

EQUIVARIANT EMBEDDINGS OF COMMUTATIVE
LINEAR ALGEBRAIC GROUPS OF CORANK ONE

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ABSTRACT. Let \mathbb{K} be an algebraically closed field of characteristic zero, $\mathbb{G}_m = (\mathbb{K} \setminus \{0\}, \times)$ be its multiplicative group, and $\mathbb{G}_a = (\mathbb{K}, +)$ be its additive group. Consider a commutative linear algebraic group $\mathbb{G} = (\mathbb{G}_m)^r \times \mathbb{G}_a$. We study equivariant \mathbb{G} -embeddings, i.e. normal \mathbb{G} -varieties X containing \mathbb{G} as an open orbit. We prove that X is a toric variety and all such actions of \mathbb{G} on X correspond to Demazure roots of the fan of X . In these terms, the orbit structure of a \mathbb{G} -variety X is described.

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1. INTRODUCTION

Let \mathbb{K} be an algebraically closed field of characteristic zero, $\mathbb{G}_m = (\mathbb{K} \setminus \{0\}, \times)$ be its multiplicative group, and $\mathbb{G}_a = (\mathbb{K}, +)$ be its additive group. It is well known that any connected commutative linear algebraic group \mathbb{G} over \mathbb{K} is isomorphic to $(\mathbb{G}_m)^r \times (\mathbb{G}_a)^s$ with some non-negative integers r and s , see [20, Theorem 15.5]. We say that r is the *rank* of the group \mathbb{G} and s is the *corank* of \mathbb{G} .

The aim of this paper is to study equivariant embeddings of commutative linear algebraic groups. Let us recall that an *equivariant embedding* of an algebraic group G is a pair (X, x) , where X is an algebraic variety equipped with a regular action $G \times X \rightarrow X$ and $x \in X$ is a point with the trivial stabilizer such that the orbit Gx is open and dense in X . We assume that the variety X is normal. If X is supposed to be complete, we speak about *equivariant compactifications* of G . For the study of compactifications of reductive groups, see e.g. [26]. More generally, equivariant embeddings of homogeneous spaces of

reductive groups is a popular object starting from early 1970th. Recent survey of results in this field may be found in [27].

Let us return to the case $\mathbb{G} = (\mathbb{G}_m)^r \times (\mathbb{G}_a)^s$. If $s = 0$ then \mathbb{G} is a torus and we come to the famous theory of toric varieties, see [13], [23], [18], [12]. Another extreme $r = 0$ corresponds to embeddings of a commutative unipotent (=vector) group. This case is also studied actively during last decades, see [19], [8], [3], [16], [14]. The next natural step is to study the mixed case $r > 0$ and $s > 0$ and to combine advantages of both torus and additive group actions.

The present paper deals with the case $s = 1$, i.e. from now on \mathbb{G} is a connected commutative linear algebraic group of corank one. In other words, $\mathbb{G} = (\mathbb{G}_m)^{n-1} \times \mathbb{G}_a$, where $n = \dim X$.

Let X be a toric variety with the acting torus \mathbb{T} . Consider an action $\mathbb{G}_a \times X \rightarrow X$ normalized by \mathbb{T} . Then \mathbb{T} acts on \mathbb{G}_a by conjugation with some character e . Such a character is called a *Demazure root* of X . If $T = \text{Ker}(e)$, then the group $\mathbb{G} := T \times \mathbb{G}_a$ acts on X with an open orbit, and X is a \mathbb{G} -embedding, see Proposition 6. Our main result (Theorem 2) states that all \mathbb{G} -embeddings can be realized this way. To this end we prove that for any \mathbb{G} -embedding X the $(\mathbb{G}_m)^{n-1}$ -action on X can be extended to an action of a bigger torus \mathbb{T} which normalizes the \mathbb{G}_a -action and X is toric with respect to \mathbb{T} .

This result can not be generalized to groups of corank two; examples of non-toric surfaces which are equivariant compactifications of \mathbb{G}_a^2 can be found in [14]. Similar examples are constructed in [14], [15] for semidirect products $\mathbb{G}_m \ltimes \mathbb{G}_a$. Such groups can be considered as non-commutative groups of corank one.

If two toric varieties are isomorphic as abstract varieties, then they are isomorphic as toric varieties [10, Theorem 4.1]. This shows that the structure of a torus embedding on a toric variety is unique up to isomorphism. A structure of a \mathbb{G} -embedding on a given variety may be non-unique, see Examples 2, 4. Such structures are given by Demazure roots and thus the number of structures is finite if X is complete, and it is at most countable for arbitrary X . At the same time, \mathbb{G}_a^6 -embeddings into \mathbb{P}^6 admit a non-trivial moduli space [19, Example 3.6].

The paper is organized as follows. Section 2 contains preliminaries on torus actions on affine varieties. We recall basic facts on affine toric varieties and introduce a description of affine T -varieties in terms of proper polyhedral divisors due to Altmann and Hausen [1]. A correspondence between \mathbb{G}_a -actions on X normalized by T and homogeneous locally nilpotent derivations (LNDs) of the algebra $\mathbb{K}[X]$ is explained. We define Demazure roots of a cone and use them to describe homogeneous LNDs on $\mathbb{K}[X]$, where X is toric. Also we give a description of homogeneous LNDs of horizontal type on algebras with grading of complexity one obtained by Liendo [22].

In Section 3 we show that if X is a normal affine T -variety of complexity one and the algebra $\mathbb{K}[X]$ admits a homogeneous LND of degree zero, then X is toric with an acting torus \mathbb{T} , T is a subtorus of \mathbb{T} , and \mathbb{T} normalizes the corresponding \mathbb{G}_a -action. This gives the result for affine \mathbb{G} -embeddings. Moreover, Proposition 3 provides an explicit description of affine \mathbb{G} -embeddings.

Section 4 deals with compactifications of \mathbb{G} . Here we use the Cox construction and a lifting of the action of \mathbb{G} to the total coordinate space \overline{X} of X to deduce the result from the affine case.

In Section 5 we recall basic facts on toric varieties and introduce the notion of a Demazure root of a fan following Demazure [13]. The action of the corresponding one-parameter subgroup on the toric variety is also described there. Let Σ be a fan and e be a Demazure root of Σ . In Section 6 we define a \mathbb{G} -embedding associated to the pair (Σ, e) and study the \mathbb{G} -orbit structure of X . It turns out that the number of \mathbb{G} -orbits on X is finite.

Finally, in Section 7 we prove that any \mathbb{G} -embedding is associated with some pair (Σ, e) . The idea is to reduce the general case to the complete one via equivariant compactification. At the end several explicit examples of \mathbb{G} -embeddings are given.

Some results of this paper appeared in preprint [5]. They form a part of the Ph.D. thesis of the second author [21].

