0\,, \\
 & \mathcal{O}_{\boldsymbol{P}^1}(-4) & \mathcal{O}_{\boldsymbol{P}^1}(-2)^{\oplus 3} & &
\end{tikzcd}$$

and

$$\begin{tikzcd}
0 \arrow[r] & P_{2*}\mathcal{O}_\Delta(f_1 - 3f_2) \arrow[r] \arrow[d, phantom, "\wr\|"] & P_{2*}\mathcal{O}_{2\Delta}(2f_1 - 2f_2) \arrow[r] & P_{2*}\mathcal{O}_\Delta(2f_1 - 2f_2) \arrow[r] \arrow[d, phantom, "\wr\|"] & 0\,. \\
 & \mathcal{O}_{\boldsymbol{P}^1}(-2) & & \mathcal{O}_{\boldsymbol{P}^1} &
\end{tikzcd}$$

Hence $P_{2*}\mathcal{O}_{2\Delta}(2f_1 - 2f_2)$ is locally free and the dual homomorphism φ^*: $\mathcal{O}_{\boldsymbol{P}^1}(2)^{\oplus 3} \to \mathcal{O}_{\boldsymbol{P}^1}(4)$ is surjective. Therefore φ^* is obtained from the natural surjection $H^0(\boldsymbol{P}^1, \mathcal{O}(2)) \otimes \mathcal{O}_{\boldsymbol{P}^1} \twoheadrightarrow \mathcal{O}_{\boldsymbol{P}^1}(2)$ by tensoring $\mathcal{O}_{\boldsymbol{P}^1}(2)$. Thus we have $P_{2*}\mathcal{O}_{2\Delta}(2f_1 - 2f_2) \cong \mathcal{O}_{\boldsymbol{P}^1}(-1) \oplus \mathcal{O}_{\boldsymbol{P}^1}(-1)$. Therefore we have $H^0(\mathcal{O}_{2\Delta}(2f_1 - 2f_2)) = 0$.

(3) It is enough to show that the natural homomorphism $\mathrm{Sym}^k \mathscr{E} \to \tau_*\mathcal{O}_S(4kf_1)$ is surjective for $k \gg 0$. Since τ is finite morphism, $\tau_*\mathcal{O}_S(4kf_1) \otimes \tau_*\mathcal{O}_S(4f_1) \to \tau_*\mathcal{O}_S(4(k+1)f_1)$ is always surjective. Thus we are done.

(4) Since $\tau\colon S \to \boldsymbol{P}^2$ is a double covering, there is a line bundle $\mathscr{L}$ on $\boldsymbol{P}^2$ such that $\mathcal{O}_{\mathscr{E}}(2) \otimes \mathcal{O}_M(-S) \cong \pi^*\mathscr{L}$. By the exact sequence:

$$0 \longrightarrow \pi^*\mathscr{L} \longrightarrow \mathcal{O}_{\mathscr{E}}(2) \longrightarrow \mathcal{O}_{\mathscr{E}}(2) \otimes \mathcal{O}_S \cong \mathcal{O}_S(8f_1) \longrightarrow 0,$$

we have $\det(\mathrm{Sym}^2 \mathscr{E}) \cong \mathscr{L} \otimes \det(\tau_*\mathcal{O}_S(8f_1))$. Therefore, by (1), $\mathscr{L} \cong \mathcal{O}_{\boldsymbol{P}^2}(2)$, hence, $\mathcal{O}_M(S) \cong \mathcal{O}_{\mathscr{E}}(2) \otimes \pi^*\mathcal{O}_{\boldsymbol{P}^2}(-2)$.

