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NORMAL AFFINE SURFACES WITH \mathbb{C}^* -ACTIONS

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Introduction

A classification of (normal) affine surfaces admitting a \mathbb{C}^* -action was given e.g., in [5, 6, 21, 22, 1, 25] and [12]–[14]. Here we obtain a simple alternative description of normal affine surfaces V with a \mathbb{C}^* -action in terms of their graded coordinate rings as well as by defining equations. Our approach is based on a generalization of the Dolgachev-Pinkham-Demazure construction [11, 22, 10]. Recall (see [12]–[14]) that a \mathbb{C}^* -action on a normal affine surface V is called *elliptic* if it has a unique fixed point which belongs to the closure of every 1-dimensional orbit, *parabolic* if the set of its fixed points is 1-dimensional, and *hyperbolic* if V has only a finite number of fixed points, and these fixed points are of hyperbolic type, that is each one of them belongs to the closure of exactly two 1-dimensional orbits.

In the elliptic case, the complement V^* of the unique fixed point in V is fibered by the 1-dimensional orbits over a projective curve C . In the other two cases V is fibered over an affine curve C , and this fibration is invariant under the \mathbb{C}^* -action.

Vice versa, given a smooth curve C and a \mathbb{Q} -divisor D on C , the Dolgachev-Pinkham-Demazure construction provides a normal affine surface $V = V_{C,D}$ with a \mathbb{C}^* -action such that C is just the algebraic quotient of V^* or of V , respectively. This surface V is of elliptic type if C is projective and of parabolic type if C is affine.

We remind this construction in Sections 1 and 2 below. In Section 3 we use it to present any normal affine surface V with a parabolic \mathbb{C}^* -action as a normalization of the surface $x^d - P(z)y = 0$ in $\mathbb{A}_{\mathbb{C}}^3$ for a certain $d \in \mathbb{N}$ and a certain polynomial $P \in \mathbb{C}[t]$ (see Theorem 3.11).

In Section 4 we deal with the hyperbolic case. We generalize the Dolgachev-Pinkham-Demazure construction in order to make it work for any hyperbolic \mathbb{C}^* -surface. Instead of one \mathbb{Q} -divisor D on a smooth affine curve C as before, it involves now two \mathbb{Q} -divisors D_+ and D_- on C . By our result *isomorphism classes of normal affine hyperbolic \mathbb{C}^* -surfaces are in 1-1-correspondence to equivalence classes*

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of triples (C, D_+, D_-) , where C is a smooth affine curve and D_+, D_- is a pair of \mathbb{Q} -divisors on C with $D_+ + D_- \leq 0$; two such triples (C, D_+, D_-) and (C', D'_+, D'_-) are considered to be equivalent if and only if $C \cong C'$ and $D_{\pm} = D'_{\pm} \pm D_0$ with a principal divisor D_0 ; cf. Theorem 4.3. We also determine the structure of the singularities, the orbits, the divisor class group and the canonical divisor in terms of the divisors D_{\pm} , see Theorems 4.15, 4.18, 4.22 and Corollary 4.24.

Using our description it is possible to represent any normal hyperbolic \mathbb{C}^* -surface fibered over $C = \mathbb{A}_{\mathbb{C}}^1$ as the normalization of a surface in $\mathbb{A}_{\mathbb{C}}^4$ given by

$$x^{dk} - P(t)y = 0, \quad x^{ek}z - Q(t) = 0 \quad \text{and} \quad y^e z^d - R(t) = 0,$$

for certain polynomials $P, Q, R \in \mathbb{C}[t]$ satisfying the relation $P^e R = Q^d$, where e, d are coprime. These polynomials can be easily computed in terms of the data (D_+, D_-) (see Proposition 4.8). For instance, if the divisor D_- is integral then this system reduces to one equation $x^e z - Q(t) = 0$ in $\mathbb{A}_{\mathbb{C}}^3$, and vice versa. When $k = 1$ then it again reduces to one equation $y^e z^d - R(t) = 0$ in $\mathbb{A}_{\mathbb{C}}^3$.

In Proposition 4.12 we show how the pair (D_+, D_-) is transformed when passing to an equivariant cyclic cover of V . We deduce, in particular, a characterization of normal hyperbolic \mathbb{C}^* -surfaces over $C = \mathbb{A}_{\mathbb{C}}^1$ with the fractional part of D_- supported at one point, as normalized cyclic quotients of the surfaces $x^e z - Q(t) = 0$ in $\mathbb{A}_{\mathbb{C}}^3$.

In the forthcoming paper [15], which is actually Part II of the present one, we will apply these results to give a simple description of all normal affine \mathbb{C}^* -surfaces equipped in addition by a \mathbb{C}^+ -action. In fact, this class consists of all normal affine surfaces which admit an algebraic group action with an open orbit.

We note that the results of this paper hold *m.m.* for graded 2-dimensional normal algebras of finite type over a Dedekind domain.

1. Generalities on graded rings

A \mathbb{Z} -graded ring $A = \bigoplus_{i \in \mathbb{Z}} A_i$ contains $A_{\geq 0} = \bigoplus_{i \geq 0} A_i$ and $A_{\leq 0} = \bigoplus_{i \leq 0} A_i$ as subrings. The following lemma is “well known”; in lack of a reference we provide a short argument.

Lemma 1.1. *If $A = \bigoplus_{i \in \mathbb{Z}} A_i$ is a finitely generated A_0 -algebra, then so are $A_{\geq 0}$ and $A_{\leq 0}$. Moreover, A is normal if and only if so are both $A_{\geq 0}$ and $A_{\leq 0}$.*

Proof. Reversing the grading interchanges the subrings $A_{\geq 0}$ and $A_{\leq 0}$. Thus it is sufficient to prove the first part for $A_{\geq 0}$. If $a_{ij} \in A_i$ with $-n \leq i \leq n, j = 1, \dots, n_i$, is a system of homogeneous generators of A , then $A_{\geq 0}$ is generated (as a module over A_0) by the multiplicatively closed system of monomials

$$a^k := \prod_{i,j} a_{ij}^{k_{ij}},$$

where $k := (k_{ij}) \in \mathbb{Z}^N$ satisfies the inequalities

$$(1) \quad k_{ij} \geq 0, \quad -n \leq i \leq n, \quad j = 1, \dots, n_i, \quad \sum_{i,j} ik_{ij} \geq 0.$$

By Gordan’s Lemma (see [20]) the rational polyhedral lattice cone $K \subseteq \mathbb{Z}^N$ defined by (1) is a finitely generated semigroup. Hence the algebra $A_{\geq 0}$ is generated by a finite system of monomials $a^k \in A_{\geq 0}$.

Next we show that the subalgebra $A_{\geq 0}$ (and then also $A_{\leq 0}$) is normal if so is A . Indeed, the integral closure $(A_{\geq 0})_{\text{norm}} \subseteq A = A_{\text{norm}}$ is graded. Take a homogeneous element $x \in (A_{\geq 0})_{\text{norm}}$ of degree $d := \deg x$, and let

$$(2) \quad x^n + \sum_{i=1}^n b_i x^{n-i} = 0, \quad \text{where } b_i \in A_{\geq 0},$$

be an equation of integral dependence. We may assume that b_i are also homogeneous, of degree $\deg b_i = di \geq 0$. Since $\deg b_i \geq 0$ we have $d \geq 0$, and so $x \in A_{\geq 0}$.

Conversely, suppose that both $A_{\geq 0}$ and $A_{\leq 0}$ are normal. The ring $A \otimes_{A_0} \text{Frac}(A_0)$ is normal and so is equal to $\text{Frac}(A_0)[u, u^{-1}]$ for a homogeneous element u of minimal degree > 0 in $A \otimes_{A_0} \text{Frac}(A_0)$. Hence A_{norm} is contained in this subring of $\text{Frac} A$. If $f \in A \otimes_{A_0} \text{Frac}(A_0)$ belongs to the normalization A_{norm} of A then so does its top homogeneous component. Thus it is enough to deal with homogeneous elements. Let a be such an element satisfying an equation of integral dependence (2) over A . We may suppose as above that $b_i \in A_{di}$ ($i = 1, \dots, n$). Since di has the same sign as $d := \deg a$, we have $a \in (A_{\geq 0})_{\text{norm}} = A_{\geq 0}$ if $d \geq 0$ and $a \in (A_{\leq 0})_{\text{norm}} = A_{\leq 0}$ if $d \leq 0$, respectively. Anyhow, $a \in A$, whence A is normal, as stated. \square

NOTATION 1.2. Let $V = \text{Spec} A$ be a normal affine surface over \mathbb{C} with an effective \mathbb{C}^* -action. The coordinate ring $A = \bigoplus_{i \in \mathbb{Z}} A_i$ is then naturally graded so that A_i is the set of elements of A on which $t \in \mathbb{C}^*$ acts via $t.f = t^i f$. Thus, $A_0 = A^{\mathbb{C}^*}$ is the subalgebra of invariants, and A_i ($i \neq 0$) consists of the quasi-invariants of weight i . Up to reversing the grading we may assume that $A_+ := \bigoplus_{i > 0} A_i \neq 0$. The subsets A_+ and $A_- := \bigoplus_{i < 0} A_i$ of A are ideals in $A_{\geq 0}$ and $A_{\leq 0}$, respectively.

The following lemma is well known (see e.g., [10], [12, Lemma 1.5]).

Lemma 1.3. (a) *If $A_0 \neq \mathbb{C}$ then the set $M := \{i \in \mathbb{Z} \mid A_i \neq 0\}$ coincides either with \mathbb{N} or with \mathbb{Z} , and A_i is a locally free A_0 -module of rank 1 for all $i \in M$. Moreover, if $u \in \text{Frac}(A_0) \cdot A_1$ is a non-zero element then*

$$A \subseteq \text{Frac}(A_0)[u, u^{-1}], \quad \text{and even} \quad A \subseteq \text{Frac}(A_0)[u] \quad \text{if } M = \mathbb{N}.$$

(b) *In particular, if $A_0 \cong \mathbb{C}[t]$ then A_i is a free A_0 -module of rank 1 for all $i \in M$.*

Proof. (a) The $K_0 := \text{Frac}(A_0)$ -algebra $A \otimes_{A_0} K_0$ is a 1-dimensional normal graded domain over the field K_0 . Hence it is isomorphic to the free polynomial ring $K_0[u]$ or the ring of Laurent polynomials $K_0[u, u^{-1}]$, where $u \in K_0 A_d$ and $d > 0$. As the \mathbb{C}^* -action is effective $d = 1$, and (a) follows.

(b) follows from [7, Ch. VII, §4, Corollary 2]. □

Lemma 1.3(a) does not hold in general without the assumption that $A_0 \neq \mathbb{C}$ as is seen by the Pham-Brieskorn surfaces $V_{p,q,r} := \{x^p + y^q + z^r = 0\} \subseteq \mathbb{C}^3$.

1.4. Usually (cf. [12]) one distinguishes between the following three cases.

- (i) *The elliptic case:* $A_- = 0, A_0 = \mathbb{C}$.
- (ii) *The parabolic case:* $A_- = 0, A_0 \neq \mathbb{C}$.
- (iii) *The hyperbolic case:* $A_- \neq 0$.

Below we provide more information in each of these cases.

2. The elliptic case

In the elliptic case the \mathbb{C}^* -action on V is good. In particular, its fixed point set $F := V^{\mathbb{C}^*}$ (which is the zero set of the augmentation ideal A_+ of A) consists of a unique point called *the vertex* of V , and the surface V is smooth outside the vertex. One considers the smooth projective curve $C := \text{Proj } A \cong V^*/\mathbb{C}^*$, where $V^* := V \setminus F$, together with the orbit morphism $\pi: V^* \rightarrow C$ (the fibers of π are the orbits of the \mathbb{C}^* -action on V^*).