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2. \mathbb{G}_a -ACTIONS ON AFFINE T -VARIETIES

Let X be an irreducible affine variety with an effective action of an algebraic torus T , M be the character lattice of T , N be the lattice of one-parameter subgroups of T , and $A = \mathbb{K}[X]$ be the algebra of regular functions on X . It is well known that there is a bijective correspondence between effective T -actions on X and effective M -gradings on A . In fact, the algebra A is graded by a semigroup of lattice points in some convex polyhedral cone $\omega \subseteq M_{\mathbb{Q}} = M \otimes_{\mathbb{Z}} \mathbb{Q}$. So we have

$$A = \bigoplus_{m \in \omega_M} A_m \chi^m,$$

where $\omega_M = \omega \cap M$ and χ^m is the character corresponding to m .

A derivation ∂ on an algebra A is said to be *locally nilpotent* (LND) if for each $f \in A$ there exists $n \in \mathbb{N}$ such that $\partial^n(f) = 0$. For any LND ∂ on A the map $\varphi_{\partial} : \mathbb{G}_a \times A \rightarrow A$, $\varphi_{\partial}(s, f) = \exp(s\partial)(f)$, defines a structure of a rational \mathbb{G}_a -algebra on A . This induces a regular action $\mathbb{G}_a \times X \rightarrow X$, where $X = \text{Spec } A$. In fact, any regular \mathbb{G}_a -action on X arises this way, see [17, Section 1.5]. A derivation ∂ on A is said to be *homogeneous* if it respects the M -grading. If $f, h \in A \setminus \ker \partial$ are homogeneous, then $\partial(fh) = f\partial(h) + \partial(f)h$ is homogeneous too and $\deg \partial(f) - \deg f = \deg \partial(h) - \deg h$. So any homogeneous derivation ∂ has a well defined *degree* given as $\deg \partial = \deg \partial(f) - \deg f$ for any homogeneous $f \in A \setminus \ker \partial$. It is easy to see that an LND on A is homogeneous if and only if the corresponding \mathbb{G}_a -action is normalized by the torus T in the automorphism group $\text{Aut}(X)$, cf. [17, Section 3.7].

Any derivation on $\mathbb{K}[X]$ extends to a derivation on the field of fractions $\mathbb{K}(X)$ by the Leibniz rule. A homogeneous LND ∂ on $\mathbb{K}[X]$ is said to be of *fiber type* if $\partial(\mathbb{K}(X)^T) = 0$ and of *horizontal type* otherwise. In other words, ∂ is of

fiber type if and only if the general orbits of corresponding \mathbb{G}_a -action on X are contained in the closures of T -orbits.

Let X be an affine toric variety, i. e. a normal affine variety with a generically transitive action of a torus T . In this case

$$A = \bigoplus_{m \in \omega_M} \mathbb{K}\chi^m = \mathbb{K}[\omega_M]$$

is the semigroup algebra. Recall that for given cone $\omega \subset M_{\mathbb{Q}}$, its *dual cone* is defined by

$$\sigma = \{n \in N_{\mathbb{Q}} \mid \langle n, p \rangle \geq 0 \ \forall p \in \omega\},$$

where $\langle \cdot, \cdot \rangle$ is the pairing between dual lattices N and M . Let $\sigma(1)$ be the set of rays of a cone σ and n_{ρ} be the primitive lattice vector on the ray ρ . For $\rho \in \sigma(1)$ we set

$$S_{\rho} := \{e \in M \mid \langle n_{\rho}, e \rangle = -1 \text{ and } \langle n_{\rho'}, e \rangle \geq 0 \ \forall \rho' \in \sigma(1), \rho' \neq \rho\}.$$

One easily checks that the set S_{ρ} is infinite for each $\rho \in \sigma(1)$. The elements of the set $\mathfrak{R} := \bigsqcup_{\rho} S_{\rho}$ are called the *Demazure roots* of σ . Let $e \in S_{\rho}$. Then ρ is called the *distinguished ray* of the root e . One can define the homogeneous LND on the algebra A by the rule

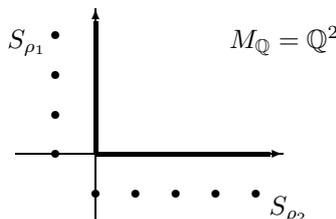
$$\partial_e(\chi^m) = \langle n_{\rho}, m \rangle \chi^{m+e}.$$

In fact, every homogeneous LND on A has a form $\alpha \partial_e$ for some $\alpha \in \mathbb{K}$, $e \in \mathfrak{R}$, see [22, Theorem 2.7]. In other words, \mathbb{G}_a -actions on X normalized by the acting torus are in bijection with Demazure roots of the cone σ .

Clearly, all homogeneous LNDs on a toric variety are of fiber type.

EXAMPLE 1. Consider $X = \mathbb{A}^k$ with the standard action of the torus $(\mathbb{K}^{\times})^k$. It is a toric variety with the cone $\sigma = \mathbb{Q}_{\geq 0}^k$ having rays $\rho_1 = \langle (1, 0, \dots, 0) \rangle_{\mathbb{Q}_{\geq 0}}, \dots, \rho_k = \langle (0, 0, \dots, 0, 1) \rangle_{\mathbb{Q}_{\geq 0}}$. The dual cone ω is $\mathbb{Q}_{\geq 0}^k$ as well. In this case

$$S_{\rho_i} = \{(c_1, \dots, c_{i-1}, -1, c_{i+1}, \dots, c_k) \mid c_j \in \mathbb{Z}_{\geq 0}\}.$$



Denote $x_1 = \chi^{(1,0,\dots,0)}, \dots, x_k = \chi^{(0,\dots,0,1)}$. Then $\mathbb{K}[X] = \mathbb{K}[x_1, \dots, x_k]$. It is easy to see that the homogeneous LND corresponding to the root $e = (c_1, \dots, c_k) \in S_{\rho_i}$ is

$$\partial_e = x_1^{c_1} \dots x_{i-1}^{c_{i-1}} x_{i+1}^{c_{i+1}} \dots x_k^{c_k} \frac{\partial}{\partial x_i}.$$

This LND gives rise to the \mathbb{G}_a -action

$$x_i \mapsto x_i + sx_1^{c_1} \dots x_{i-1}^{c_{i-1}} x_{i+1}^{c_{i+1}} \dots x_k^{c_k}, \quad x_j \mapsto x_j, \quad j \neq i, \quad s \in \mathbb{G}_a.$$

Let us recall that the *complexity* of an action of a torus T on an irreducible variety X is the codimension of a general T -orbit on X , or, equivalently, the transcendence degree of the field of rational invariants $\mathbb{K}(X)^T$ over \mathbb{K} . In particular, actions of complexity zero are precisely actions with an open T -orbit.