(5) We put $D := \pi^{-1}(C)$. Then, by (2), $D \cong \boldsymbol{P}^1 \times \boldsymbol{P}^1$ and $\mathcal{O}_{\mathscr{E}}(1) \otimes \mathcal{O}_D \cong \mathcal{O}_D(s_1 + 3s_2)$, where s_2 is a fiber of $D \to C$ and s_1 is a fiber of another projection $D \to \boldsymbol{P}^1$. By (4), we have $\mathcal{O}_{\mathscr{E}}(2) \cong \mathcal{O}_M(S + D)$. Assume that there is an irreducible curve γ on M such that $(\mathcal{O}_{\mathscr{E}}(1)\cdot\gamma) < 0$. Then, $\gamma \subseteqq D$ or $\gamma \subseteqq S$. Since $\mathcal{O}_{\mathscr{E}}(1) \otimes \mathcal{O}_S \cong \mathcal{O}_S(4f_1)$ and $\mathcal{O}_{\mathscr{E}}(1) \otimes \mathcal{O}_D \cong \mathcal{O}_D(s_1 + 3s_2)$, this is a contradiction.

(6) By the exact sequence

$$\begin{array}{ccccccccc} 0 \longrightarrow & \mathcal{O}_M(1) \otimes \mathcal{O}_M(-S) & \longrightarrow & \mathcal{O}_M(1) & \longrightarrow & \mathcal{O}_M(1) \otimes \mathcal{O}_S & \longrightarrow 0, \\ & \wr\Vert & & & & \wr\Vert & \\ & \mathcal{O}_{\mathscr{E}}(-1) \otimes \pi^*\mathcal{O}_{\boldsymbol{P}^2}(3) & & & & \mathcal{O}_S(5f_1 + f_2) & \end{array}$$

we have $\pi_*\mathcal{O}_M(1) \cong \tau_*\mathcal{O}_S(5f_1 + f_2)$. Therefore $H^0(M, \mathcal{O}_M(1)) \cong H^0(S, \mathcal{O}_S(5f_1 + f_2))$. Q.E.D.

Remark 2.1. There is a SL_2-action on $(M, \mathcal{O}_M(1))$ compatible to $\tau\colon S \to \boldsymbol{P}^2$. The last isomorphism in (6) is an isomorphism as a SL_2-module.

2. Let us consider the subvector space $L \subseteqq H^0(S, \mathcal{O}_S(5f_1 + f_2))$ generated by the following 7 elements (cf. Lemma (1.6) in [9]):

$$\begin{cases} e_0 := x^5 \otimes u \\ e_1 := x^4y \otimes u + \frac{1}{5}x^5 \otimes v \\ e_2 := x^3y^2 \otimes u + \frac{1}{2}x^4y \otimes v \\ e_3 := x^2y^3 \otimes u + x^3y^2 \otimes v \\ e_4 := \frac{1}{2}xy^4 \otimes u + x^2y^3 \otimes v \\ e_5 := \frac{1}{5}y^5 \otimes u + xy^4 \otimes v \\ e_6 := y^5 \otimes v \end{cases}$$

Then L is an SL_2-invariant subspace. By the isomorphism $H^0(M, \mathcal{O}_M(1)) \cong H^0(S, \mathcal{O}_S(5f_1 + f_2))$, L can be considered as a subspace of $H^0(M, \mathcal{O}_M(1))$.

LEMMA 2.2. (1) *The homomorphism* $L \otimes \mathcal{O}_M \to \mathcal{O}_M(1)$ *is surjective. Especially, we have a morphism* ψ: $M \to \boldsymbol{P}(L) \cong \boldsymbol{P}^6$, *which is* SL_2*-linear.*

(2) *The image* $V := \psi(M)$ *is isomorphic to the Fano* 3*-fold* V_5 *of degree* 5 *in* $\boldsymbol{P}^6$.