A useful class of examples of normal affine surfaces with a good \mathbb{C}^* -action is provided by the affine cones over projective curves. For an ample divisor D on a smooth projective curve C the ring

$$A_{C,D} := \bigoplus_{k \geq 0} H^0(C, \mathcal{O}_C(kD)) \cdot u^k \subseteq \text{Frac}(C)[u],$$

where u is an indeterminate, is the coordinate ring of a normal affine surface $V := \text{Spec } A_{C,D}$ with a good \mathbb{C}^* -action. Alternatively this surface V is obtained by blowing down the zero section of the line bundle associated to $\mathcal{O}_C(-D)$. We will refer to such surfaces as affine cones over C (although $A_{C,D}$ is not generated by elements of degree one, in general).

Let furthermore a finite group G act on V freely off the vertex, and assume that this action commutes with the given good \mathbb{C}^* -action on V . Then the quotient V/G is again a normal affine surface with a good \mathbb{C}^* -action. Conversely, the following result is true.

Theorem 2.1 ([11, 22, 10, 24]). *Every normal affine surface with a good \mathbb{C}^* -action appears as the quotient of an affine cone over a smooth projective curve by a finite group acting freely off the vertex of the cone.*

Generalizing the construction above, for a smooth projective curve C and a \mathbb{Q} -divisor D on C one considers the graded ring

$$A_{C,D} := \bigoplus_{k \geq 0} H^0(C, \mathcal{O}([kD])) \cdot u^k,$$

where $\lfloor E \rfloor$ denotes the integral part of a \mathbb{Q} -divisor E . We have the following result.

Theorem 2.2 ([22], [10, Theorem 3.5]). *Given a normal affine surface $V = \text{Spec } A$ with a good \mathbb{C}^* -action there exists a \mathbb{Q} -divisor D on the curve $C = \text{Proj } A$ such that $A \cong A_{C,D}$.*

The affine toric surfaces provide an interesting family of elliptic \mathbb{C}^* -surfaces.

EXAMPLE 2.3 ([20, 9]). We remind that a normal affine toric surface $V = V_\sigma$ is associated to a strictly convex rational polyhedral cone $\sigma \subseteq \mathbb{R}^2$. If $\dim \sigma = 0$ or $= 1$ then $V_\sigma \cong \mathbb{C}^* \times \mathbb{C}^*$ or $V_\sigma \cong \mathbb{A}_{\mathbb{C}}^1 \times \mathbb{C}^*$, respectively, and so $A^\times \neq \mathbb{C}^*$. Consequently, these two cannot be elliptic \mathbb{C}^* -surfaces. Otherwise, if $\dim \sigma = 2$ then choosing an appropriate base e_1, e_2 of the lattice one may suppose that σ is the cone $C(e_2, de_1 - ee_2)$, where $d \geq 1, 0 \leq e < d$ and $\text{gcd}(e, d) = 1$. We denote $V_{d,e} := V_\sigma$; then $V_{d,e} = \text{Spec } A_{d,e}$, where

$$A_{d,e} := \bigoplus_{b \geq 0, ad - be \geq 0} \mathbb{C} \cdot x^a y^b \subseteq \mathbb{C}[x, y]$$

is the semigroup algebra of the dual cone $\sigma^\vee = C(e_1, ee_1 + de_2)$.

The 2-torus $\mathbb{T} = (\mathbb{C}^*)^2$ acts on $V_{d,e}$ with an open orbit $V_{d,e}^* := V_{d,e} \setminus \{0\}$. Thus one can introduce on $V_{d,e}$ a number of elliptic, parabolic as well as hyperbolic \mathbb{C}^* -actions by choosing appropriate 1-parameter algebraic subgroups of the torus \mathbb{T} .

In [23, 2, 3, 9] one can find a description of minimal sets of generators of the algebras $A_{d,e}$ as above, as well as defining equations for the affine varieties $V_{d,e} = \text{Spec } A_{d,e} \hookrightarrow \mathbb{C}^N$. An explicit presentation of these algebras as in Theorem 2.2 is given in [10, 5.1].

We would like to emphasize the well known relation between affine toric surfaces and cyclic quotient singularities (see [10, 5.2] or [20, Proposition 1.24]).

Lemma 2.4. *If B is the normalization of $A := A_{d,e}$ in the field $L := \text{Frac}(A)[u]$ with $u := \sqrt[d]{x}$, then B is the polynomial ring $B = \mathbb{C}[u, v]$ with $v := u^e y$. The Galois group $\langle \zeta \rangle \cong \mathbb{Z}_d$ of $L : \text{Frac}(A)$ acts on B via the representation, say $G_{d,e}$*

$$\zeta \cdot u = \zeta u, \quad \zeta \cdot v = \zeta^e v,$$

and $A = B^{\mathbb{Z}_d}$. Consequently, there is an isomorphism

$$V_{d,e} \cong \mathbb{A}_{\mathbb{C}}^2/G_{d,e} = \mathbb{A}_{\mathbb{C}}^2/\mathbb{Z}_d.$$

Proof. For the convenience of the reader we give a short argument. By definition, A is generated over \mathbb{C} by the monomials

$$x^a y^b \quad \text{with} \quad b \geq 0, \quad ad - be \geq 0.$$

As $x^a y^b = u^{ad-be} v^b$, this shows that A embeds naturally into $\mathbb{C}[u, v]$ and that even $A = \mathbb{C}[x, y] \cap \mathbb{C}[u, v]$. In particular A is a normal domain. Because of $u^d = x \in A$ and $v^d = x^e y^d \in A$ the ring B is integral over A , whence it is the normalization of A .

The second part follows from the first one, since L is a cyclic extension of $\text{Frac}(A)$ with Galois group \mathbb{Z}_d acting via $\zeta.u = \zeta u$ and $\zeta.z = z$ for all $z \in A$. □

REMARK 2.5. Assuming that $e > 0$ and letting $\xi := \zeta^e$ one obtains

$$(\zeta u, \zeta^e v) = (\xi^{e'} u, \xi v),$$

where $0 \leq e' < d$ and $ee' \equiv 1 \pmod d$ (note that for $d = 1$ this means $e' = 0$). Hence, with $\tau(u, v) := (v, u)$ the conjugate \mathbb{Z}_d -action $G'_{d,e'} := \tau^{-1} G_{d,e} \tau$ on $\mathbb{A}_{\mathbb{C}}^2$

$$\xi.(u, v) = (\xi^{e'} u, \xi v)$$

has the same orbits as $G_{d,e}$ thus providing an isomorphism of affine surfaces

$$V_{d,e} \cong \mathbb{A}_{\mathbb{C}}^2/G_{d,e} \cong \mathbb{A}_{\mathbb{C}}^2/G'_{d,e'} \cong \mathbb{A}_{\mathbb{C}}^2/G_{d,e'} \cong V_{d,e'}.$$

Moreover, $V_{d,e} \cong V_{d',e'}$ if and only if $d = d'$ and either $e = e'$ or $ee' \equiv 1 \pmod d$.

3. The parabolic case

In the parabolic case one considers a normal affine surface V with a \mathbb{C}^* -action such that the coordinate ring $A = \bigoplus_{i \geq 0} A_i$ is positively graded and A_0 is a 1-dimensional domain. Thus A_0 corresponds to a smooth affine curve $C = \text{Spec } A_0$, which can be identified with the algebraic quotient $V//\mathbb{C}^*$ (indeed, $A_0 = A^{\mathbb{C}^*}$ is the ring of invariants of the \mathbb{C}^* -action on A). The embedding $A_0 \hookrightarrow A$ corresponds to the quotient morphism $\pi: V \rightarrow C$, and the projection $A \rightarrow A_0$ gives an embedding $\iota: C \hookrightarrow V$ which provides a retraction of π and whose image is the fixed point set. Every fiber of $\pi: V \rightarrow C$ is the closure of a non-trivial orbit; it contains a unique fixed point (a *source* of this orbit) [12, Lemma 1.7].

A simple example of a parabolic \mathbb{C}^* -surface is the cylinder $C \times \mathbb{A}_{\mathbb{C}}^1$ over a smooth affine curve C , where \mathbb{C}^* acts on the second factor. More examples can be produced

by applying equivariant affine modifications to $C \times \mathbb{A}_{\mathbb{C}}^1$ (see [16, Theorem 1.1]). Actually, one obtains in this way all normal affine surfaces with a parabolic \mathbb{C}^* -action.

3.1. The Dolgachev-Pinkham-Demazure construction (see Theorem 2.2) is available also in the parabolic case. Let $C = \text{Spec } A_0$ be an affine curve over \mathbb{C} with function field $K_0 := \text{Frac}(A_0)$, and let D be a \mathbb{Q} -Cartier divisor on C . Similarly as in the elliptic case we can introduce the algebra

$$A_0[D] := A_{C,D} = \bigoplus_{n \geq 0} H^0(C, \mathcal{O}_C([nD])) \cdot u^n \subseteq K_0[u].$$

More explicitly, if $f \in K_0$ then

$$(3) \quad fu^n \in A := A_0[D] \Leftrightarrow \text{div } f + nD \geq 0.$$

By [10, 2.2] the algebra A is finitely generated over A_0 and normal (see also Corollary 3.8(b) below). Notice also that $u \in A_1$ if and only if $D \geq 0$.

The following theorem is well known (cf. [10, Theorem 3.5]); for the convenience of the reader we include a short proof.

Theorem 3.2. *Let $C = \text{Spec } A_0$ be a normal affine algebraic curve with function field $K_0 := \text{Frac}(A_0)$. If $A = \bigoplus_{i \geq 0} A_i$ is a normal finitely generated A_0 -algebra of dimension 2 with $A_1 \neq 0$ then the following hold.*

(a) *A is isomorphic to $A_0[D]$ for some \mathbb{Q} -divisor D on C . More precisely, if $u \in K_0 \cdot A_1$ is a non-zero element and if the divisor D is defined by the equality*

$$\pi^* D = \text{div } u - \iota(C),$$

then A and $A_0[D]$ are equal when considered as subrings of $K_0[u]$.

(b) *For two \mathbb{Q} -divisors D and D' on C , the rings $A = A_0[D]$ and $A' = A_0[D']$ are isomorphic as graded A_0 -algebras if and only if D and D' are linearly equivalent.*

Proof. (a) Since $u \in K_0 \cdot A_1$ is homogeneous, the divisor $\text{div } u$ on the normal surface $V = \text{Spec } A$ is invariant under the induced \mathbb{C}^* -action on V , and so we have

$$\text{div } u = \sum_{i=1}^m p_i F_i + \iota(C)$$

with $p_i \in \mathbb{Z}$, where $F_i = \pi^{-1}(x_i)_{\text{red}}$ are the fibers of π over distinct points $x_i \in C$, $i = 1, \dots, m$. Letting $\pi^* x_i = q_i F_i$ with $q_i \in \mathbb{N}$ ($i = 1, \dots, m$), the \mathbb{Q} -divisor $D := \sum_{i=1}^m p_i/q_i x_i$ on V satisfies

$$\text{div } u = \pi^*(D) + \iota(C).$$

Since V is normal, for a rational function $\varphi \in K_0$ on C the following equivalences hold:

$$\begin{aligned} \varphi u^n \in A_n &\Leftrightarrow \operatorname{div}(\varphi u^n) \geq 0 \Leftrightarrow \pi^* \operatorname{div} \varphi + n \operatorname{div} u \geq 0 \Leftrightarrow \\ \pi^* \operatorname{div} \varphi + n\pi^*(D) + n\nu(C) \geq 0 &\Leftrightarrow \operatorname{div} \varphi + nD \geq 0 \Leftrightarrow \varphi \in H^0(C, \mathcal{O}_C(\lfloor nD \rfloor)). \end{aligned}$$

Hence $A_n = H^0(C, \mathcal{O}_C(\lfloor nD \rfloor)) \cdot u^n$ for all $n \geq 0$, as desired.