Now we recall a description of normal affine T -varieties of complexity one in terms of proper polyhedral divisors. Let N and M be two mutually dual lattices with the pairing denoted by $\langle \cdot, \cdot \rangle$, σ be a strongly convex cone in $N_{\mathbb{Q}}$, and $\omega \subseteq M_{\mathbb{Q}}$ be the dual cone. A polyhedron $\Delta \subseteq N_{\mathbb{Q}}$, which can be decomposed as Minkowski sum of a bounded polyhedron and the cone σ , is called *σ -tailed*. Let C be a smooth curve. A *σ -polyhedral divisor* on C is a formal sum

$$\mathfrak{D} = \sum_{z \in C} \Delta_z \cdot z,$$

where Δ_z are the σ -tailed polyhedra and only finite number of them are not equal to σ . The divisor \mathfrak{D} is *trivial*, if $\Delta_z = \sigma$ for all $z \in C$.

The finite set $\text{Supp } \mathfrak{D} := \{z \in C \mid \Delta_z \neq \sigma\}$ is called the *support* of \mathfrak{D} . For every $m \in \omega_M$ we can obtain the \mathbb{Q} -divisor $\mathfrak{D}(m) = \sum_{z \in C} h_z(m) \cdot z$, where $h_z(m) :=$

$\min_{p \in \Delta_z} \langle p, m \rangle$. So a σ -polyhedral divisor is just a piecewise-linear function from ω_M to the group of \mathbb{Q} -divisors on C . One can define the M -graded algebra

$$A[C, \mathfrak{D}] = \bigoplus_{m \in \omega_M} A_m \chi^m,$$

where

$$A_m = H^0(C, \mathfrak{D}(m)) := \{f \in \mathbb{K}(X) \mid \text{div } f + \mathfrak{D}(m) \geq 0\},$$

where the multiplication of homogeneous elements is given as in $\mathbb{K}(X)$.

A σ -polyhedral divisor on smooth curve C is called *proper* if either C is affine, or C is projective and the polyhedron $\text{deg } \mathfrak{D} := \sum_{z \in C} \Delta_z$ is a proper subset of σ .

The next theorem expresses the main results of [1] specialized to the case of torus actions of complexity one.

THEOREM 1. (1) *Let C be a smooth curve and \mathfrak{D} a proper σ -polyhedral divisor on C . Then the M -graded algebra $A[C, \mathfrak{D}]$ is a normal finitely generated effectively graded $(\text{rk } M + 1)$ -dimensional domain. Conversely, for each normal finitely generated domain A with a grading of complexity one there exist a smooth curve C and a proper σ -polyhedral divisor \mathfrak{D} on C such that A is isomorphic to $A[C, \mathfrak{D}]$.*

(2) *The M -graded domains $\text{Spec } A[C, \mathfrak{D}]$ and $\text{Spec } A[C, \mathfrak{D}']$ are isomorphic if and only if for every $z \in C$ there exists a lattice vector $v_z \in N$ such that*

$$\mathfrak{D} = \mathfrak{D}' + \sum_z (v_z + \sigma) \cdot z,$$

and for all $m \in \omega_M$ the divisor $\sum_z \langle v_z, m \rangle \cdot z$ is principal.

The following result is obtained in [1, Section 11].

PROPOSITION 1. *Let \mathfrak{D} be a proper σ -polyhedral divisor on a smooth curve C , $X = \text{Spec } A[C, \mathfrak{D}]$, and $T \times X \rightarrow X$ be the corresponding torus action. Then this action can be realized as a subtorus action on a toric variety if and only if either $C = \mathbb{A}^1$ and \mathfrak{D} can be chosen supported in at most one point, or $C = \mathbb{P}^1$ and \mathfrak{D} can be chosen supported in at most two points.*

Also we need a description of homogeneous LNDs of horizontal type for a T -variety X of complexity one from [22]. Below we follow the approach given in [7]. We have $\mathbb{K}[X] = A[C, \mathfrak{D}]$ for some C and \mathfrak{D} . It turns out that C is isomorphic to \mathbb{A}^1 or \mathbb{P}^1 whenever there exists a homogeneous LND of horizontal type on $A[C, \mathfrak{D}]$, see [22, Lemma 3.15].

Let C be \mathbb{A}^1 or \mathbb{P}^1 , $\mathfrak{D} = \sum_{z \in C} \Delta_z \cdot z$ a σ -polyhedral divisor on C , $z_0 \in C$, $z_\infty \in C \setminus \{z_0\}$, and v_z a vertex of Δ_z for every $z \in C$. Put $C' = C$ if $C = \mathbb{A}^1$ and $C' = C \setminus \{z_\infty\}$ if $C = \mathbb{P}^1$. A collection $\tilde{\mathfrak{D}} = \{\mathfrak{D}, z_0; v_z, \forall z \in C\}$ if $C = \mathbb{A}^1$ and $\tilde{\mathfrak{D}} = \{\mathfrak{D}, z_0, z_\infty; v_z, \forall z \in C'\}$ if $C = \mathbb{P}^1$ is called a *colored σ -polyhedral divisor* on C if the following conditions hold:

- (*) $v_{\text{deg}} := \sum_{z \in C'} v_z$ is a vertex of $\text{deg } \mathfrak{D}|_{C'} := \sum_{z \in C'} \Delta_z$;
- (**) $v_z \in N$ for all $z \in C'$, $z \neq z_0$.

Let $\tilde{\mathfrak{D}}$ be a colored σ -polyhedral divisor on C and $\delta \subseteq N_{\mathbb{Q}}$ be the cone generated by $\text{deg } \mathfrak{D}|_{C'} - v_{\text{deg}}$. Denote by $\tilde{\sigma} \subseteq (N \oplus \mathbb{Z})_{\mathbb{Q}}$ the cone generated by $(\delta, 0)$ and $(v_{z_0}, 1)$ if $C = \mathbb{A}^1$, and by $(\delta, 0)$, $(v_{z_0}, 1)$ and $(\Delta_{z_\infty} + v_{\text{deg}} - v_{z_0} + \delta, -1)$ if $C = \mathbb{P}^1$. By definition, put d the minimal positive integer such that $d \cdot v_{z_0} \in N$. A pair $(\tilde{\mathfrak{D}}, e)$, where $e \in M$, is said to be *coherent* if

- (i) there exists $s \in \mathbb{Z}$ such that $\tilde{e} = (e, s) \in M \oplus \mathbb{Z}$ is a Demazure root of the cone $\tilde{\sigma}$ with distinguished ray $\tilde{\rho} = (d \cdot v_{z_0}, d)$;
- (ii) $\langle v, e \rangle \geq 1 + \langle v_z, e \rangle$ for all $z \in C' \setminus \{z_0\}$ and all vertices $v \neq v_z$ of the polyhedron Δ_z ;
- (iii) $d \cdot \langle v, e \rangle \geq 1 + \langle v_{z_0}, e \rangle$ for all vertices $v \neq v_{z_0}$ of the polyhedron Δ_{z_0} ;
- (iv) if $Y = \mathbb{P}^1$, then $d \cdot \langle v, e \rangle \geq -1 - d \cdot \sum_{z \in Y'} \langle v_z, e \rangle$ for all vertices v of the polyhedron Δ_{z_∞} .