Proof. (1) We have only to show that g: $L \otimes \mathcal{O}_{\boldsymbol{P}^2} \to \mathcal{E} \otimes \mathcal{O}_{\boldsymbol{P}^2}(1)$ is surjective. Since SL_2 acts on g, the support of Coker(g) is SL_2-invariant. Now SL_2 acts on $\boldsymbol{P}^2$ with two orbits $\boldsymbol{P}^2 \backslash C$ and C. First, take a point $p \in \boldsymbol{P}^2 \backslash C$. Then $g \otimes \boldsymbol{C}(p)$: $L \to (\mathcal{E} \otimes \mathcal{O}_{\boldsymbol{P}^2}(1)) \otimes \boldsymbol{C}(p)$ is described as follows:

Let α: $L \otimes \mathcal{O}_S \to \mathcal{O}_S(5f_1 + f_2)$ be the natural homomorphism and let $\alpha(q)$: $L \to \mathcal{O}_S(5f_1 + f_2) \otimes \boldsymbol{C}(q) \cong \boldsymbol{C}$ be the evaluation map for $q \in S$. Then $g \otimes \boldsymbol{C}(p)$: $L \to \boldsymbol{C}^{\oplus 2}$ is nothing but $\alpha(q_1) \oplus \alpha(q_2)$: $L \to \boldsymbol{C}^{\oplus 2}$, where $\{q_1, q_2\} := \tau^{-1}(p)$. For example, take a point $p = (0:1:0) \in \boldsymbol{P}^2$. Then $q_1 = ((1:0), (0:1))$ and $q_2 = ((0:1), (1:0))$ in $S = \boldsymbol{P}^1 \times \boldsymbol{P}^1$. Then the calculation is as follows:

$$\begin{cases} \alpha_1(e_0) = \alpha_1(e_2) = \cdots = \alpha_1(e_6) = 0\,, & \alpha_1(e_1) = \frac{1}{5} \\ \alpha_2(e_0) = \cdots = \alpha_2(e_4) = \alpha_2(e_5) = 0\,, & \alpha_2(e_5) = \frac{1}{5}\,, \end{cases}$$

where $\alpha_1 := \alpha_1(q_1)$, $\alpha_2 := \alpha_2(q_2)$.

Therefore $g \otimes \boldsymbol{C}(p)$ is surjective for any $P \in \boldsymbol{P}^2 \backslash C$.

Next take $p := (1:0:0) \in C$, $q = ((1:0), (1:0)) \in S$. Let $z_1 = y/x$, $z_2 = v/u$ be the local coordinate around q. Then $\mathfrak{m}_p\mathcal{O}_S = (z_1 + z_2, z_1 \cdot z_2) \subsetneqq \mathfrak{m}_q$. The evaluation map $q \otimes \boldsymbol{C}(p)$: $L \to \boldsymbol{C}^{\oplus 2}$ is now the composition

$$\beta\colon L \longrightarrow L \otimes \mathcal{O}_S \longrightarrow \mathcal{O}_S/\mathfrak{m}_p\mathcal{O}_S \cong \boldsymbol{C}1 \oplus \boldsymbol{C}\bar{z}_1\,.$$

Since we have isomorphisms

$$\begin{array}{ccc} \mathcal{O}_S(f_1)_q & \cong & \mathcal{O}_{S,q} \\ \cup & & \cup \\ x & \longmapsto & 1 \\ y & \longmapsto & 0 \end{array} \qquad \begin{array}{ccc} \mathcal{O}_S(f_2)_q & \cong & \mathcal{O}_{S,q} \\ \cup & & \cup \\ u & \longmapsto & 1 \\ v & \longmapsto & 0\,, \end{array}$$

β: $g \otimes \boldsymbol{C}(p)$ is calculated by evaluating $x = u = 1$ and $y = \bar{z}_1 = -v = -\bar{z}_2$. Therefore $\beta(e_0) = 1$, $\beta(e_1) = \frac{4}{5}\bar{z}_1$, $\beta(e_2) = 0$, $\beta(e_3) = 0$, $\beta(e_4) = 0$, $\beta(e_5) = 0$, $\beta(e_6) = 0$. Thus $g \otimes \boldsymbol{C}(p)$ is surjective for any $p \in C$.