(b) Any isomorphism of graded A_0 -algebras

$$\varphi: A_0[D] = \bigoplus_{n \geq 0} H^0(C, \mathcal{O}_C(\lfloor nD \rfloor)) \cdot u^n \longrightarrow A_0[D'] = \bigoplus_{n \geq 0} H^0(C, \mathcal{O}_C(\lfloor nD' \rfloor)) \cdot u'^n,$$

extends to an isomorphism of graded K_0 -algebras

$$\varphi_{K_0}: K_0[u] \rightarrow K_0[u']$$

and so has the form $u^n \mapsto f^n u'^n$, $n \geq 0$, for some non-zero $f \in K_0$. Conversely, such a morphism φ_{K_0} maps $A_0[D]$ isomorphically onto $A_0[D']$ if and only if

$$H^0(C, \mathcal{O}_C(\lfloor nD' \rfloor)) = f^n \cdot H^0(C, \mathcal{O}_C(\lfloor nD \rfloor)) \quad \forall n.$$

As

$$f^n \cdot H^0(C, \mathcal{O}_C(\lfloor nD \rfloor)) = H^0(C, \mathcal{O}_C(\lfloor nD - n \operatorname{div} f \rfloor)),$$

the existence of an isomorphism φ as above is equivalent to the existence of an element $f \in K_0$ with $D' = D - \operatorname{div} f$. □

3.3. We denote $\{D\} = D - \lfloor D \rfloor$ the fractional part of a \mathbb{Q} -divisor D . Since principal divisors are \mathbb{Z} -divisors, we have $\{D\} = \{D'\}$ as soon as $D \sim D'$.

If $C = \operatorname{Spec} \mathbb{C}[t] = \mathbb{A}_{\mathbb{C}}^1$ then the converse is also true. Indeed, any \mathbb{Z} -divisor on $\mathbb{A}_{\mathbb{C}}^1$ is principal, and so the linear equivalence class of a \mathbb{Q} -divisor D on $\mathbb{A}_{\mathbb{C}}^1$ is uniquely determined by the fractional part $\{D\}$ of D . Thus we obtain the following corollary.

Corollary 3.4. *For every normal parabolic \mathbb{C}^* -surface $V = \operatorname{Spec} A$ with $A = \bigoplus_{n \geq 0} A_n$ and $A_0 = \mathbb{C}[t]$, there is a unique isomorphism $A \cong A_0[D]$ of graded A_0 -algebras, where $D = 0$ or $D = \sum_{i=1}^n (p_i/q_i)x_i$ with $0 < p_i < q_i$, $\operatorname{gcd}(p_i, q_i) = 1 \forall i = 1, \dots, n$ and $x_i \in \mathbb{A}_{\mathbb{C}}^1$, $x_i \neq x_j$ for $i \neq j$.*

The next lemma is also well known; in lack of a reference we provide a short argument.

Lemma 3.5. *Let D be a \mathbb{Q} -divisor on a normal affine variety S and consider the graded ring $A := \bigoplus_{i \geq 0} A_i$, where $A_i := H^0(S, \mathcal{O}_S(\lfloor iD \rfloor)) \cdot u^i$. For $d \in \mathbb{N}$ the following conditions are equivalent.*

- (i) dD is integral.
- (ii) $A_{d+m} = A_d A_m$ for all $m \geq 0$.
- (iii) The d -th Veronese subring $A^{(d)} := \bigoplus_{m \geq 0} A_{md}$ is isomorphic to the symmetric algebra $S_{A_0}(A_d)$ i.e., $A_{md} = S_{A_0}^m A_d$.

Proof. Condition (ii) is equivalent to

$$\mathcal{O}_S(\lfloor(m+d)D\rfloor) \cong \mathcal{O}_S(\lfloor mD\rfloor) \otimes \mathcal{O}_S(\lfloor dD\rfloor) \quad \forall m \geq 0,$$

and the latter condition is equivalent to

$$(ii') \quad \lfloor(m+d)D\rfloor = \lfloor mD\rfloor + \lfloor dD\rfloor \quad \forall m \geq 0.$$

Similarly, (iii) is equivalent to

$$(iii') \quad \lfloor mdD\rfloor = m \lfloor dD\rfloor \quad \forall m \geq 0.$$

The equivalence of (i), (ii') and (iii') now follows from the elementary fact that for a rational number $r = p/q$ and $d \in \mathbb{N}$ the following conditions are equivalent:

$$(1) dr \in \mathbb{Z} \quad (2) \lfloor(m+d)r\rfloor = \lfloor mr\rfloor + \lfloor dr\rfloor \quad \forall m \geq 0 \quad (3) \lfloor mdr\rfloor = m \lfloor dr\rfloor \quad \forall m \geq 0.$$

□

NOTATION 3.6. We denote $d(A)$ the smallest positive integer d satisfying the equivalent conditions of Lemma 3.5.

REMARK 3.7. In the situation of Theorem 3.2, one can recover D from the graded ring $A = A_0[D]$ more algebraically as follows. Consider $d \in \mathbb{N}$ with $A_d A_i = A_{d+i}$ for all $i \geq 0$ (or, equivalently, $A_{id} = S^i(A_d)$, see Lemma 3.5) and let v be a generator of A_d as A_0 -module; this exists after a suitable localization of A_0 . If $u^d = fv$ with $f \in \text{Frac } A_0$, then $D = \text{div}(f)/d$. In fact, the ideal vA is equal to $A_{\geq d}$ and so its zero set has no irreducible components in the fibers of π . Thus $\text{div } v = d \cdot \iota(C)$ on V . Since

$$\pi^*(D) = \text{div } u - \iota(C) \quad \text{and} \quad d \cdot \text{div } u = \text{div } v + \text{div } f$$

as divisors on V , we obtain $D = \text{div}(f)/d$.

A parabolic \mathbb{C}^* -surface $V = \text{Spec } A_0[D]$ has at most cyclic quotient singularities, as follows from Miyanishi's Theorem (see [17, Lemma 1.4.4(1)]). In the next result (see [10, Section 5]) we describe their structure in terms of the divisor D .

Proposition 3.8. (a) If $A_0 = \mathbb{C}[t]$ and if D is supported on the origin in $\text{Spec } A_0 = \mathbb{A}_{\mathbb{C}}^1$ so that $D = -(e/d)[0]$ with $\text{gcd}(e, d) = 1$, then $A := A_0[-(e/d)[0]]$

is naturally isomorphic to the semigroup algebra

$$A_{d,e} = \bigoplus_{b \geq 0, ad-be \geq 0} \mathbb{C} \cdot t^a u^b$$

graded via $\deg t = 0, \deg u = 1$ (cf. Example 2.3). Consequently, $V := \text{Spec } A$ is isomorphic to the toric surface $V_{d,e'} = \text{Spec } A_{d,e'} \cong \mathbb{A}_{\mathbb{C}}^2 / G_{d,e'}$, where $e' \equiv e \pmod d$ and $0 \leq e' < d$.

(b) If $C = \text{Spec } A_0$ is any normal affine curve over \mathbb{C} and D is a \mathbb{Q} -divisor on C , then the surface $V = \text{Spec } A_0[D]$ is normal with at most cyclic quotient singularities. More precisely, if $D(a) = -e/d$ with $\gcd(e, d) = 1$ then V has a quotient singularity of type (d, e') at $\iota(a)$, where e' is as in (a).

Proof. The first part of (a) follows immediately from (3) in 3.1, whereas the second one is a consequence of Lemma 2.4.

Tensoring the isomorphism in (a) with $- \otimes_{\mathbb{C}[t]} \mathbb{C}[[t]]$ we obtain that (b) holds if $A_0 \cong \mathbb{C}[[t]]$. The general case follows from this by taking completions at the maximal ideals of A_0 . □

The algebra $A_0[D]$ is finitely generated over A_0 , so there exist $f_1, \dots, f_n \in K_0$ and $m_1, \dots, m_n \in \mathbb{N}$ such that

$$A = A_0[f_1 u^{m_1}, \dots, f_n u^{m_n}] \subseteq K_0[u].$$

In the next result we show how to compute D from such a representation.

Proposition 3.9. *Let $C = \text{Spec } A_0$ be a smooth affine curve and $K_0 := \text{Frac } A_0$. If a 2-dimensional subring B of the polynomial ring $K_0[u]$ is represented as*

$$B = A_0[f_1 u^{m_1}, \dots, f_n u^{m_n}] \subseteq K_0[u], \quad m_i > 0 \ \forall i$$

with $f_1, \dots, f_n \in K_0$ and $\gcd(m_1, \dots, m_n) = 1$, then its normalization $A = B_{\text{norm}}$ coincides as an A_0 -subalgebra of $K_0[u]$ with $A_0[D]$, where

$$D := - \min_{1 \leq i \leq n} \frac{\text{div } f_i}{m_i}.$$

Proof. By definition of D we have $\text{div } f_i + m_i D \geq 0$ so by (3) $f_i u^{m_i} \in A_0[D]$ and B is a subring of $A_0[D]$. As $A_0[D]$ is normal (see Proposition 3.8(b)), A is also contained in $A_0[D]$. Let us show that these subrings coincide.

According to Theorem 3.2, we can represent A as $A = A_0[D']$ with $\pi^*(D') = \text{div } u - \iota(C)$. In particular $f_i u^{m_i} \in A = A_0[D']$, so again by (3) $\text{div } f_i + m_i D' \geq 0$ or, equivalently, $D' \geq -(1/m_i) \text{div } f_i$. Thus $D' \geq D$ and $A_0[D] \subseteq A_0[D'] = A$. As

we have already shown the converse inclusion we obtain that $A = A_0[D]$, as desired. \square

The following examples of parabolic \mathbb{C}^* -surfaces ruled over $\mathbb{A}_{\mathbb{C}}^1$ are basic (see Theorem 3.11 below).

EXAMPLE 3.10. For a unitary polynomial $P \in \mathbb{C}[t]$ and for an integer $d \geq 1$ we let

$$B_{d,P}^+ := \mathbb{C}[t, u, v]/(u^d - P(t)v) \cong \mathbb{C} \left[t, u, \frac{u^d}{P(t)} \right]$$

graded via

$$\deg t = 0, \quad \deg u = 1, \quad \deg v = d.$$

The normalization

$$A_{d,P}^+ := (B_{d,P}^+)_{\text{norm}}$$

is a positively graded finitely generated \mathbb{C} -algebra of dimension 2 with $A_0 = \mathbb{C}[t]$. By Proposition 3.9 and Corollary 3.4 we have

$$A_{d,P}^+ \cong A_0[D] \cong A_0[\{D\}], \quad \text{where} \quad D = D(d, P) := \frac{\text{div}(P)}{d}.$$

For $P(t) = \prod_{i=1}^n (t - x_i)^{r_i}$ (where $x_i \neq x_j$ if $i \neq j$) we obtain

$$D = \sum_{i=1}^n \frac{r_i}{d} x_i, \quad \text{and} \quad \{D\} = \sum_{i=1}^n \left\{ \frac{r_i}{d} \right\} x_i,$$

whereas $D = 0$ if $P = 1$. Replacing D by $\{D\}$ we may suppose that

$$(*) \quad \gcd(d, r_1, \dots, r_n) = 1, \quad 0 < r_i < d \quad \forall i = 1, \dots, n, \quad \text{if } d \geq 2, \quad \text{and } P = 1 \text{ if } d = 1.$$

If two pairs (d, P) and (\tilde{d}, \tilde{P}) satisfy $(*)$ and if $A_{d,P}^+ \cong A_{\tilde{d},\tilde{P}}^+$ as graded A_0 -algebras then by Corollary 3.4 we have $\text{div}(P)/d = \text{div}(\tilde{P})/\tilde{d}$, and so $d = \tilde{d}$ and $P = \tilde{P}$.