It follows from [7, Theorem 1.10] that homogeneous LNDs of horizontal type on $A[C, \mathfrak{D}]$ are in bijection with the coherent pairs $(\tilde{\mathfrak{D}}, e)$. Namely, let $(\tilde{\mathfrak{D}}, e)$ be a coherent pair. Without loss of generality we may assume that $z_0 = 0$, $z_\infty = \infty$ if $C = \mathbb{P}^1$, and $v_z = 0 \in N$ for all $z \in C' \setminus \{z_0\}$. Let $\mathbb{K}(C) = \mathbb{K}(t)$. Then the homogeneous LND of horizontal type corresponding to $(\tilde{\mathfrak{D}}, e)$ is given by

$$(1) \quad \partial(\chi^m \cdot t^r) = d(\langle v_0, m \rangle + r)\chi^{m+e} \cdot t^{r+s} \quad \text{for all } m \in M, r \in \mathbb{Z}.$$

In particular, the vector e is the degree of the derivation ∂ .

3. THE AFFINE CASE

Let (X, x) be an equivariant embedding of the group $\mathbb{G} = (\mathbb{G}_m)^{n-1} \times \mathbb{G}_a$, where $n = \dim X$. In this section we assume that X is normal and affine. Let us denote the subgroup $(\mathbb{G}_m)^{n-1}$ of \mathbb{G} by T . Since the action of T on X is effective, it has complexity one and defines an effective grading of the algebra $\mathbb{K}[X]$ by the lattice M . In particular, the graded algebra $\mathbb{K}[X]$ has the form $A[C, \mathfrak{D}]$ for some smooth curve C and some proper σ -polyhedral divisor on C , where σ is a cone in $N_{\mathbb{Q}}$.

Since the action of the subgroup \mathbb{G}_a commutes with T -action on X , the corresponding homogeneous LND on $\mathbb{K}[X]$ has degree zero. Moreover, the group \mathbb{G} acts on X with an open orbit. It implies that the \mathbb{G}_a -action on X is of horizontal type, and hence either $C = \mathbb{A}^1$ or $C = \mathbb{P}^1$.

PROPOSITION 2. *Let $X = \text{Spec } A[C, \mathfrak{D}]$ be a T -variety of complexity one. Suppose that there exists a homogeneous LND of horizontal type and of degree zero on $A[C, \mathfrak{D}]$. Then*

- (1) *if $C = \mathbb{A}^1$, then one can assume (via Theorem 1) that \mathfrak{D} is a trivial σ -polyhedral divisor;*
- (2) *if $C = \mathbb{P}^1$, then one can choose $\mathfrak{D} = \Delta_{\infty} \cdot [\infty]$, where $\Delta_{\infty} \not\subseteq \sigma$ is some σ -tailed polyhedron.*

Proof. Let $(\tilde{\mathfrak{D}}, 0)$ be the coherent pair corresponding to the homogeneous LND of horizontal type. Without loss of generality we may assume that $z_0 = 0$ and $z_{\infty} = \infty$ if $C = \mathbb{P}^1$. By definition of a coherent pair, there exists $s \in \mathbb{Z}$ such that $(0, s)$ is a Demazure root of the cone $\tilde{\sigma}$ with distinguished ray (dv_0, d) . It implies that $s = -1$, $d = 1$, and hence $v_0 \in N$. Further, the inequality $\langle v, 0 \rangle \geq 1 + \langle v_z, 0 \rangle$ should be satisfied for every $z \in C'$ and every vertex $v \neq v_z$ of Δ_z . It means that each polyhedron Δ_z , where $z \in C'$, has only one vertex v_z . Replacing σ -polyhedral divisor \mathfrak{D} with $\mathfrak{D}' = \mathfrak{D} + \sum_{z \in C'} (-v_z + \sigma) \cdot z$ and using Theorem 1, we obtain the assertion. The condition $\Delta_{\infty} \not\subseteq \sigma$ follows from the fact that \mathfrak{D} is a proper σ -polyhedral divisor. □

COROLLARY 1. *Under the conditions of Proposition 2 the variety X is toric with T being a subtorus of the acting torus \mathbb{T} .*

Proof. It follows immediately from Propositions 1 and 2. □

The next proposition is a specification of Corollary 1. In particular, it shows that the \mathbb{G}_a -action on X is normalized by the acting torus \mathbb{T} .

PROPOSITION 3. *Under the conditions of Proposition 2,*

- (1) *if $C = \mathbb{A}^1$, then $X \cong Y \times \mathbb{A}^1$, where Y is the toric variety corresponding to the cone σ and \mathbb{G}_a acts on \mathbb{A}^1 by translations;*
- (2) *if $C = \mathbb{P}^1$, then X is the toric variety with the cone $\tilde{\sigma} \subset N \oplus \mathbb{Z}$ generated by $(\sigma, 0), (\Delta_{\infty}, -1)$ and $(0, 1)$. The \mathbb{G}_a -action on X is given by Demazure root $\tilde{e} = (0, -1) \in M \oplus \mathbb{Z}$ of the cone $\tilde{\sigma}$.*

Proof. Let $\mathbb{K}(C) = \mathbb{K}(t)$. If $C = \mathbb{A}^1$ then \mathfrak{D} is trivial and

$$A[C, \mathfrak{D}] = \bigoplus_{m \in \omega_M} \mathbb{K}[t] \cdot \chi^m = \mathbb{K}[\omega_M] \otimes \mathbb{K}[t] = \mathbb{K}[Y] \otimes \mathbb{K}[t].$$

Hence $X \cong Y \times \mathbb{A}^1$. Applying formula (1), we obtain that the homogeneous LND is given by

$$(2) \quad \partial(\chi^m \cdot t^r) = r\chi^m \cdot t^{r-1}$$

for all $m \in \omega_M$ and $r \in \mathbb{Z}_{\geq 0}$. Thus \mathbb{G}_a acts on $Y \times \mathbb{A}^1$ as $(y, t) \mapsto (y, t + s)$.