(2) Let $h_0, h_1, \cdots, h_6 \in L^\vee$ be the dual basis of $\{e_0, e_1, \cdots, e_6\}$. Since $\boldsymbol{P}(L) \cong L^\vee \backslash \{0\}/\boldsymbol{C}^*$, we denote the point of $\boldsymbol{P}(L)$ corresponding to $\sum_{j=0}^{6} \lambda_j h_j$

$\in L^{\vee}\setminus\{0\}$ by $[\sum_{j=0}^{6}\lambda_j h_j]$. If $\psi(M)$ contains the point $[h_1-h_5]\in \boldsymbol{P}(L)$, then $\psi(M)$ contains the SL_2-orbit $SL_2[h_1-h_5]$ and its closure $\overline{SL_2[h_1-h_5]}$. On the other hand, we know that the closure $\overline{SL_2[h_1-h_5]}$ is isomorphic to V_5 by [§ 3, 7]. Here h_1-h_5 corresponds to $f_6(x,y)=xy(x^4-y^4)$ in their notation. Therefore we have only to show that $\psi(M)$ contains $[h_1-h_5]$ $\in \boldsymbol{P}(L)$. Let $P:=(0:1:0)\in \boldsymbol{P}^2$. Then by (1), the evaluation map $g\otimes \boldsymbol{C}(p)\colon L\to \boldsymbol{C}\oplus\boldsymbol{C}$ with $(g\otimes\boldsymbol{C}(p))(e_1)=(\frac{1}{5},0)$, $(g\otimes\boldsymbol{C}(p))(e_5)=(0,\frac{1}{5})$, and $(g\otimes\boldsymbol{C}(p))(e_j)=(0,0)$ $(j\neq 1,5)$. Therefore the point $q\in\pi^{-1}(p)\cong\boldsymbol{P}^1$ corresponding to the linear function $\boldsymbol{C}\oplus\boldsymbol{C}\ni(a,b)\mapsto a-b\in\boldsymbol{C}$ is mapped to $[h_1-h_5]$ by ψ. Q.E.D.

Remark 2.2. (1) By Lemma (1.5) in [8], $V:=\psi(M)$ has three SL_2-orbits $\psi(M)\setminus\psi(S)$, $\psi(S)\setminus\psi(\Delta_{\boldsymbol{P}^1})$, and $\psi(\Delta_{\boldsymbol{P}^1})$, in particular, $\psi(\Delta_{\boldsymbol{P}^1})$ is a smooth rational curve of degree 6 in V.

(2) $\psi|_S\colon S\to\psi(S)$ is the same morphism as in Lemma (1.6) in [8]. Especially, $\psi|_S$ is one to one and $\operatorname{Sing}\psi(S)=\psi(\Delta_{\boldsymbol{P}^1})$, where $\operatorname{Sing}\psi(S)$ is the singular locus of $\psi(S)$.

Let us denote $\psi(S)$ and $\psi(\Delta_{\boldsymbol{P}^1})$ by B and Σ.

LEMMA 2.3. (1) *ψ is a finite morphism of degree* 3.

(2) *ψ is étale outsides B*

(3) *$\psi^*B=S+2D$, hence ψ is not Galois.*

(4) *We put $M_t:=\pi^{-1}(t)$ for $t\in\boldsymbol{P}^2$. Then $\ell_t:=\psi(M_t)$ is a line of $V\subsetneqq\boldsymbol{P}^6$ and $\psi|_{M_t}\colon M_t\to\ell_t$ is an isomorphism.*

(5) *For $t_1\neq t_2\in\boldsymbol{P}^2$, we have $\ell_{t_1}\neq\ell_{t_2}$.*

(6) *Let ℓ be a line in $V\subsetneqq\boldsymbol{P}^6$. Then there is a point $t\in\boldsymbol{P}^2$ such that $\ell=\ell_t$.*

Proof. (1) By Lemma (2.1)-(5), $\mathcal{O}_M(1)$ is ample. Therefore ψ is a finite morphism and $\psi^*\mathcal{O}_V(1)\cong\mathcal{O}_M(1)$. Thus $\deg\psi=(\mathcal{O}_M(1))^3/(\mathcal{O}_V(1))^3=15/5$ $=3$.