Thus we obtain the following classification result.

Theorem 3.11. *For every normal affine surface $V = \text{Spec } A$, where $A = \bigoplus_{i \geq 0} A_i$ with $A_0 = \mathbb{C}[t]$, there is a unique pair (d, P) satisfying condition $(*)$ and an equivariant isomorphism of A_0 -schemes*

$$\varphi: V \longrightarrow V_{d,P}^+ := \text{Spec } A_{d,P}^+.$$

REMARK 3.12. 1. In the situation of Theorem 3.11 above, the Veronese subring $A^{(d)}$ is equal to $A_0[v] = \mathbb{C}[t, v]$. The cyclic group \mathbb{Z}_d acts on A via the \mathbb{C}^* -action and $A^{(d)}$ coincides with the ring of invariants $A^{\mathbb{Z}_d}$, whereas A is the normalization of $A^{(d)}$ in the fraction field $\text{Frac}(A)$. Thus the morphism $V \rightarrow \mathbb{A}_{\mathbb{C}}^2 = \text{Spec } \mathbb{C}[t, v]$ induced by the inclusion $\mathbb{C}[t, v] \subseteq A$ represents V as a cyclic covering of the plane branched along the curve $u = 0$, and V is the normalization of a surface $\{u^d - P(t)v = 0\}$ in \mathbb{C}^3 . 2. More generally, let $C = \text{Spec } A_0$ be any smooth affine curve and let $A = \bigoplus_{i \geq 0} A_i$ be a normal 2-dimensional A_0 -algebra of finite type. If $A_1 = u \cdot A_0$ and $A_d = v \cdot A_0$, $d := d(A)$, for suitable elements $u \in A_1$ and $v \in A_d$ then A is the normalization of an algebra $A_0[u, v]/(u^d - P_+v)$ graded via $\deg u = 1$, $\deg v = d$, for a certain $d \in \mathbb{N}$ and a certain element $P_+ \in A_0$.

4. The hyperbolic case

Let $A = \bigoplus_{i \in \mathbb{Z}} A_i$ be the coordinate ring of a normal affine surface $V = \text{Spec } A$ with \mathbb{C}^* -action such that A_+ , A_- are both non-zero. Here again there is a quotient morphism $\pi: V \rightarrow C = \text{Spec } A_0$ induced by the inclusion $A_0 \hookrightarrow A$. Every fiber of π is either a non-trivial orbit or a union of two 1-dimensional orbits and a hyperbolic fixed point, which is a source for one of them and a sink for the other one [12, Lemma 1.7]. Thus the fixed point set F is finite and contains $\text{Sing } V$.

By Lemma 1.1 the proper subalgebras $A_{\geq 0}$ and $A_{\leq 0}$ of A are normal and finitely generated, and so $V_+ := \text{Spec } A_{\geq 0}$ and $V_- := \text{Spec } A_{\leq 0}$ are normal affine surfaces with a parabolic \mathbb{C}^* -action birationally dominated by V . The natural embeddings $A_0 \hookrightarrow A_{\geq 0} \hookrightarrow A$ and $A_0 \hookrightarrow A_{\leq 0} \hookrightarrow A$ yield the commutative diagram

$$(4) \quad \begin{array}{ccccc} & & V & & \\ & \xleftarrow{\sigma_+} & & \xrightarrow{\sigma_-} & \\ V_+ & & V & & V_- \\ & \searrow \pi_+ & \downarrow \pi & \swarrow \pi_- & \\ & & C & & \end{array}$$

where σ_{\pm} are equivariant birational morphisms. Hence σ_{\pm} are equivariant affine modifications [16, Theorem 1.1]. More precisely the following result holds.

Proposition 4.1. *V can be obtained from V_{\pm} by blowing up a \mathbb{C}^* -invariant subscheme and deleting the proper transform of a \mathbb{C}^* -invariant divisor D^{\pm} on V_{\pm} , which contains the fixed point curve $\iota_{\pm}(C) \subseteq V_{\pm}$.*

Proof. Let us show this for V_+ , the proof for V_- being similar. Choose a system of homogeneous generators a_1, \dots, a_n of the finitely generated A_0 -subalgebra $A_{\leq 0}$ and let $f_0 \in A_+$ be a non-zero element of degree $m = -\min_i \deg a_i$. Letting $f_i := a_i f_0$ for

$i = 1, \dots, n$ we obtain

$$A = A_{\geq 0} \left[\frac{f_1}{f_0}, \dots, \frac{f_n}{f_0} \right] = A_{\geq 0} \left[\frac{I}{f_0} \right] := \left\{ \frac{x_k}{f_0^k} \mid x_k \in I^k, k \geq 0 \right\},$$

where I is the graded ideal of $A_{\geq 0}$ generated by f_0, \dots, f_n . Thus $V = \text{Spec } A$ is obtained by blowing up $V_+ = \text{Spec } A_{\geq 0}$ with center I and deleting the proper transform of the \mathbb{C}^* -invariant divisor $\text{div } f_0$ on V_+ . As this divisor contains $\iota_+(C)$, the result follows. □

For a more precise description of the affine modifications σ_{\pm} see Remark 4.20.

4.2. The Dolgachev-Pinkham-Demazure construction is still available in the hyperbolic case. In [10, Theorem 3.5] it is done under the additional assumption that $A_{-n} \otimes A_n \rightarrow A_0$ is an isomorphism for all n . Here we generalize the construction in order to make it work for any hyperbolic \mathbb{C}^* -surface.

Let D_+, D_- be \mathbb{Q} -divisors on the smooth affine curve $C := \text{Spec } A_0$. For $n \geq 0$ we consider the A_0 -submodules

$$A_{-n} := H^0(C, \mathcal{O}_C(\lfloor nD_- \rfloor)) \cdot u^{-n} \quad \text{and} \quad A_n := H^0(C, \mathcal{O}_C(\lfloor nD_+ \rfloor)) \cdot u^n$$

of $\text{Frac}(A_0)[u, u^{-1}]$, where u is an indeterminate of degree 1. If $D_+ + D_- \leq 0$ then for $n \geq m \geq 0$ we have

$$\lfloor nD_+ \rfloor + \lfloor mD_- \rfloor \leq \lfloor (n - m)D_+ \rfloor,$$

whence $A_n \cdot A_{-m} \subseteq A_{n-m}$. Similarly, for $0 \leq n \leq m$ we have $A_n \cdot A_{-m} \subseteq A_{n-m}$. Thus

$$A := A_0[D_+, D_-] := \bigoplus_{n \in \mathbb{Z}} A_n$$

is a finitely generated A_0 -subalgebra of $\text{Frac}(A_0)[u, u^{-1}]$ with $A_{\geq 0} = A_0[D_+]$ and $A_{\leq 0} \cong A_0[D_-]$. The grading on A defines a natural hyperbolic \mathbb{C}^* -action on the surface $V := \text{Spec } A$. The latter surface is normal as so are the algebras $A_0[D_+]$ and $A_0[D_-]$ (see Lemma 1.1 and Corollary 3.8(b)). Conversely, we have the following theorem.

Theorem 4.3. *If $C = \text{Spec } A_0$ is a smooth affine curve and $A = \bigoplus_{i \in \mathbb{Z}} A_i$ is a normal graded finitely generated domain of dimension 2 with $A_{\pm} \neq 0$, then the following hold.*

(a) *A is isomorphic to $A_0[D_+, D_-]$, where D_+, D_- are \mathbb{Q} -divisors on C satisfying $D_+ + D_- \leq 0$. More precisely, if $u \in \text{Frac}(A_0) \cdot A_1$ and if the divisors D_+, D_- on C are defined by*

$$(5) \quad \pi_+^*(D_+) = \text{div}(u) - \iota_+(C) \quad \text{and} \quad \pi_-^*(D_-) = \text{div}(u^{-1}) - \iota_-(C),$$

where π_{\pm} are as in diagram (4) above and $\iota_{\pm}: C \hookrightarrow V_{\pm}$ are the natural embeddings, then $D_+ + D_- \leq 0$ and $A \cong A[D_+, D_-]$.

(b) $A_0[D_+, D_-] \cong A_0[D'_+, D'_-]$ as graded A_0 -algebras if and only if, for a rational function $\varphi \in \text{Frac}(A_0)$, one has

$$D'_+ = D_+ + \text{div } \varphi \quad \text{and} \quad D'_- = D_- - \text{div } \varphi.$$

Proof. (a) By Theorem 3.2 and its proof we have equalities

$$A_{\geq 0} = A_0[D_+] \quad \text{and} \quad A_{\leq 0} = A_0[D_-]$$

as subalgebras of $\text{Frac}(A_0)[u, u^{-1}]$, whence $A = A_0[D_+, D_-]$. It remains to show that $D_+ + D_- \leq 0$. Applying in (5) the functors σ_+^* and σ_-^* respectively, we obtain

$$\pi^*(D_+) = \text{div}(u) - \sigma_+^* \iota_+^*(C) \quad \text{and} \quad \pi^*(D_-) = \text{div}(u^{-1}) - \sigma_-^* \iota_-^*(C).$$

Taking the sum of these equalities yields $\pi^*(D_+ + D_-) = -(\sigma_+^* \iota_+^*(C) + \sigma_-^* \iota_-^*(C))$, whence $D_+ + D_- \leq 0$, as required. Finally (b) follows from Theorem 3.2(b) and its proof. □

Consequently, if $A_0 = \mathbb{C}[t]$ then A admits a unique presentation $A = A_0[D_+, D_-]$ with $D_+ = \{D_+\}$ and $D_+ + D_- \leq 0$.

It follows from Theorem 4.3 that outside $|D_+| \cup |D_-|$, the map $\pi: V \rightarrow C$ is a locally trivial principal \mathbb{C}^* -bundle. More generally, the Dolgachev-Pinkham-Demazure construction shows the following result (cf. [1], [12, Proposition 1.11]).

Corollary 4.4. *In all three cases, outside of a finite subset of the curve C the projection $\pi: V^* \rightarrow C$ and $\pi: V \rightarrow C$, respectively, defines a locally trivial fiber bundle. This is a principal \mathbb{C}^* -bundle in the elliptic and hyperbolic cases, and a line bundle in the parabolic case.*

Note that if $u \in A_1 \cup A_{-1}$ is a non-zero element then its restriction to a general fiber of π gives a fiber coordinate and so a trivialization over a Zariski open subset of C .

REMARK 4.5. *The algebra $A = A_0[D_+, D_-]$ contains an invertible element of degree $d > 0$ if and only if $D_- = -D_+$ and dD_+ is a principal divisor on $C = \text{Spec } A_0$. In fact, if $v \in A$ is an invertible element of degree $d > 0$ then we can write*

$$v = fu^d \in A_d \quad \text{and} \quad v^{-1} = f^{-1}u^{-d} \in A_{-d},$$

where $f \in \text{Frac}(A_0)$ satisfies

$$\text{div}(f) + dD_+ \geq 0 \quad \text{and} \quad -\text{div}(f) + dD_- \geq 0.$$

Thus $0 \geq D_+ + D_- \geq 0$, whence $D_- = -D_+$. Since $A_d = vA_0$ it also follows that dD_+ is principal. Conversely, if $D_+ = -D_-$ and if dD_+ is principal, then $vA_0 = A_d$ is free over A_0 and $v = fu^d$ with $\operatorname{div} f + dD_+ = 0$ by Remark 3.7. Hence also $\operatorname{div} f^{-1} + dD_- = 0$, so $f^{-1}u^{-d} \in A$ and $v = fu^d$ is a unit in A .