If $C = \mathbb{P}^1$ then $\mathfrak{D} = \Delta_\infty \cdot [\infty]$ and we obtain

$$A[C, \mathfrak{D}] = \bigoplus_{m \in \omega_M} \bigoplus_{r=0}^{h_\infty(m)} \mathbb{K}\chi^m \cdot t^r = \bigoplus_{(m,r) \in \tilde{\omega}_{\tilde{M}}} \mathbb{K}\chi^m \cdot t^r = \mathbb{K}[\tilde{\omega}_{\tilde{M}}],$$

where $\tilde{M} = M \oplus \mathbb{Z}$ and $\tilde{\omega} \subset \tilde{M}_\mathbb{Q}$ is the cone dual to $\tilde{\sigma}$. So we see that $A[C, \mathfrak{D}]$ is a semigroup algebra and X is a toric variety with the cone $\tilde{\sigma}$. In this case formula (2) gives the LND corresponding to the Demazure root $\tilde{e} = (0, -1)$. \square

4. THE COMPLETE CASE

In this section we study equivariant compactifications of the group \mathbb{G} . First we briefly recall the main ingredients of the Cox construction, see [4, Chapter 1] for more details.

Let X be a normal variety with finitely generated divisor class group $\text{Cl}(X)$ and only constant invertible regular functions.

Suppose that $\text{Cl}(X)$ is free. Denote by $\text{WDiv}(X)$ the group of Weil divisors on X and fix a subgroup $K \subseteq \text{WDiv}(X)$ which maps onto $\text{Cl}(X)$ isomorphically. The *Cox ring* of the variety X is defined as

$$R(X) = \bigoplus_{D \in K} H^0(X, D),$$

where $H^0(X, D) = \{f \in \mathbb{K}(X) \mid \text{div } f + D \geq 0\}$ and multiplication on homogeneous components coincides with multiplication in $\mathbb{K}(X)$ and extends to $R(X)$ by linearity.

If $\text{Cl}(X)$ has torsion, we choose a finitely generated subgroup $K \subseteq \text{WDiv}(X)$ that projects to $\text{Cl}(X)$ surjectively. Denote by $K_0 \subset K$ the kernel of this projection. Take compatible bases D_1, \dots, D_s and $D_1^0 = d_1 D_1, \dots, D_r^0 = d_r D_r$ in K and K_0 respectively. Let us choose the set of rational functions $\mathcal{F} = \{F_D \in \mathbb{K}(X)^\times : D \in K_0\}$ such that $\text{div}(F_D) = D$ and $F_{D+D'} = F_D F_{D'}$. Suppose that $D, D' \in K$ and $D - D' \in K_0$. The map $f \mapsto F_{D-D'} f$ is an isomorphism of the vector spaces $H^0(X, D)$ and $H^0(X, D')$. The linear span of the elements $f - F_{D-D'} f$ over all D, D' with $D - D' \in K_0$ and all $f \in H^0(X, D)$ is an ideal $I(K, \mathcal{F})$ of the graded ring $T_K(X) := \bigoplus_{D \in K} H^0(X, D)$. The Cox ring of the variety X is given by

$$R(X) = T_K(X)/I(K, \mathcal{F}).$$

This construction does not depend on the choice of K and \mathcal{F} , see [2, Lemma 3.1 and Proposition 3.2] and [4, Proposition 1.4.2.2].

Suppose that the Cox ring $R(X)$ is finitely generated. Then $\overline{X} := \text{Spec } R(X)$ is a normal affine variety with an action of the quasitorus $H_X := \text{Spec } \mathbb{K}[\text{Cl}(X)]$. There is an open H_X -invariant subset $\widehat{X} \subseteq \overline{X}$ such that the complement $\overline{X} \setminus \widehat{X}$ is of codimension at least two in \overline{X} , there exists a good quotient $p_X: \widehat{X} \rightarrow \widehat{X} // H_X$, and the quotient space $\widehat{X} // H_X$ is isomorphic to X , see [4, Construction 1.6.3.1]. So we have the following diagram

$$\begin{array}{ccc} \widehat{X} & \xrightarrow{i} & \overline{X} = \text{Spec } R(X) \\ \downarrow // H_X & & \\ X & & \end{array}$$

Let us return to equivariant compactifications of \mathbb{G} .

PROPOSITION 4. *Let $\mathbb{G} = T \times \mathbb{G}_a$ and X be a normal compactification of \mathbb{G} . Then the T -action on X can be extended to an action of a bigger torus \mathbb{T} such that \mathbb{T} normalizes \mathbb{G}_a and X is a toric variety with the acting torus \mathbb{T} .*

Proof. The variety X is rational with torus action of complexity one. By [4, Theorem 4.3.1.5], the divisor class group $\text{Cl}(X)$ and the Cox ring $R(X)$ are finitely generated.

There exists a finite epimorphism $\epsilon: \mathbb{G}' \rightarrow \mathbb{G}$ of connected linear algebraic groups and an action $\mathbb{G}' \times \widehat{X} \rightarrow \widehat{X}$ which commutes with the quasitorus H_X and $p_X(g' \cdot \widehat{x}) = \epsilon(g') \cdot p_X(\widehat{x})$ for all $g' \in \mathbb{G}'$ and $\widehat{x} \in \widehat{X}$, see [4, Theorem 4.2.3.1]. The group \mathbb{G}' has a form $T' \times \mathbb{G}_a$, where ϵ defines a finite epimorphism of tori $T' \rightarrow T$ and is identical on \mathbb{G}_a .

Since $\overline{X} = \text{Spec } \mathbb{K}[\widehat{X}]$, the action of \mathbb{G}' extends to the affine variety \overline{X} . This variety is an embedding of the group $(T'H_X^0) \times \mathbb{G}_a$. By Proposition 3, it is toric with an acting torus $\overline{\mathbb{T}}$ normalizing the \mathbb{G}_a -action and $T'H_X^0$ is a subtorus of $\overline{\mathbb{T}}$. Since X is complete, [25, Corollary 2.5] implies that the subset \widehat{X} is invariant under the torus $\overline{\mathbb{T}}$. By [4, Lemma 4.2.1.3], the action of $\overline{\mathbb{T}}$ descends to an action of the torus $\mathbb{T} := \overline{\mathbb{T}}/H_X^0$ on X . Here \mathbb{T} normalizes \mathbb{G}_a , its action extends the action of T on X , and X is toric with respect to \mathbb{T} . \square

5. TORIC VARIETIES AND DEMAZURE ROOTS

We keep notations of Section 2. Let X be a toric variety of dimension n with an acting torus \mathbb{T} and Σ be the corresponding fan of convex polyhedral cones in the space $N_{\mathbb{Q}}$, see [18] or [12] for details.

