TITLE:
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CITATION:
Arakawa, Tomoyuki. A remark on the C 2-cofiniteness condition on vertex algebras. Mathematische Zeitschrift 2012, 270(1-2): 559-575

ISSUE DATE:
2012-02

URL:
http://hdl.handle.net/2433/153402

RIGHT:
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A REMARK ON THE $C_2$-COFINITENESS CONDITION ON VERTEX ALGEBRAS

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Abstract. We show that a finitely strongly generated, non-negatively graded vertex algebra $V$ is $C_2$-cofinite if and only if it is lisse in the sense of Beilinson, Feigin and Mazur [BFM]. This shows that the $C_2$-cofiniteness is indeed a natural finiteness condition.

1. Introduction

The purpose of this note is to clarify the equivalence of the two finiteness conditions on vertex algebras.

One of them is the finiteness condition introduced by Zhu [Zhu96], which is now called the $C_2$-cofiniteness condition. This condition has been assumed in many significant theories of vertex operator algebras, such as [Zhu96, DLM00, Miy04, NT05, Hua08b, Hua08a]. However the original definition looks rather technical, and hence it has been often considered as a mere technical condition.

The other is the finiteness condition defined by Beilinson, Feigin and Mazur [BFM] in the case of the Virasoro (vertex) algebra, which is called lisse. The definition is as follows. Let $\mathcal{L}$ be the Virasoro (Lie) algebra, $U(\mathcal{L})$ its universal enveloping algebra. There is a natural increasing filtration of $U(\mathcal{L})$ in the Lie theory, called the standard filtration, and the associated graded algebra $\text{gr} U(\mathcal{L})$ of $U(\mathcal{L})$ is isomorphic to the symmetric algebra $S(\mathcal{L})$ of $\mathcal{L}$. Let $M$ be a finitely generated $\mathcal{L}$-module, $\{\Gamma_p M\}$ a good filtration (i.e., a filtration compatible with the standard filtration of $\mathcal{L}$ such that the associated graded space $\text{gr}^F M$ is finitely generated over $S(\mathcal{L})$). The singular support $SS(M)$ of $M$ is the support of the $S(\mathcal{L})$-module $\text{gr}^F M$, which is known to be independent of the choice of a good filtration. A $\mathcal{L}$-module $M$ is called lisse if $\dim SS(M) = 0$. In the case that $M$ is a highest weight representation of $\mathcal{L}$ then $M$ is lisse if and only if any element of $\mathcal{L}$ acts locally nilpotently on $\text{gr}^F M$. This implies that lisse representations are natural analogues of finite-dimensional representations.

Let $V$ be a finitely strongly generated, non-negatively graded vertex algebra. The notion of singular supports can be naturally extended to $V$ by using the canonical filtration introduced by Li [Li05]. More precisely, define the associated variety $X_M$ of a $V$-module $M$ as the support of the $V/C_2(V)$-module $M/C_2(M)$. Then the singular support of $M$ can be naturally defined as a subscheme of the infinite jet scheme of $X_M$. Having defined the associated variety and the singular support, the equivalence of the $C_2$-cofiniteness condition and the lisse condition easily follows...
from the fact that the jet scheme of a zero-dimensional variety is zero-dimensional (see Theorems 3.3.3, 3.3.4).

We note that in the case that $V$ is a Virasoro vertex algebra and $M$ is a $V$-module, the Li filtration of $M$ is slightly different from the Lie theoretic filtration defined by considering it as a module over the Virasoro (Lie) algebra $L$. Nevertheless $M$ is lisse if and only if it is so in the sense of [BFM] provided that $M$ is a highest weight representation of $L$ (see Proposition 3.4.2). In the case that $V$ is an affine vertex algebra associated with a Lie algebra the Li filtration is essentially the same as the Lie theoretic filtration, although it is a decreasing filtration (see Propositions 2.6.1, 2.7.1).

In a separate paper [Ara] we prove the $C_2$-cofiniteness for a large family of $W$-algebras using the methods in this note, including all the (non-principal) exceptional $W$-algebras recently discovered by Kac and Wakimoto [KW08].

Notation. The ground field will be $\mathbb{C}$ throughout the note.

2. Graded Poisson vertex algebras associated with vertex algebras

2.1. Vertex algebras and their modules. A (quantum) field on a vector space $V$ is a formal series

$$a(z) = \sum_{n \in \mathbb{Z}} a(n) z^{-n-1} \in (\text{End} V)[[z, z^{-1}]]$$

such that $a(n)v = 0$ with $n \gg 0$ for any $v \in V$. Let $Fields(V)$ denote the space of all fields on $V$.