The following analogue of Proposition 3.9 holds with a similar proof.

Lemma 4.6. *Let $C = \operatorname{Spec} A_0$ be a smooth affine curve with function field $K_0 = \operatorname{Frac}(A_0)$. If a graded 2-dimensional domain $B \subseteq K_0[u, u^{-1}]$ is represented as*

$$B = A_0[h_1u^{-n_1}, \dots, h_ku^{-n_k}, f_1u^{m_1}, \dots, f_nu^{m_n}] \quad (\text{where } n_i, m_j > 0 \ \forall i, j)$$

with $h_1, \dots, h_k, f_1, \dots, f_n \in K_0$ and $B_0 = A_0$, then its normalization $A = B_{\text{norm}}$ coincides (as a graded A_0 -subalgebra of $K_0[u, u^{-1}]$) with $A_0[D_+, D_-]$, where

$$D_- = - \min_{1 \leq i \leq k} \frac{\operatorname{div} h_i}{n_i} \quad \text{and} \quad D_+ = - \min_{1 \leq j \leq n} \frac{\operatorname{div} f_j}{m_j}.$$

We notice that the assumption $A_0 = B_0$ amounts to the inequalities

$$\frac{\operatorname{div} h_i}{n_i} + \frac{\operatorname{div} f_j}{m_j} \geq 0 \quad \forall i, j,$$

which in turn are equivalent to $D_+ + D_- \leq 0$.

The following lemma provides additional information in the case that $[D_{\pm}]$ and $d_{\pm}(A)D_{\pm}$ are principal divisors¹.

Lemma 4.7. *Let $A = \bigoplus_{i \in \mathbb{Z}} A_i = A_0[D_+, D_-] \subseteq \operatorname{Frac}(A_0)[u, u^{-1}]$, and let $d_{\pm} = d_{\pm}(A)$ be the minimal positive integer such that the divisor $d_{\pm}D_{\pm}$ is integral. If $A_{\pm 1} = u_{\pm} \cdot A_0$, $A_{\pm d_{\pm}} = v_{\pm} \cdot A_0$ and*

$$u_+u_- = Q, \quad u_{\pm}^{d_{\pm}} = P_{\pm}v_{\pm}$$

for some elements $Q, P_{\pm} \in A_0$, then

$$(6) \quad D_+ = \frac{\operatorname{div} P_+}{d_+} + D_0 \quad \text{and} \quad D_- = \frac{\operatorname{div} P_-}{d_-} - D_0 - \operatorname{div} Q,$$

where D_0 is the integral divisor $D_0 = \operatorname{div}(u/u_+)$ on $C = \operatorname{Spec} A_0$. Consequently,

$$(7) \quad \frac{\operatorname{div} P_+}{d_+} + \frac{\operatorname{div} P_-}{d_-} \leq \operatorname{div} Q.$$

¹or, equivalently, that $A_{\pm 1}$ and $A_{\pm d_{\pm}}$ are free A_0 -modules of rank 1.

Furthermore, P_+ and P_- are uniquely determined by D_+ and D_- through

$$(8) \quad \{D_+\} = \frac{\operatorname{div} P_+}{d_+} \quad \text{and} \quad \{D_-\} = \frac{\operatorname{div} P_-}{d_-}.$$

Proof. We have $u^{d_+} = P_+ \cdot (u/u_+)^{d_+} v_+$ and $u^{-d_-} = P_- \cdot (u/u_+)^{-d_-} Q^{-d_-} v_-$ and so by Remark 3.7

$$D_+ = \frac{\operatorname{div}(P_+ \cdot (u/u_+)^{d_+})}{d_+} = \frac{\operatorname{div} P_+}{d_+} + D_0, \quad \text{and}$$

$$D_- = \frac{\operatorname{div}(P_- \cdot (u/u_+)^{-d_-} Q^{-d_-})}{d_-} = \frac{\operatorname{div} P_-}{d_-} - D_0 - \operatorname{div} Q.$$

Now (7) follows from the inequality $D_+ + D_- \leq 0$. To show (8), after localizing A_0 we can assume that $P_\pm = S_\pm^{d_\pm} T_\pm$, where $S_\pm, T_\pm \in A_0$ are elements with

$$\operatorname{div} S_\pm = \left\lfloor \frac{\operatorname{div} P_\pm}{d_\pm} \right\rfloor \quad \text{and} \quad \operatorname{div} T_\pm = \left\{ \frac{\operatorname{div} P_\pm}{d_\pm} \right\},$$

respectively. The relation $(u_\pm/S_\pm)^{d_\pm} = T_\pm v_\pm$ then shows that u_\pm/S_\pm is integral over A and so by the normality of A is contained in $A_{\pm 1}$. As u_\pm is a generator of $A_{\pm 1}$ this forces that $S_\pm \in A_0^\times$ are units, proving (8). \square

In many cases the surfaces $V = \operatorname{Spec} A_0[D_+, D_-]$ can be represented by explicit equations as follows.

Proposition 4.8. *With the assumptions as in Lemma 4.7 the following hold.*

(a) $A = A_0[D_+, D_-]$ is the normalization of the A_0 -algebra

$$(9) \quad B := A_0[u_-, v_+, v_-] / \left(u_-^{d_-} - v_- P_-, v_+^{d'_+} v_-^{d'_-} - P, v_+ u_-^{d_+} - Q_+ \right)$$

graded via $\deg u_- = -1, \deg v_\pm = \pm d_\pm$, where $k := \operatorname{gcd}(d_+, d_-), d'_\pm := d_\pm/k$ and

$$(10) \quad P := \frac{Q^{kd'_+ d'_-}}{P_+^{d'_-} P_-^{d'_+}} \in A_0, \quad Q_+ := \frac{Q^{d_+}}{P_+} \in A_0.$$

(b) $V = \operatorname{Spec} A$ is a cyclic branched covering of degree k of the normalization of the hypersurface $\{v_+^{d'_-} v_-^{d'_+} - P = 0\}$ in $C \times \mathbb{A}_C^2$.

(c) If $k = 1$ i.e., if d_+ and d_- are coprime and if v_+ is not invertible, then $V = \operatorname{Spec} A$ can be represented as the normalization of a hypersurface X in $A_C^3 = \operatorname{Spec} \mathbb{C}[s, v_+, v_-]$ with equation

$$q(s, v_+^{d_-} \cdot v_-^{d_+}) = 0,$$

where $q \in \mathbb{C}[s, t]$ is a suitable irreducible polynomial.

Proof. (a) First we note that A is integral over the subring $A_0[v_{\pm}]$. Indeed, if $w \in A_k$ with $k \neq 0$ then $w^{d_{\pm}} = av_{\pm}^k$ if $k > 0$ and $w^{d_{\pm}} = av_{\pm}^k$ if $k < 0$, where $a \in A_0$ (see Lemma 3.5). Since A and its subring $A_0[u_{\pm}, v_{\pm}]$ have the same field of fractions, it follows that A is the normalization of $A_0[u_{\pm}, v_{\pm}]$.

To find the relations between the generators of $A_0[u_{\pm}, v_{\pm}]$, note that $v_{\pm} = u_{\pm}^{d_{\pm}}/P_{\pm}$ and so

$$v_+^{d'_+} v_-^{d'_-} = \frac{u_+^{d_+ d'_+} u_-^{d_- d'_-}}{P_+^{d'_+} P_-^{d'_-}} = \frac{Q^{kd'_+ d'_-}}{P_+^{d'_+} P_-^{d'_-}} = P \in A_0.$$

Similarly

$$v_+ u_-^{d_+} = \frac{u_+^{d_+} u_-^{d_+}}{P_+} = \frac{Q^{d_+}}{P_+} = Q_+ \in A_0.$$

The general fibers of the natural map $\text{Spec } B \rightarrow C = \text{Spec } A_0$ are irreducible, and every fiber is 1-dimensional and in the closure of the generic fiber. Thus the surface $\text{Spec } B$ is irreducible, and (a) follows.

(b) Since $k = \text{gcd}(d_+, d_-)$, the ring $A_0[v_{\pm}]$ contains nonzero elements of degree k and is contained in the Veronese subring $A^{(k)}$ of A . Hence the fraction fields of both rings coincide. As A and then also $A^{(k)}$ is integral over $A_0[v_{\pm}]$ the normalization of $A_0[v_{\pm}]$ is just $A^{(k)}$. The cyclic group \mathbb{Z}_k acts on A via the \mathbb{C}^* -action with invariant ring $A^{(k)}$. Thus $V \rightarrow \text{Spec } A^{(k)}$ is a cyclic branched covering of degree k , and (b) follows.

(c) In case $k = 1$ the algebra $A = A^{(k)}$ is itself the normalization of the hypersurface $A_0[v_+, v_-]/(v_+^{d_+} v_-^{d_-} - P)$. Notice that P is non-constant as A is a domain and, by our assumption, the elements v_{\pm} are not invertible. For a general element s of A_0 the map $\varphi = (s, t)$ is a finite morphism of $C = \text{Spec } A_0$ onto a plane curve $\tilde{C} \subseteq \mathbb{A}_{\mathbb{C}}^2$ with an irreducible equation $q(s, t) = 0$, where $t := P = v_+^{d_+} v_-^{d_-} \in A_0$. This implies (c). \square

Remarks 4.9. 1. It is worthwhile mentioning how to get, under the assumptions as in (c), a representation $A \cong A_0[D_+, D_-]$ in terms of P in (10). Choose $p, q \in \mathbb{Z}$ with $|\frac{d_+ p}{d_- q}| = 1$ so that $u' := v_+^q v_-^p$ has degree 1. By an easy calculation $u'^{d_+} = v_+ P^p$ and $u'^{-d_-} = v_- / P^q$, whence by Remark 3.7 $A \cong A_0[D_+, D_-]$ with

$$D_+ = \frac{p}{d_+} \text{div } P, \quad D_- = -\frac{q}{d_-} \text{div } P, \quad \text{and} \quad D_+ + D_- = -\frac{\text{div } P}{d_+ d_-}.$$

2. In analogy with (c), any parabolic \mathbb{C}^* -surface $V = \text{Spec } A$ with $A = A_0[D]$, where $[D]$ and $d(A)D$ are principal divisors on $C = \text{Spec } A_0$, can be obtained as the normalization of a surface $u^d - tv = 0 = q(s, t)$ in $\mathbb{A}_{\mathbb{C}}^4 = \text{Spec } \mathbb{C}[s, t, u, v]$ graded via $\text{deg } s = \text{deg } t = 0, \text{deg } u = 1, \text{deg } v = d$, where $q \in \mathbb{C}[s, t]$ is a suitable irreducible polynomial (see also Remark 3.12(2)).

The special case $d_+ = 1$ leads to the following example.