(2) Since $V\setminus B$ is an open orbit of SL_2, ψ is étale over $V-B$.

(3) Since $(\mathcal{O}_V(1)^2\cdot B)=(\mathcal{O}_M(1)^2\cdot S)=(\mathcal{O}_S(5f_1+f_2))_S^2=10$, we have $\mathcal{O}_V(B)$ $\mathcal{O}_V(2)$. Therefore $\mathcal{O}_M(\psi^*B-S)\cong\pi^*\mathcal{O}_{\boldsymbol{P}^2}(4)$. Since ψ^*B-S is a SL_2-invariant effective divisor, its support must be D. Thus $\psi^*B=S+2D$.

(4) It is clear since $(\psi^*\mathcal{O}_V(1)\cdot M_t)=(\mathcal{O}_M(1)\cdot M_t)=1$.

(5) Assume that $\ell_{t_1}=\ell_{t_2}$. Since $\psi|_S\colon S\to B$ is one to one, we have $M_{t_1}\cap S=M_{t_2}\cap S$. Hence $t_1=t_2$.

(6) Let ℓ be a line of V. If $\ell\not\subset B$, then ℓ contains a point $p\in V\setminus B$.

By Corollary (1.2) in § 1, we have $\#\{\text{lines through } p\} \leqq 3$. Thus by (4), (5) above, $\{\text{lines through } p\} = \{\ell_{t_1}, \ell_{t_2}, \ell_{t_3}\}$, where $\{t_1, t_2, t_3\} = \pi(\psi^{-1}(p))$. Therefore $\ell = \ell_{t_2}$. If $\ell \subseteqq B$, then $\ell = \ell_t$ for some $t \in C$, because $\psi|_D$: $D \to B$ is one to one by (3) and $\mathcal{O}_M(1) \otimes \mathcal{O}_D \cong \mathcal{O}_D(s_1 + 5s_2)$ by Lemma 2.1–(2).

THEOREM I. *The $\boldsymbol{P}^1$-bundle π: $M \to \boldsymbol{P}^2$ is the universal family of lines on $V = V_5$.*

Proof. Let T be the space of lines on V, that is, T is a subscheme of the Grassmannian $G(2, 7)$ parametrizing lines of $V \subseteqq \boldsymbol{P}^6$. Since $N_{\ell|V} \cong \mathcal{O} \oplus \mathcal{O}$ or $\mathcal{O}(-1) \oplus \mathcal{O}(1)$ for any line ℓ on V, we have $H^1(\ell, N_{\ell|V}) = 0$ and $H^0(\ell, N_{\ell|V}) \cong \boldsymbol{C}^2$. Therefore T is smooth surface. By the universal property of T, we have a morphism δ: $\boldsymbol{P}^2 \to T$ corresponding to the family (π, ψ): $M \hookrightarrow \boldsymbol{P}^2 \times V$. By Lemma (1.3)–(5), (6), δ is one to one surjective. Therefore δ must be isomorphic.

We put $U_n := \{x \in V;$ there is at most n lines through $x\}$. Then,

COROLLARY 2.1. *$U_3 = V$, $U_2 = B$ and $U_1 = \Sigma$.*

§ 3. Compactifications of $\boldsymbol{C}^3$

Take any point $t \in C \hookrightarrow \boldsymbol{P}^2$ and put $\ell_t := \psi(\pi^{-1}(t))$. Then ℓ_t is a line of type $(-1, 1)$. Let $\sigma : V' \to V$ be blowing up of V along the line ℓ_t and $\overline{E}_t$ be the proper transform in V' of the ruled surface E_t swept out by lines which intersect the line ℓ_t. Then, by Lemma 1.1–(b), we have the birational morphism $\varphi: V' \to W_t$ of V' onto a smooth quadric hypersurface $W_t \cong \boldsymbol{Q}^3$ in $\boldsymbol{P}^4$, a quadric cone $Q_t := \varphi(\sigma^{-1}(\ell_t)) \cong \boldsymbol{Q}_0^2$, and a twisted cubic curve $Y_t := \varphi(\overline{E}_t) \hookrightarrow Q_t$. Let g_t be the unique generating line of Q_t such that $Y_t \cap g_t = \{v_t\}$, where v_t is the vertex of Q_t. Take any point $v \in g_t \backslash \{v_t\} \cong \boldsymbol{C}$. Let Q_v be the quadric cone in W_t with the vertex v, and put $H_t^v := \sigma(\varphi^{-1}(Q_v))$.