As before, let $\Sigma(1)$ be the set of rays of the fan Σ and n_{ρ} be the primitive lattice vector on the ray ρ . For $\rho \in \Sigma(1)$ we consider the set S_{ρ} of all vectors $e \in M$ such that

- (1) $\langle n_{\rho}, e \rangle = -1$ and $\langle n_{\rho'}, e \rangle \geq 0 \quad \forall \rho' \in \sigma(1), \rho' \neq \rho$;
- (2) if σ is a cone of Σ and $\langle v, e \rangle = 0$ for all $v \in \sigma$, then the cone generated by σ and ρ is in Σ as well.

Note that condition (1) implies condition (2) if Σ is a maximal fan with support $|\Sigma|$. This is the case if X is affine or complete.

The elements of the set $\mathfrak{R} := \bigsqcup_{\rho} S_{\rho}$ are called the *Demazure roots* of the fan Σ ,

cf. [13, Définition 4] and [23, Section 3.4]. Again elements $e \in \mathfrak{R}$ are in bijection with \mathbb{G}_a -actions on X normalized by the acting torus, see [13, Théoreme 3] and [23, Proposition 3.14]. If X is affine, the \mathbb{G}_a -action given by a Demazure root e coincides with the action given by the locally nilpotent derivation ∂_e of the algebra $\mathbb{K}[X]$ as defined in Section 2. Let us denote the image under this action of the group \mathbb{G}_a in $\text{Aut}(X)$ by H_e . Thus H_e is a one-parameter unipotent subgroup normalized by \mathbb{T} in $\text{Aut}(X)$.

We recall basic facts from toric geometry. There is a bijection between cones $\sigma \in \Sigma$ and \mathbb{T} -orbits \mathcal{O}_{σ} on X such that $\sigma_1 \subseteq \sigma_2$ if and only if $\mathcal{O}_{\sigma_2} \subseteq \overline{\mathcal{O}_{\sigma_1}}$. Here $\dim \mathcal{O}_{\sigma} = n - \dim \langle \sigma \rangle$. Moreover, each cone $\sigma \in \Sigma$ defines an open affine \mathbb{T} -invariant subset U_{σ} on X such that \mathcal{O}_{σ} is a unique closed \mathbb{T} -orbit on U_{σ} and $\sigma_1 \subseteq \sigma_2$ if and only if $U_{\sigma_1} \subseteq U_{\sigma_2}$.

Let ρ_e be the distinguished ray corresponding to a root e , n_e be the primitive lattice vector on ρ_e , and R_e be the one-parameter subgroup of \mathbb{T} corresponding to n_e .

Our aim is to describe the action of H_e on X .

PROPOSITION 5. *For every point $x \in X \setminus X^{H_e}$ the orbit $H_e x$ meets exactly two \mathbb{T} -orbits \mathcal{O}_1 and \mathcal{O}_2 on X , where $\dim \mathcal{O}_1 = \dim \mathcal{O}_2 + 1$. The intersection $\mathcal{O}_2 \cap H_e x$ consists of a single point, while*

$$\mathcal{O}_1 \cap H_e x = R_e y \quad \text{for any } y \in \mathcal{O}_1 \cap H_e x.$$

Proof. It follows from the proof of [23, Proposition 3.14] that the affine charts U_{σ} , where $\sigma \in \Sigma$ is a cone containing ρ_e , are H_e -invariant, and the complement of their union is contained in X^{H_e} , cf. [9, Lemma 2.4]. This reduces the proof to the case X is affine. Then the assertion is proved in [6, Proposition 2.1]. \square

A pair of \mathbb{T} -orbits $(\mathcal{O}_1, \mathcal{O}_2)$ on X is said to be *H_e -connected* if $H_e x \subseteq \mathcal{O}_1 \cup \mathcal{O}_2$ for some $x \in X \setminus X^{H_e}$. By Proposition 5, $\mathcal{O}_2 \subseteq \overline{\mathcal{O}_1}$ for such a pair (up to permutation) and $\dim \mathcal{O}_1 = \dim \mathcal{O}_2 + 1$. Since the torus normalizes the subgroup H_e , any point of $\mathcal{O}_1 \cup \mathcal{O}_2$ can actually serve as a point x .

LEMMA 1. *A pair of \mathbb{T} -orbits $(\mathcal{O}_{\sigma_1}, \mathcal{O}_{\sigma_2})$ is H_e -connected if and only if $e|_{\sigma_2} \leq 0$ and σ_1 is a facet of σ_2 given by the equation $\langle v, e \rangle = 0$.*

Proof. The proof again reduces to the affine case, where the assertion is [6, Lemma 2.2]. \square

6. THE ORBIT STRUCTURE

We keep notations of the previous section. Let us begin with a construction mentioned in the Introduction. Let X be a toric variety with the acting torus \mathbb{T} . Consider a non-trivial action $\mathbb{G}_a \times X \rightarrow X$ normalized by \mathbb{T} and thus represented by a Demazure root e of the fan Σ of X . Then \mathbb{T} acts on \mathbb{G}_a by

conjugation with the character e and the semidirect product $\mathbb{T} \ltimes \mathbb{G}_a$ acts on X as well. Let $T = \text{Ker}(e) \subseteq \mathbb{T}$ and consider the group $\mathbb{G} := T \times \mathbb{G}_a$.

PROPOSITION 6. *The variety X is an embedding of \mathbb{G} .*

Proof. Take a point $x \in X$ whose stabilizers in \mathbb{T} and \mathbb{G}_a are trivial. It suffices to show that the stabilizer of x in \mathbb{G} is trivial. To this end, note that by the Jordan decomposition [20, Theorem 15.3] any subgroup of $T \times \mathbb{G}_a$ is a product of subgroups in T and \mathbb{G}_a respectively. \square

Remark 1. The \mathbb{G} -embedding of Proposition 6 is defined by the pair (Σ, e) .

Since $\langle n_e, e \rangle = -1$, we have $\mathbb{T} = T \times R_e$.