EXAMPLE 4.10 (cf. [4, Example 4.11]). For a unitary polynomial $P \in \mathbb{C}[t]$, we let $A = A_{d,P} = B_{\text{norm}}$ be the normalization of the \mathbb{C} -algebra

$$B = B_{d,P} := \mathbb{C}[t, u, v]/(u^d v - P(t))$$

graded via $\deg t = 0$, $\deg u = 1$, $\deg v = -d$ so that the normal affine surface $V := \text{Spec } A$ is equipped with a hyperbolic \mathbb{C}^* -action. As $B \cong A_0[u, Pu^{-d}]$ we can write

$$A \cong A_0[D_+, D_-], \quad \text{where} \quad D_+ = 0 \quad \text{and} \quad D_- = -\frac{\text{div } P}{d}$$

(see Lemma 4.6). We can recover P_{\pm} and Q in Lemma 4.7 as follows. By the construction given there $P_+ = 1$ and by (8) $\{D_-\} = \text{div}(P_-)/d_-$. This gives

$$(11) \quad \text{div } P_- = d_- \left\{ -\frac{\text{div } P}{d} \right\} \quad \text{and} \quad \text{div } Q = \frac{\text{div } P}{d} + \frac{\text{div } P_-}{d_-}$$

(see (6)). In particular,

$$A_{\geq 0} \cong A_0[u] \cong \mathbb{C}[t, u] \quad \text{and} \quad A_{\leq 0} \cong A_{d_-, P_-}^+$$

(cf. Example 3.10) as graded A_0 -algebras, where for the second isomorphism we have to reverse the grading of one of the rings.

This discussion provides the following characterization of the algebras $A_{d,P}$.

Proposition 4.11. *If $A = A_0[D_+, D_-]$, where $A_0 \cong \mathbb{C}[t]$ and D_+, D_- are \mathbb{Q} -divisors on $\mathbb{A}_{\mathbb{C}}^1$ with $D_+ + D_- \leq 0$, then the following conditions are equivalent.*

- (i) D_+ is integral i.e., $\{D_+\} = 0$.
- (ii) $A_{\geq 0} \cong A_0[u]$ as graded A_0 -algebras, where $\deg u = 1$.
- (iii) $A \cong A_{d,P}$ as graded A_0 -algebras, where $D_+ + D_- = -\text{div}(P)/d$.

Next we study the effect of base change to the Dolgachev-Pinkham-Demazure representation.

Proposition 4.12. *Let $C = \text{Spec } A_0$ be an affine curve with function field $K_0 = \text{Frac}(A_0)$ and let*

$$A := A_0[D_+, D_-] \subseteq K_0[u, u^{-1}],$$

where D_{\pm} are \mathbb{Q} -divisors on C satisfying $D_+ + D_- \leq 0$. Let L be the field $L := \text{Frac}(A)[\sqrt[d]{tu^b}]$, where $t \in K_0$ and $b \geq 0$, $d > 0$. If A' is the normalization of A in L then the following hold.

1. A'_0 is the normalization of A_0 in $K_0[s]$ with $s := \sqrt[k]{t}$, where $k := \gcd(b, d)$.
2. $A' \cong A'_0[D'_+, D'_-]$ with

$$D'_\pm := \frac{k}{d} (p^*(D_\pm) \pm \beta \operatorname{div} s) ,$$

where $p: C' := \operatorname{Spec} A'_0 \rightarrow C$ is the projection and β is defined by $\beta b \equiv k \pmod{d}$.

Proof. We let $b = b'k$ and $d = d'k$. The normalization A' admits a natural $(1/d)$ -grading, and the element $u^* := \sqrt[d]{tu^b}$ is of degree $b/d = b'/d'$. If we write $k = \beta b + \delta d$, then the element $u' := u^{*\beta} u^\delta \in \operatorname{Frac}(A')$ has minimal possible positive degree $1/d'$. Thus

$$A' \subseteq \operatorname{Frac}(A'_0)[u', u'^{-1}].$$

To compute A'_0 , we note that $u^{*n} u^{-m}$ with $n, m \in \mathbb{N}$ has degree 0 if and only if $nb'/d' = m$. In particular, $n = n'd'$ is an integer multiple of d' . Thus $K'_0 := \operatorname{Frac} A'_0$ is generated over K_0 by $u^{*d'} u^{-b'} = t^{1/k}$ (i.e., $n' = 1$). As d' and k are coprime, it follows that $s = \sqrt[k]{t}$ also belongs to K'_0 and that this field is actually generated by s over K_0 , proving (1).

After localizing A_0 we may assume that there is an element $v_+ \in A$ of degree $d_+ = d(A_{\geq 0})$ with $A_{d_+} = v_+ A_0$ (see 3.6). We claim that then $A'_{sd_+} = v_+^s A'_0$ for all $s \geq 0$. If not, then for some $s > 0$ and some non-unit $x \in A'_0$ the element v_+^s/x belongs to A' , so it is integral over A and there is an equation

$$\frac{v_+^{sm}}{x^m} + a_1 \frac{v_+^{s(m-1)}}{x^{m-1}} + \dots + a_m = 0 ,$$

where $m \geq 0$ and $a_i \in A_{i s d_+}$. Thus $a_i = v_+^{s i} q_i$ for some elements $q_i \in A_0$, whence dividing the equation above by v_+^{sm} we obtain that

$$\frac{1}{x^m} + q_1 \frac{1}{x^{m-1}} + \dots + q_m = 0 .$$

As A'_0 is integrally closed this is only possible if $x \in A'_0$ contradicting the choice of x .

Thus $v = v_+$ is an element satisfying the assumptions of Remark 3.7, and we compute with it the divisor D'_+ as follows (the calculation for D'_- is analogous). If we consider the new grading of A' by assigning to u' the degree 1, then v_+^k becomes an element of degree dd_+ . Moreover, if $u^{d_+} = P_+ v_+$ with $P_+ \in K_0$ then by Remark 3.7 $D_+ = (\operatorname{div}(P_+))/d_+$. Since

$$\begin{aligned} u'^{dd_+} &= (u^{*\beta} u^\delta)^{dd_+} = (tu^b)^{\beta d_+} u^{\delta d d_+} \\ &= t^{\beta d_+} u^{d_+(\beta b + \delta d)} = t^{\beta d_+} u^{d_+ k} \\ &= t^{\beta d_+} P_+^k v_+^k \end{aligned}$$

we obtain again by Remark 3.7 that on C'

$$D'_+ = \frac{\operatorname{div}(t^{\beta d_+} P_+^k)}{dd_+} = \frac{\beta}{d} \operatorname{div}(t) + \frac{k}{d} p^*(D_+),$$

and (2) follows. □

Let us consider the following important example.

EXAMPLE 4.13. With $A_0 := \mathbb{C}[t]$, suppose that $D_+ = -(e/d)[0]$ and that D_- is any \mathbb{Q} -divisor on $\mathbb{A}_{\mathbb{C}}^1 = \operatorname{Spec} A_0$ satisfying $D_+ + D_- \leq 0$. Applying Proposition 4.12 to $s := \sqrt[d]{t}$ (i.e. $b = 0$) we get that the normalization of $A := A_0[D_+, D_-]$ in the field $L := \operatorname{Frac}(A)[s]$ is given by

$$A' = A'_0[-e[0], D'_-] \subseteq \mathbb{C}(s)[u, u^{-1}],$$

where $A'_0 = \mathbb{C}[s]$ and $D'_- = p^*(D_-)$ (as before, $p: \operatorname{Spec} \mathbb{C}[s] \rightarrow \operatorname{Spec} \mathbb{C}[t]$ denotes the projection $s \mapsto s^d$). The divisor $D'_+ = -e[0]$ being integral we have

$$A' \cong A'_0[0, D'_+ + D'_-] \subseteq \mathbb{C}(s)[\tilde{u}, \tilde{u}^{-1}],$$

where $\tilde{u} := s^e u$.

More concretely, if $k := d_-(A)$, $e := k \cdot D_-(0)$ and if we choose a unitary polynomial $Q \in \mathbb{C}[t]$ with $D_- = -(\operatorname{div}(Qt^e))/k$ then $D'_+ + D'_- = -\{\operatorname{div}(Q(s^d)s^{ke+de})\}/k$. By Example 4.10 $A' \cong A_{k,P}$ is the normalization of

$$(12) \quad B_{k,P} = \mathbb{C}[s, \tilde{u}, v] / (\tilde{u}^k v - P(s)), \quad \text{where } P(s) := Q(s^d)s^{ke+de}.$$

The field extension $\operatorname{Frac}(A) \subseteq \operatorname{Frac}(A)[s]$ is Galois with Galois group $\mathbb{Z}_d = \langle \zeta \rangle$, where $\zeta \cdot s = \zeta s$. Thus

$$A \cong (A_{k,P})^{\mathbb{Z}_d},$$

and the action of ζ on $\tilde{u} = s^e u$ is given by $\zeta \cdot \tilde{u} = \zeta^e \tilde{u}$. Therefore, the group \mathbb{Z}_d acts on $A_{k,P}$ via

$$(13) \quad \zeta \cdot s = \zeta s, \quad \zeta \cdot \tilde{u} = \zeta^e \tilde{u} \quad \text{and} \quad \zeta \cdot v = v.$$

Thus we obtain the following characterization.

Proposition 4.14. *For an algebra $A = A_0[D_+, D_-]$ with $A_0 = \mathbb{C}[s]$ the following conditions are equivalent.*

- (i) $\{-D_+\} = (e/d)[0]$, where $0 \leq e < d$ and $\operatorname{gcd}(e, d) = 1$.

(ii) $A \cong (A_{k,P})^{\mathbb{Z}_d}$, where $A_{k,P}$ is the normalization of $B_{k,P}$ in (12) and where $\mathbb{Z}_d = \langle \zeta \rangle$ acts via the formulas in (13).

Like in the parabolic case V may possess at most cyclic quotient singularities. The type of quotient singularities is determined from the divisors D_+, D_- by the following result. As before, $C = \text{Spec } A_0$ is a smooth affine curve with function field $K_0 = \text{Frac } A_0$ and $A := A_0[D_+, D_-]$ with \mathbb{Q} -divisors D_+ and D_- on C . Denote $\pi: V = \text{Spec } A \rightarrow C$ the canonical projection.

Theorem 4.15. (a) *The set of singular points $\text{Sing } V$ is contained in the fixed point set F which is the zero locus $F = V(I)$ of the ideal $I := A_+A + A_-A$ of A .*
 (b) *The map $\pi|_F: F \rightarrow C$ is injective, and $\pi(F) = \{a \in C \mid D_+(a) + D_-(a) < 0\}$.*
 (c) *For a point $a' \in F$ with image $a := \pi(a') \in C$ we write*

$$D_+(a) = -\frac{e_+}{m_+} \quad \text{and} \quad D_-(a) = \frac{e_-}{m_-}$$

with the convention that

$$m_+ > 0, \quad m_- < 0, \quad \gcd(e_+, m_+) = \gcd(e_-, m_-) = 1 \quad \text{and} \\ m_+ = 1 \quad \text{if} \quad D_+(a) = 0, \quad m_- = -1 \quad \text{if} \quad D_-(a) = 0.$$

Let $p, q \in \mathbb{Z}$ with $\left| \frac{p}{q} \frac{e_+}{m_+} \right| = 1$. Then $a' \in F$ is a quotient singularity of type

$$(\Delta(a), e), \quad \text{where} \quad \Delta(a) := -\left| \frac{e_+}{m_+} \frac{e_-}{m_-} \right| \quad \text{and} \quad e \equiv \left| \frac{p}{q} \frac{e_-}{m_-} \right| \pmod{\Delta(a)}.$$

In particular, $a' \in \text{Sing } V$ if and only if $\Delta(a) \neq 1$.

Proof. As in the proof of Proposition 3.8(b) we can reduce the statement to the case that $A_0 = \mathbb{C}[t]$ and $|D_+| \cup |D_-|$ is contained in the origin, so that $D_{\pm} = \mp e_{\pm}/m_{\pm}[0]$.