Then, by (4.3) in [2] and [6] (see also § 1), we have the following

LEMMA 3.1. (1) *For any $t \in C$, (V, E_t) is a compactification of $\boldsymbol{C}^3$ with the non-normal boundary E_t. Conversely, let (V, H) be a compactification of $\boldsymbol{C}^3$ with a non-normal boundary H. Then there is a point $t \in C$ such that $H = E_t$.*

(2) *For any $t \in C$ and any $v \in g_t \backslash \{v_t\} \cong \boldsymbol{C}$, (V, H_t^v) is a compactification of $\boldsymbol{C}^3$ with the normal boundary H_t^v. Conversely, let (V, H) be a com-*

pactification of C^3 with a normal boundary H. Then there is a point $t \in C$ and a point $v \in g_t \backslash \{v_t\}$ such that $H = H_t^v$.

Remark 3.1. Let Z_t be the line P^2 which is tangent to C at the point $t \in C$. Then $E_t = \psi(\pi^{-1}(Z_t))$ and $\pi^{-1}(Z_t) \backslash (s_t \cup \pi^{-1}(t)) \cong E_t \backslash \ell_t$, where s_t is the negative section of $\pi^{-1}(Z_t) \cong F_3$.

We put

$\Lambda_1 := \{\lambda \in \check{P}^6;\ H_\lambda$ is a non-normal hyperplane section of V such that $V \backslash H_\lambda \cong C^3\}$, and

$\Lambda_2 := \{\lambda \in \check{P}^6;\ H_\lambda$ is a normal hyperplane section of V such that $V \backslash H_\lambda \cong C^3\}$,

where $\check{P}^6 := P(\check{L})$.

Then we have

COROLLARY 3.1. $\dim_C \Lambda_1 = 1$ *and* $\dim_C \Lambda_2 = 2$.

COROLLARY 3.2. *For each $t \in C$, $\{\lambda \in \Lambda_1;\ \ell_t \subseteqq H_\lambda\} = \{$one point$\}$ and $\{\lambda \in \Lambda_2;\ \ell_t \subseteqq H_\lambda\} \cong C$.*

Now, take a point $t_0 = (1:0:0) \in C$. Then $\ell_{t_0} \hookrightarrow P^6$ is written as follows:

$$\ell_{t_0} = \{h_2 = h_3 = h_4 = h_5 = h_6 = 0\}$$

(see the proof of Lemma 2.2–(1)).

Since V is SL_2-invariant, Λ_1 and Λ_2 are also SL_2-invariant

By Lemma (1.4) of [9], the 2-dimensional SL_2-orbits are $SL_2x^3y^3$, $SL_2x^4y^2 = SL_2x^2y^4$, $SL_2x^5y = SL_2xy^5$, and further $SL_2y^6 = SL_2x^6$ is the only one SL_2-orbit of dimension one on P^6. Therefore we have $\Lambda_1 = SL_2y^6$. By an easy calculation, we have

$$\{\lambda \in SL_2x^3y^3;\ \ell_{t_0} \subseteqq H_\lambda\} \cong C \cup C\,,$$
$$\{\lambda \in SL_2x^2y^4;\ \ell_{t_0} \subseteqq H_\lambda\} \cong C \cup C\,,$$
$$\{\lambda \in SL_2xy^5;\ \ell_{t_0} \subseteqq H_\lambda\} \cong C\,.$$

Thus, by Corollary 3.2, we must have $\Lambda_2 = SL_2xy^5$. We put $\Lambda := \Lambda_1 \cup \Lambda_2$. Then $\Lambda = \overline{SL_2xy^5}$. Therefore, by Lemma (1.6) of [9], Λ is the image of $P^1 \times P^1$ with diagonal SL_2-operations by a linear system L of bidegree $(5, 1)$ on $P^1 \times P^1$.