LEMMA 2. *Any $(T \times \mathbb{G}_a)$ -invariant subset in X is also \mathbb{T} -invariant.*

Proof. Note that an orbit $\mathbb{T}x$ does not coincide with the orbit Tx if and only if the stabilizer of x in \mathbb{T} is contained in T . For $x \in \mathcal{O}_\sigma$ this condition is equivalent to $e|_\sigma = 0$. It shows that for every $x \in X^{\mathbb{G}_a}$ we have $\mathbb{T}x = Tx$. If $x \in X \setminus X^{\mathbb{G}_a}$, then by Proposition 5 the orbit $\mathbb{G}_a x$ is invariant under R_e . This proves that any orbit of $(T \times \mathbb{G}_a)$ is R_e - and T -invariant, thus the assertion. \square

PROPOSITION 7. *Let X be a \mathbb{G} -embedding given by a pair (Σ, e) . Then any \mathbb{G} -orbit on X is either a union $\mathcal{O}_1 \cup \mathcal{O}_2$ of two \mathbb{T} -orbits on X or a unique \mathbb{T} -orbit; the first possibility occurs if and only if the pair $(\mathcal{O}_1, \mathcal{O}_2)$ is H_e -connected. In particular, the number of \mathbb{G} -orbits on X is finite.*

Proof. The assertion follows directly from Lemma 2 and Proposition 5. \square

PROPOSITION 8. *Let X be a \mathbb{G} -embedding given by a pair (Σ, e) . Then the stabilizer of any point $x \in X$ in \mathbb{G} is connected and the closure of any \mathbb{G} -orbit on X is a (normal) toric variety. If X is smooth, then the closure of any \mathbb{G} -orbit is smooth.*

Proof. The stabilizer of a point x in \mathbb{G} is the direct product of stabilizers in T and in \mathbb{G}_a . An algebraic subgroup of \mathbb{G}_a is either $\{0\}$ or \mathbb{G}_a itself, while the stabilizer in T is the kernel of the (primitive) character e restricted to the (connected) stabilizer of x in \mathbb{T} . Thus the stabilizer of x in \mathbb{G} is connected. Proposition 7 shows that any \mathbb{G} -orbit on X contains an open \mathbb{T} -orbit, and thus the closure of a \mathbb{G} -orbit coincides with the closure of some \mathbb{T} -orbit. Now the last two assertions follow from [18, Section 3.1]. \square

Remark 2. If X contains l torus invariant prime divisors, then the number of \mathbb{G} -invariant prime divisors on X is $l - 1$. On a toric variety, the closure of any torus orbit is an intersection of torus invariant prime divisors. In contrast, not every \mathbb{G} -orbit closure on X is an intersection of \mathbb{G} -invariant prime divisors, see Example 3.

7. THE GENERAL CASE

We are going to show that every \mathbb{G} -embedding can be realized as in Proposition 6.

THEOREM 2. *Let $\mathbb{G} = T \times \mathbb{G}_a$ and X be a normal equivariant \mathbb{G} -embedding. Then the T -action on X can be extended to an action of a bigger torus \mathbb{T} such that \mathbb{T} normalizes \mathbb{G}_a and X is a toric variety with the acting torus \mathbb{T} . In particular, every \mathbb{G} -embedding comes from a pair (Σ, e) , where Σ is a fan and e is a Demazure root of Σ .*

Proof. We begin with a classical result of Sumihiro. Let X be a normal variety with a regular action $G \times X \rightarrow X$ of a linear algebraic group G . By [24, Theorem 3], there exists a normal complete G -variety \mathbf{X} such that X can be embedded equivariantly as an open subset of \mathbf{X} . In other words, \mathbf{X} is an equivariant compactification of X .

Let X be a normal embedding of \mathbb{G} and \mathbf{X} be an equivariant compactification of X . By Proposition 4, the T -action on \mathbf{X} can be extended to an action of a bigger torus \mathbb{T} such that \mathbb{T} normalizes \mathbb{G}_a and \mathbf{X} is a toric variety with the acting torus \mathbb{T} . Since the subset $X \subseteq \mathbf{X}$ is $(T \times \mathbb{G}_a)$ -invariant, it is invariant under \mathbb{T} , see Lemma 2. This provides the desired structure of a toric variety on X . \square

PROPOSITION 9. *A complete toric variety X admits a structure of a \mathbb{G} -embedding if and only if $\text{Aut}(X)^0 \neq \mathbb{T}$.*

Proof. The variety X admits a structure of a \mathbb{G} -embedding if and only if $\text{Aut}(X)^0$ contains at least one root subgroup. It is well known that the group $\text{Aut}(X)^0$ is generated by \mathbb{T} and root subgroups [13, Proposition 11], [23, Section 3.4], [11, Corollary 4.7]. \square

Consider two structures of a \mathbb{G} -embedding on a variety X . We say that such structures are *equivalent*, if there is an automorphism of X sending one structure to the other. Since the structure of a toric variety on X is unique up to automorphism, we may assume that our two structures share the same acting torus \mathbb{T} and the same fan Σ , and are given by two roots e, e' of Σ . Then the structures are equivalent if and only if e can be sent to e' by an automorphism of the torus \mathbb{T} . This leads to the following result.

PROPOSITION 10. *Two structures of a \mathbb{G} -embedding given by pairs (Σ, e) and (Σ, e') are equivalent if and only if there is an automorphism ϕ of the lattice N which preserves the fan Σ and such that the induced automorphism ϕ^* of the dual lattice M sends e to e' .*

Let us finish with explicit examples of \mathbb{G} -embeddings into a given variety.

EXAMPLE 2. We find all structures of \mathbb{G} -embeddings on \mathbb{A}^2 . The cone of \mathbb{A}^2 as a toric variety is $\mathbb{Q}_{\geq 0}^2$. The set of Demazure roots of $\mathbb{Q}_{\geq 0}^2$ is

$$\mathfrak{R} = \{(-1, k) \mid k \in \mathbb{Z}_{\geq 0}\} \sqcup \{(k, -1) \mid k \in \mathbb{Z}_{\geq 0}\},$$

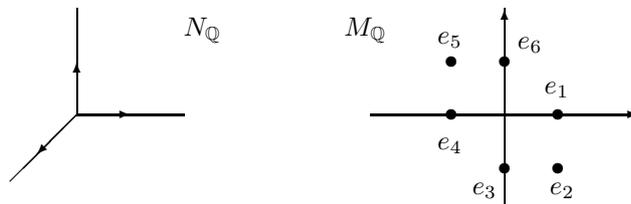
see Example 1. The \mathbb{G} -action on \mathbb{A}^2 corresponding to the root $(-1, k)$ is given by

$$(3) \quad (t, s) \circ (x_1, x_2) = (t^k x_1 + st^k x_2^k, tx_2),$$

where $(x_1, x_2) \in \mathbb{A}^2$, $s \in \mathbb{G}_a$, and $t \in \mathbb{K}^\times$. If $k \neq 0$, then there is a line of \mathbb{G}_a -fixed points and the stabilizer of a non-zero point on this line is a cyclic group of order k . If $k = 0$, then there is no \mathbb{G}_a -fixed point. So formula (3) gives non-equivalent \mathbb{G} -actions for different k . With $k \neq 0$ we have three \mathbb{G} -orbits on \mathbb{A}^2 , while for $k = 0$ there are two \mathbb{G} -orbits.

Note that \mathbb{G} -actions defined by the roots $(k, -1)$ and $(-1, k)$ are equivalent via the automorphism $x_1 \leftrightarrow x_2$ of \mathbb{A}^2 .