(a) The set $\text{Sing } V$ is finite and invariant under the \mathbb{C}^* -action. Hence it is contained in the fixed point set F .
 (b) The map $A_0 \rightarrow A/I$ is obviously surjective. Thus

$$\pi|_F: F = \text{Spec} \left(\frac{A}{I} \right) \rightarrow C$$

is a closed embedding. Moreover, $F = \emptyset$ if and only if $1 \in I$ if and only if $1 = a_+a_-$ for some homogeneous elements of A of opposite degrees, and the latter happens if and only if $D_+ + D_- = 0$ by Remark 4.5.

(c) Notice first that the elements

$$v_+ := t^{e_+} u^{m_+}, \quad v_- := t^{e_-} u^{m_-} \in K_0[u, u^{-1}]$$

belong to A . Indeed, by definition, the ideal $I+tA$ of A (this is just the maximal ideal of the point $a' \in F$) is generated by the monomials $t^e u^m$ with $(e, m) \in \mathbb{Z} \times \mathbb{Z}$, where $(e, m) \neq (0, 0)$ and

$$e + mD_+(0) \geq 0 \quad \text{if } m \geq 0, \quad e - mD_-(0) \geq 0 \quad \text{if } m \leq 0.$$

In other words, (e, m) is an element of the cone $\Gamma := C((e_+, m_+), (e_-, m_-))$ generated by the vectors (e_\pm, m_\pm) in the plane. Hence A is a toric algebra generated by the semigroup $\Gamma \cap \mathbb{Z}^2$, and so is a quotient $A_{d,e}$ for some $d, e \geq 0$ (see Lemma 2.4). To determine d, e , we must find a basis of \mathbb{Z}^2 such that (e_+, m_+) is one of the basis vectors. This is done as follows.

If we choose $p, q \in \mathbb{Z}$ with $\begin{vmatrix} p & e_+ \\ q & m_+ \end{vmatrix} = 1$, then the vectors $\tilde{e}_1 := (e_+, m_+)$ and $\tilde{e}_2 := (p, q)$ form a basis of \mathbb{Z}^2 , and

$$(e_-, m_-) = \Delta' \tilde{e}_1 + \Delta \tilde{e}_2, \quad \text{where } \Delta' := \begin{vmatrix} p & e_- \\ q & m_- \end{vmatrix} \text{ and } \Delta := \Delta(0).$$

As \tilde{e}_1 and (e_-, m_-) form a basis of the cone Γ , it follows from Lemma 2.4 that A has a quotient singularity of type (Δ, e) , where $0 \leq e < \Delta$ and $e \equiv \begin{vmatrix} p & e_- \\ q & m_- \end{vmatrix} \pmod{\Delta}$. Note that Δ and Δ' are coprime since so are e_- and m_- .

The determinant Δ has always positive sign as

$$(14) \quad D_+(0) + D_-(0) = \frac{\Delta}{m_+ m_-} \leq 0 \quad \text{and} \quad m_+ > 0, \quad m_- < 0,$$

and so (c) follows. □

Corollary 4.16. *If $A_{d,P}$ is the normalization of the algebra*

$$B_{d,P} = \mathbb{C}[t, u, v] / (u^d v - P(t)),$$

where $P(t) = \prod_{i=1}^k (t - a_i)^{r_i}$ with $a_i \neq a_j$ for $i \neq j$ (see Example 4.10), then the singular points of the surface $V_{d,P} = \text{Spec } A_{d,P}$ are the points $a'_i \in V_{d,P}$ ($1 \leq i \leq k$), where $t = a_i, u = v = 0$ and $r_i \nmid d$.

Proof. It was shown in Example 4.10 that $D_+ = 0$ and $D_-(a_i) = -r_i/d$. Therefore, $\Delta(a_i) = e_+ > 1$ if and only if $r_i \nmid d$, which implies our assertion. □

In the sequel we use the following notation.

DEFINITION 4.17. Let $O = \mathbb{C}^*_z$ be the orbit through a point $z \in V \setminus F$. Following [12] we say that O is of type (d, q) if d is the order of the stabilizer

$$\text{Stab}_z = \ker(\mathbb{C}^* \rightarrow \text{Aut } O) \subseteq \mathbb{C}^*, \quad \text{so that } \text{Stab}_z = \langle \zeta \rangle \cong \mathbb{Z}_d,$$

and q ($0 \leq q < d$) is determined from the tangent representation of Stab_z on the tangent plane $T_z V$ via pseudo-reflections

$$\text{Stab}_z \ni \zeta \longmapsto \begin{pmatrix} 1 & 0 \\ 0 & \zeta^q \end{pmatrix}.$$

The orbit O is called *principal* if $d = 1$ and *exceptional* otherwise (see [12]–[14] for a detailed description of the structure of V near the exceptional orbits).

In the next result we will characterize the orbit types of the surface $V = \text{Spec } A$ with $A := A_0[D_+, D_-]$, where D_+ and D_- are \mathbb{Q} -divisors on the smooth affine curve $C = \text{Spec } A_0$. Let $\pi: V \rightarrow C$ denote the projection. To examine the orbits over a point $a \in C$, we write

$$D_+(a) = -\frac{e_+}{m_+} \quad \text{and} \quad D_-(a) = \frac{e_-}{m_-}$$

with the conventions as in Theorem 4.15(c). Let q_+ be defined by $0 \leq q_+ < m_+$ and $q_+ e_+ \equiv -1 \pmod{m_+}$, and similarly q_- by $0 \leq q_- < -m_-$ and $q_- e_- \equiv 1 \pmod{m_-}$. With this notation the following result holds.

Theorem 4.18. *The exceptional orbits of V are located over $|D_+| \cup |D_-|$. The orbits over a given point $a \in |D_+| \cup |D_-|$ are as follows.*

- (a) *If $D_+(a) + D_-(a) = 0$ then $\pi^*(a) = m_+ O$ consists of one orbit O of type (m_+, q_+) with multiplicity m_+ . Moreover, O appears with coefficient $-e_+$ in $\text{div } u$.*
- (b) *If $D_+(a) + D_-(a) < 0$ then $\pi^{-1}(a)$ contains two orbits O^+ and O^- of types (m_+, q_+) and $(-m_-, q_-)$, respectively. Their closures \bar{O}^\pm intersect in the unique fixed point of the fiber, and $\pi^*(a) = m_+ \bar{O}^+ - m_- \bar{O}^-$. Moreover, \bar{O}^\pm appears with multiplicity $\mp e_\pm$ in $\text{div } u$.*

Proof. With the same reasoning as in the proof of Proposition 3.8(b) it is sufficient to treat the case where $A_0 = \mathbb{C}[t]$ and D_\pm are supported on $a = 0 \in \mathbb{A}_\mathbb{C}^1$, i.e. $D_\pm = \mp e_\pm / m_\pm [0]$. Note that in this case $m_+ = d(A_{\geq 0})$ and $m_- = -d(A_{\leq 0})$.

(a) If $D_+ + D_- = 0$, so that $e_+ = -e_- =: e$ and $m_+ = -m_- =: m$ then A is the semigroup algebra $\mathbb{C}[\Gamma \cap \mathbb{Z}^2]$, where Γ is the cone generated over \mathbb{R} by the vectors $\pm(e, m)$ and $(1, 0)$. Obviously Γ is the half space of all $(x, y) \in \mathbb{R}^2$ satisfying $mx - ey \geq 0$. If we choose $p, q \in \mathbb{Z}$ with $|\begin{smallmatrix} p & e \\ q & m \end{smallmatrix}| = 1$ then the vectors (p, q) and (e, m) form a basis of \mathbb{Z}^2 , and (p, q) lies in the half space Γ . Thus

$$\Gamma \cap \mathbb{Z}^2 = \mathbb{Z} \cdot (e, m) + \mathbb{N} \cdot (p, q),$$

and so A is the algebra of Laurent polynomials

$$(15) \quad A = \mathbb{C}[x, x^{-1}, y], \quad \text{where} \quad x := t^e u^m \in A_m \quad \text{and} \quad y := t^p u^q \in A_q.$$

Clearly then

$$(16) \quad t = x^{-q}y^m \quad \text{and} \quad u = x^p y^{-e}.$$

The action of \mathbb{C}^* is given by $\lambda \cdot x = \lambda^m x$ and $\lambda \cdot y = \lambda^q y$, whence there is only one orbit O over $t = 0$, and it is given by the equation $y = 0$. By (16) we have

$$\pi^*(0) = \text{div } t = m \cdot O \quad \text{and} \quad \text{div } u = -e \cdot O.$$

The stabilizer of any point of O is the group $E_m \subseteq \mathbb{C}^*$ of m -th roots of unity, and the type of the orbit is $(m, q) = (m_+, q_+)$, as required in (a).

(b) Let now $D_+ + D_- < 0$. Consider a generator $v_{\pm} = t^{e_{\pm}} u^{m_{\pm}}$ of $A_{m_{\pm}}$ as A_0 -module (cf. the proof of Theorem 4.15(c)). The localization $A_{v_{\pm}} = A[t^{-e_{\pm}} u^{-m_{\pm}}]$ is the subring $A_0[D_+, -D'_-]$ of $\text{Frac}(A_0)[u, u^{-1}]$ with $D'_- := \min(D_-, -D_+)$ (see Lemma 4.6). As $D_+ + D_- \leq 0$ we have $D'_- = -D_+$, so by (a) the open subset $\text{Spec } A_{v_+}$ of V contains an orbit O^+ of type (m_+, q_+) , and it has multiplicities m_+ and $-e_+$ in $\pi^*(0)$ and $\text{div } u$, respectively. Similarly, $\text{Spec } A_{v_-}$ contains an orbit O^- of type $(-m_-, q_-)$, which has multiplicities $-m_-$ and e_- in $\pi^*(0)$ and $\text{div } u$, respectively. We have $\text{div}(v_+ v_-) = \Delta \cdot (\bar{O}^+ + \bar{O}^-)$, where by our assumption $\Delta = m_+ m_- (D_+(0) + D_-(0)) > 0$ (see (14)). Thus the fiber of π over $t = 0$ can be given by $v_+ \cdot v_- = 0$, where the functions v_+, v_- vanish on \bar{O}^- and \bar{O}^+ , respectively. The intersection $\bar{O}^+ \cap \bar{O}^-$ is given by $v_+ = v_- = 0$, and so is the unique fixed point of the fiber. □

EXAMPLE 4.19. In the example of the algebra $A = A_{d,P}$ treated in Corollary 4.16 we have $D_+ = 0$ and $D_- = -\text{div}(P)/d = \sum_i -(r_i/d)[a_i]$ (see Example 4.10). The exceptional orbits are located over the points $a_i \in \mathbb{A}_{\mathbb{C}}^1$, and $\pi^{-1}(a_i) = O_i^+ \cup \{a'_i\} \cup O_i^-$, where a'_i is the unique fixed point of the fiber (located over the point $(0, 0, a_i)$ of $\text{Spec } B_{d,P} \subseteq \mathbb{C}^3$). Applying Theorem 4.18, the orbit O_i^+ is principal, and if we write $r_i/d = e_i/m_i$ with $\text{gcd}(e_i, m_i) = 1$ then O_i^- is of type (m_i, q_i) , where

$$q_i e_i \equiv -1 \pmod{m_i} \quad \text{with} \quad 0 \leq q_i < m_i.$$

REMARK 4.20. We can now precise the character of the affine modifications $\sigma_{\pm}: V \rightarrow V_{\pm}$ as in Proposition 4.1. Doing this locally we assume first that $A_0 = \mathbb{C}[t]$ and D_{\pm} is supported on $a = 0 \in \mathbb{A}_{\mathbb{C}}^1$. If $D_+ + D_- = 0$ then $A = A_{\geq 0}[v_{\pm}^{-1}] = (A_{\geq 0})_{v_{\pm}}$, whence $\sigma_+: V \rightarrow V_+$ is an open embedding and $V_+ \setminus V$ is the divisor $\text{div } v_+ = m_+ \iota_+(C)$. In case $D_+ + D_- < 0$, letting in the proof of Proposition 4.1 $f_0 := v_+^{-m_-}$, we obtain that $\sigma_+: V \rightarrow V_+$ consists in blowing up a graded ideal $I \subseteq (t, v_+)$ of the algebra $A_{\geq 0}$ supported at a fixed point and deleting the proper transform of the divisor $\text{div } v_+ = m_+ \iota_+(C)$. The exceptional curve in V is the orbit closure $\bar{O}^- = \{v_+ = 0\}$.