Thus we have

THEOREM 3.1. *$\Lambda_1 = SL_2y^6$, $\Lambda_2 = SL_2xy^5$ and $\Lambda = \overline{SL_2xy^5}$. In particular, $\Lambda_1 \cong P^1$ and $\Lambda_2 \cong P^1 \times P^1 \backslash \{$diagonal$\}$.*

We will show explicitly below that for any $\lambda \in \Lambda$, $V \backslash H_\lambda \cong \boldsymbol{C}^3$.

By p. 505 in [9], $V := V_5 \hookrightarrow \boldsymbol{P}^6$ can be written as follows:

$$\begin{cases} h_0h_4 - 4h_1h_3 + 3h_2^2 = 0 \\ h_0h_5 - 3h_1h_4 + 2h_2h_3 = 0 \\ h_0h_6 - 9h_2h_4 + 8h_3^2 = 0 \\ h_1h_6 - 3h_2h_5 + 2h_3h_4 = 0 \\ h_2h_6 - 4h_3h_5 + 3h_4^2 = 0 , \end{cases}$$

where $(h_0: h_1: h_2: h_3: h_4: h_5: h_6)$ is the homogeneous coordinate of $\boldsymbol{P}^6$.

We have $(0:0:0:0:0:0:1) \in SL_2y^6$. In $V \cap \{h_6 \neq 0\}$, we consider the following coordinate transformation

$$\begin{cases} x_0 = h_0 - 9h_2h_4 + 8h_3^2 \\ x_1 = h_1 - 3h_2h_5 + 3h_3h_4 \\ x_2 = h_2 - 4h_3h_5 + 3h_4^2 \\ x_3 = h_3 \\ x_4 = h_4 \\ x_5 = h_5 \\ h_6 = 1 . \end{cases}$$

Then we have

$$V \cap \{h_6 \neq 0\} \cong \{x_0 = x_1 = x_2 = 0\} \cong \boldsymbol{C}^3 ,$$

and the line $\{h_2 = h_3 = h_4 = h_5 = h_6 = 0\}$ is the singular locus of the boundary $V \cap \{h_6 = 0\}$.

We have $(0:0:0:0:0:1:0) \in SL_2xy^5$. In $V \cap \{h_5 \neq 0\}$, we consider the coordinate transformation

$$\begin{cases} x_0 = h_0 - 3h_1h_4 + 2h_2h_3 \\ x_1 = h_1 \\ x_2 = 3h_2 - h_1h_6 - 2h_3h_4 \\ x_3 = 4h_3 - h_2h_6 - 3h_4^2 \\ x_4 = h_4 \\ x_6 = h_6 \\ h_5 = 1 . \end{cases}$$

Then we have

$$V \cap \{h_5 \neq 0\} \cong \{x_0 = x_2 = x_3 = 0\} \cong \boldsymbol{C}^3 ,$$

and the boundary $V \cap \{h_5 = 0\}$ has a singularity of A_4-type at the point

$(1:0:0:0:0:0:0)$.

Therefore, for any $\lambda \in SL_2y^6$ (resp. SL_2xy^5), H_λ is non-normal (resp. normal with a rational double point of A_4-type), and further $V \backslash H_\lambda \cong \boldsymbol{C}^3$.

Since Λ_1 and Λ_2 are SL_2-orbits, we have the following

COROLLARY 3.3 (cf. [6]). *Let (V, H) and (V, H') be two compactifications of $\boldsymbol{C}^3$ with normal (resp. non-normal) boundaries H and H'. Then there is an automorphism α of V such that $H' = \alpha(H)$.*

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