EXAMPLE 3. Let $X = \mathbb{P}^2$. It is a complete toric variety with a fan Σ generated by the vectors $(1, 0)$, $(0, 1)$ and $(-1, -1)$:



The set of Demazure roots is

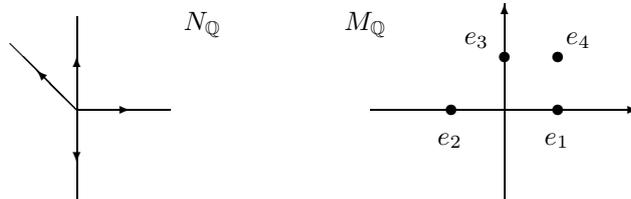
$$\mathfrak{R} = \{e_1 = (1, 0), e_2 = (1, -1), e_3 = (0, -1), e_4 = (-1, 0), e_5 = (-1, 1), e_6 = (0, 1)\}.$$

We see that for any i and j there exists isomorphism of the fan Σ sending e_i to e_j . So any \mathbb{G} -embedding into \mathbb{P}^2 is equivalent to

$$(t, s) \circ [z_0 : z_1 : z_2] = [tz_0 + stz_1 : tz_1 : z_2].$$

This time seven \mathbb{T} -orbits glue to five \mathbb{G} -orbits.

EXAMPLE 4. Consider the Hirzebruch surface \mathbb{F}_1 . The corresponding complete fan Σ is generated by the vectors $(1, 0)$, $(0, 1)$, $(0, -1)$, and $(-1, 1)$:



The set of Demazure roots is

$$\mathfrak{R} = \{e_1 = (1, 0), e_2 = (-1, 0), e_3 = (0, 1), e_4 = (1, 1)\}.$$

By an automorphism, we can send e_1 to e_2 and e_3 to e_4 . For the first equivalence class we have six \mathbb{G} -orbits, while in the second one the number of \mathbb{G} -orbits is seven.

REFERENCES

- [1] Klaus Altmann and Jürgen Hausen. Polyhedral divisors and algebraic torus actions. *Math. Ann.* 334 (2006), no. 3, 557–607
- [2] Ivan Arzhantsev. On factoriality of Cox rings. *Math. Notes* 85 (2009), no. 5, 623–629
- [3] Ivan Arzhantsev. Flag varieties as equivariant compactifications of \mathbb{G}_a^n . *Proc. Amer. Math. Soc.* 139 (2011), no. 3, 783–786
- [4] Ivan Arzhantsev, Ulrich Derenthal, Jürgen Hausen, and Antonio Laface. *Cox rings*. Cambridge Studies in Adv. Math. 144, Cambridge University Press, New York, 2015
- [5] Ivan Arzhantsev and Polina Kotenkova. \mathbb{G}_a -actions on T -varieties of complexity one. Preprint 22-B2014, 15.01.2014, VINITI RAN, 40 pages (Russian)
- [6] Ivan Arzhantsev, Karine Kuyumzhiyan, and Michail Zaidenberg. Flag varieties, toric varieties, and suspensions: three instances of infinite transitivity. *Sbornik: Math.* 203 (2012), no. 7, 923–949
- [7] Ivan Arzhantsev and Alvaro Liendo. Polyhedral divisors and SL_2 -actions on affine T -varieties. *Michigan Math. J.* 61 (2006), no. 4, 731–762
- [8] Ivan Arzhantsev and Elena Sharoyko. Hassett-Tschinkel correspondence: Modality and projective hypersurfaces. *J. Algebra* 348 (2011), no. 1, 217–232
- [9] Ivan Bazhov. On orbits of the automorphism group on a complete toric variety. *Beiträge zur Algebra und Geometrie* 54 (2013), no. 2, 471–481
- [10] Florian Berchtold. Lifting of morphisms to quotient presentations. *Manuscripta Math.* 110 (2003), no. 1, 33–44
- [11] David Cox. The homogeneous coordinate ring of a toric variety. *J. Alg. Geom.* 4 (1995), no. 1, 17–50
- [12] David Cox, John Little, and Henry Schenck. *Toric Varieties*. Graduate Studies in Math. 124, AMS, Providence, RI, 2011
- [13] Michel Demazure. Sous-groupes algébriques de rang maximum du groupe de Cremona. *Ann. Sci. Ecole Norm. Sup.* 3 (1970), 507–588
- [14] Ulrich Derenthal and Daniel Loughran. Singular del Pezzo surfaces that are equivariant compactifications. *J. Math. Sci.* 171 (2010), no. 6, 714–724
- [15] Ulrich Derenthal and Daniel Loughran. Equivariant compactifications of two-dimensional algebraic groups. *Proc. Edinburgh Math. Soc.* 58 (2015), no. 1, 149–168
- [16] Evgeni Feigin. \mathbb{G}_a^M degeneration of flag varieties. *Selecta Math. New Ser.* 18 (2012), no. 3, 513–537
- [17] Gene Freudenburg. *Algebraic theory of locally nilpotent derivations*. Encyclopaedia Math. Sci. 136, Springer, Berlin, 2006
- [18] William Fulton. *Introduction to toric varieties*. Annales of Math. Studies 131, Princeton University Press, Princeton, NJ, 1993
- [19] Brendan Hassett and Yuri Tschinkel. Geometry of equivariant compactifications of \mathbb{G}_a^n . *Int. Math. Res. Notices* 1999 (1999), no. 22, 1211–1230

- [20] James Humphreys. *Linear Algebraic Groups*. Graduate Texts in Math. 21, Springer Verlag, New York, 1975
- [21] Polina Kotenkova. *Torus actions and locally nilpotent derivations*. Ph.D. Thesis, Lomonosov Moscow State University, April 2014, 72 pages (Russian)
- [22] Alvaro Liendo. Affine \mathbb{T} -varieties of complexity one and locally nilpotent derivations. *Transform. Groups* 15 (2010), no. 2, 389–425
- [23] Tadao Oda. *Convex bodies and algebraic geometry: an introduction to toric varieties*. A Series of Modern Surveys in Math. 15, Springer Verlag, Berlin, 1988
- [24] Hideyasu Sumihiro. Equivariant completions. *J. Math. Kyoto Univ.* 14 (1974), 1–28
- [25] Joanna Świącicka. Quotients of toric varieties by actions of subtori. *Colloq. Math.* 82 (1999), no. 1, 105–116
- [26] Dmitri Timashev. Equivariant compactifications of reductive groups. *Sbornik Math.* 194 (2003), no. 4, 589–616
- [27] Dmitri Timashev. *Homogeneous spaces and equivariant embeddings*. Invariant Theory and Algebraic Transformation Groups 8, Encyclopaedia of Math. Sci. 138, Springer-Verlag, Heidelberg, 2011

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