Globalizing we see that $\sigma_{\pm}: V \rightarrow V_{\pm}$ blows up a graded ideal with support at the fixed points $b'_1, \dots, b'_l \in \iota_{\pm}(C)$ over the points $b_i := \pi_{\pm}(b'_i) \in C$ with $D_+(b_i) +$

$D_-(b_i) < 0$, and deleting the proper transform of the fixed point curve $\iota_{\pm}(C) \subseteq V_{\pm}$. Moreover the exceptional set of σ_{\pm} is $\bar{O}_1^{\mp} \cup \dots \cup \bar{O}_l^{\mp}$.

4.21. We let as before $C = \text{Spec } A_0$ be a smooth affine curve with function field $K_0 = \text{Frac } A_0$, and we let D_+, D_- be \mathbb{Q} -divisors on C . In what follows we compute the Picard group and the divisor class group of $A := A_0[D_+, D_-]$ (see also [18, Thm. 5.1] and [26, Cor. 1.7] for the elliptic case). We denote by a_1, \dots, a_k the points in C for which $D_+(a) = -D_-(a) \neq 0$, and we let $b_1, \dots, b_l \in C$ be the points with $D_+(b) + D_-(b) < 0$. Let us write

$$D_{\pm}(a_i) = \mp \frac{e_i}{m_i}, \quad D_+(b_j) = -\frac{e_j^+}{m_j^+} \quad \text{and} \quad D_-(b_j) = \frac{e_j^-}{m_j^-}$$

with the conventions as in Theorem 4.15. If $\pi: V := \text{Spec } A \rightarrow C$ denotes the canonical map then the preimage $\pi^{-1}(a_i)$ consists of only one orbit O_i , and $\pi^{-1}(b_j)$ consists of two orbit closures $\bar{O}_j^+ \cup \bar{O}_j^-$, so that

$$(17) \quad \pi^*(a_i) = m_i O_i \quad \text{and} \quad \pi^*(b_j) = m_j^+ \bar{O}_j^+ - m_j^- \bar{O}_j^-$$

as divisors on V , see Theorem 4.18.

Theorem 4.22. *The divisor class group $\text{Cl } A$ of A is the group*

$$\pi^*(\text{Cl } A_0) \oplus \bigoplus_{i=1}^k \mathbb{Z}[O_i] \oplus \bigoplus_{j=1}^l \left(\mathbb{Z}[\bar{O}_j^+] \oplus \mathbb{Z}[\bar{O}_j^-] \right)$$

modulo the relations

$$\begin{aligned} \pi^*(a_i) &= m_i [O_i], \quad i = 1, \dots, k, \\ \pi^*(b_j) &= m_j^+ [\bar{O}_j^+] - m_j^- [\bar{O}_j^-], \quad j = 1, \dots, l, \\ 0 &= \sum_{j=1}^k e_j [O_j] + \sum_{j=1}^l \left(e_j^+ [\bar{O}_j^+] - e_j^- [\bar{O}_j^-] \right). \end{aligned}$$

Proof. Let $\text{Div}_h A \subseteq \text{div } A$ be the subgroup of all Weil divisors on V that are homogeneous, i.e. finite sums of irreducible divisors given by homogeneous prime ideals. The homogeneous principal divisors $\text{Prin}_h A$ form a subgroup of $\text{Div}_h A$, which consists of all divisors $\text{div } f$, where $f = g/h \in \text{Frac } A$ is a quotient of homogeneous elements. By [8, §1, Ex. 16]

$$\text{Cl } A \cong \text{Cl}_h A := \text{Div}_h A / \text{Prin}_h A.$$

The group $\text{Div}_h A$ is freely generated by all \mathbb{C}^* -invariant subvarieties of codimension 1 in V , that is by all irreducible components of the fibers of $\pi: V \rightarrow C$. If $D_+(a) =$

$D_-(a) = 0$ then the fiber over a is the prime divisor $\pi^*(a)$. If $a = a_i$ for some i then the fiber over a consists of just one orbit O_i of type (m_i, q_i) , and by (17) $\pi^*(a_i) = m_i O_i$ as divisors on V . If $a = b_j$ for some j then by (17) $\pi^*(b_j) = m_j^+ \bar{O}_j^+ - m_j^- \bar{O}_j^-$. Thus the natural map $\pi^* : \text{div } A_0 \rightarrow \text{Div}_h A$ is injective, and

$$(18) \quad \text{Div}_h A \cong \frac{\pi^*(\text{div } A_0) \oplus \bigoplus_{i=1}^k \mathbb{Z}[O_i] \oplus \bigoplus_{j=1}^l (\mathbb{Z}[\bar{O}_j^+] \oplus \mathbb{Z}[\bar{O}_j^-])}{(\pi^*(a_i) - m_i[O_i], \pi^*(b_j) - m_j^+[\bar{O}_j^+] + m_j^-[\bar{O}_j^-])}.$$

The group $\text{Prin}_h A$ is generated by all divisors $\text{div}(fu^k) = \text{div } f + k \text{div } u$, where $f \in K_0^\times$ is non-zero. Dividing out $\pi^*(\text{Prin } A_0) = \pi^* \text{div}(K_0^\times)$ in (18) gives the group

$$(19) \quad \frac{\pi^*(\text{Cl } A_0) \oplus \bigoplus_{i=1}^k \mathbb{Z}[O_i] \oplus \bigoplus_{j=1}^l (\mathbb{Z}[\bar{O}_j^+] \oplus \mathbb{Z}[\bar{O}_j^-])}{(\pi^*(a_i) - m_i[O_i], \pi^*(b_j) - m_j^+[\bar{O}_j^+] + m_j^-[\bar{O}_j^-])}.$$

By Theorem 4.18 the divisor of u is given by

$$\text{div } u = - \sum_{j=1}^k e_j [O_j] + \sum_{j=1}^l (-e_j^+ [\bar{O}_j^+] + e_j^- [\bar{O}_j^-]).$$

Hence, taking (19) modulo this relation leads to the divisor class group, as required. □

Corollary 4.23. *A is factorial if and only if $C \subseteq \mathbb{A}_{\mathbb{C}}^1$ (i.e. A_0 is a localization of $\mathbb{C}[t]$) and one of the following two conditions is satisfied.*

- (i) $l = 0$ and $\text{gcd}(m_i, m_j) = 1$ for $1 \leq i < j \leq k$.
- (ii) $l = 1, m_i = 1$ for all i and $|\frac{e^+}{m^+} \frac{e^-}{m^-}| = \pm 1$, where $e^\pm := e_1^\pm$ and $m^\pm := m_1^\pm$.

Proof. If C is a curve of genus $g \geq 1$ then the group $\text{Cl } A$ is not finitely generated. Thus assuming that A is factorial, C is isomorphic to an open subset of $\mathbb{A}_{\mathbb{C}}^1$. By Theorem 4.22 the group $\text{Cl } A$ has then $k + 2l$ generators and $k + l + 1$ independent relations, whence necessarily $l \leq 1$. In the case $l = 1$ the number of generators and the number of relations are equal, and so the order of $\text{Cl } A$ is the absolute value of the determinant

$$\begin{vmatrix} e^+ & e^- & e_1 & e_2 & \cdots & e_k \\ m^+ & m^- & 0 & 0 & \cdots & 0 \\ 0 & 0 & m_1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & m_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & m_k \end{vmatrix} = \begin{vmatrix} e^+ & e^- \\ m^+ & m^- \end{vmatrix} \cdot m_1 \cdot m_2 \cdot \cdots \cdot m_k.$$

Thus, if $\text{Cl } A = 0$ then all the factors of this product are equal to 1, and we are in case (ii). If $l = 0$ then $\text{Cl } A$ is the group $\bigoplus_{i=1}^k \mathbb{Z}_{m_i} \cdot [O_i]$ modulo the relation

$\sum_i e_i[O_i] = 0$. As e_i and m_i are coprime, this group is trivial if and only if (i) holds. Conversely, if (i) or (ii) is satisfied then the discussion above shows that $\text{Cl } A$ is trivial, finishing the proof. \square

Finally, we determine the Picard group and the canonical divisor of A . The local divisor class group at the point b_j is generated by \bar{O}_j^\pm modulo the relations

$$R_j := e_j^+ \bar{O}_j^+ - e_j^- \bar{O}_j^- = 0 \quad \text{and} \quad S_j := m_j^+ \bar{O}_j^+ - m_j^- \bar{O}_j^- = 0.$$

Since the Picard group $\text{Pic } A$ is the kernel of the map of $\text{Cl } A$ into the direct product of all local divisor class groups, this group is the subgroup of $\text{Cl } A$ generated by $\pi^*(\text{Cl } A_0)$, $[O_i]$, R_j and S_j . As $S_j = \pi^*(b_j)$, we obtain the following result.

Corollary 4.24. *Pic A is the group*

$$\pi^*(\text{Cl } A_0) \oplus \bigoplus_{i=1}^k \mathbb{Z}[O_i] \oplus \bigoplus_{j=1}^l \mathbb{Z}R_j$$

modulo the relations

$$\begin{aligned} \pi^*(a_i) &= m_i[O_i], \quad i = 1, \dots, k, \\ 0 &= \sum_{j=1}^k e_j[O_j] + \sum_{j=1}^l R_j. \end{aligned}$$

In particular, Pic A vanishes if and only if $C \subseteq \mathbb{A}_{\mathbb{C}}^1$ and case (i) in Corollary 4.23 is satisfied or $l = 1$ and $m_i = 1$ for all $1 \leq i \leq k$.

Corollary 4.25. ² *The canonical divisor of the surface $V = \text{Spec } A$ is given by*

$$K_V = \pi^*(K_C) + \sum_{i=1}^k (m_i - 1)[O_i] + \sum_{j=1}^l \left((m_j^+ - 1)[\bar{O}_j^+] + (-m_j^- - 1)[\bar{O}_j^-] \right).$$

Proof. We claim that multiplication by the meromorphic differential form du/u on V gives an isomorphism

$$\frac{du}{u} \wedge - : \pi^*(\omega_C) \left(\sum_{j=1}^k (m_j - 1)[O_j] + \sum_{j=1}^l \left((m_j^+ - 1)[\bar{O}_j^+] + (-m_j^- - 1)[\bar{O}_j^-] \right) \right) \xrightarrow{\cong} \omega_V.$$

This is a local problem, so with the same arguments as in the proof of Theorem 4.18 we can reduce to the case that $A_0 \cong \mathbb{C}[t]$ and $D_+ = -D_- = -(e/d)[0]$, where e, m are

²cf. [26, Thm. 2.8] and [19, Lemma 2.6].

coprime. In this case (15) in the proof of Theorem 4.18 shows that $A = \mathbb{C}[x, x^{-1}, y]$ with $x := t^e u^m$ and $y := t^p u^q$, where p, q are integers with $\left| \begin{smallmatrix} p & e \\ q & m \end{smallmatrix} \right| = 1$. Moreover by (16) $t = x^{-q} y^m$ and $u = x^p y^{-e}$. By an elementary calculation $(du/u) \wedge dt = x^{-q-1} y^{m-1} dx \wedge dy$, whence the result follows. \square

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