A vertex algebra is a vector space $V$ equipped with the following data:

- a linear map $Y(?, z) : V \to Fields(V)$, $a \mapsto a(z) = \sum_{n \in \mathbb{Z}} a(n) z^{-n-1}$,
- a vector $1 \in V$, called the vacuum vector,
- a linear operator $T : V \to V$, called the translation operator.

These data are subjected to satisfy the following axioms:

(i) $(Ta)(z) = \partial_z a(z)$,
(ii) $1(z) = id_V$,
(iii) $a(z)1 \in V[[z]]$ and $a(-1)1 = a$,
(iv) A Hamiltonian of $V$ is a semisimple operator $H$ on $V$ satisfying

\[ [H, a(n)] = - (n + 1) a(n) + (Ha)(n) \]

for all $a \in V$, $n \in \mathbb{Z}$. A vertex algebra equipped with a Hamiltonian $H$ is called graded. Let $V_\Delta = \{a \in V : Ha = \Delta a\}$ for $\Delta \in \mathbb{C}$, so that $V = \bigoplus_{\Delta \in \mathbb{C}} V_\Delta$. For $a \in V_\Delta$, $\Delta$ is called the conformal weight of $a$ and denoted by $\Delta_a$. We have

$$a(n)b \in V_{\Delta_a + \Delta_b - n - 1}$$

for homogeneous elements $a, b \in V$. 
Throughout the note $V$ is assumed to be $\frac{1}{r_0}\mathbb{Z}_{\geq 0}$-graded for some $r_0 \in \mathbb{N}$, that is, $V$ is graded and $V_\Delta = 0$ for $\Delta \not\in \frac{1}{r_0}\mathbb{Z}_{\geq 0}$.

A graded vertex algebra $V$ is called conformal if there exists a vector $\omega$ (called the conformal vector) and $cv \in \mathbb{C}$ (called the central charge) satisfying
\[
\omega(0) = T, \quad \omega(1) = H,
\]
\[
[\omega(m+1); \omega(n+1)] = (m-n)\omega(m-n+1) + \frac{(m^3 - m)}{12}\delta_{m+n,0}cv.
\]

A $\mathbb{Z}$-graded conformal vertex algebra is also called a vertex operator algebra.

A vertex algebra $V$ is called finitely strongly generated if there exists a finitely many elements $a^1, \ldots, a^r$ such that $V$ is spanned by the elements of the form
\[
a^{i_1}_{(-n_1)} \cdots a^{i_r}_{(-n_r)}1
\]
with $r \geq 0$, $n_i \geq 1$.

A module over a vertex algebra $V$ is a vector space $M$ together with a linear map
\[
Y^M(?, z) : V \rightarrow \text{Fields}(M), \quad a \mapsto a^M(z) = \sum_{n \in \mathbb{Z}} a^M_{(n)} z^{-n-1},
\]
which satisfies the following axioms:

(i) $1^M(z) = \text{id}_M$,

(ii)
\[
\sum_{j \geq 0} \binom{m}{j} (a_{(n+j)}b^M_{(m+k-j)})
= \sum_{j \geq 0} (-1)^j \binom{n}{j} \left( a^M_{(n+m-j)} b^M_{(k+j)} - (-1)^{n+k} a^M_{(n+k-j)} b^M_{(m+j)} \right).
\]

A $V$-module $M$ is called graded if there is a compatible semisimple action of $H$ on $M$, that is, $M = \bigoplus_{n \in \mathbb{C}} M_d$, where $M_d = \{ m \in M; Hm = dm \}$, and $[H, a^M_{(n)}] = -(n+1)a^M_{(n)} + (Ha)^M_{(n)}$ for all $a \in V$. We have $a^M_{(n)} M_d \subset M_{d+\Delta_n-n-1}$ for a homogeneous element $a \in V$.

Throughout the note a $V$-module $M$ is assumed to be lower truncated, that is, $M$ is graded and there exists a finites subset $\{d_1, \ldots, d_r\} \subset \mathbb{C}$ such that $M_d \neq 0$ unless $d \in d_i + \frac{1}{r_0}\mathbb{Z}_{\geq 0}$ for some $i$.

For a $V$-module $M$, set
\[
C_2(M) = \text{span}_\mathbb{C}\{ a_{(-2)}m; a \in V, m \in M \}.
\]
Then
\[
C_2(M) = \text{span}_\mathbb{C}\{ a_{(-n)}m; a \in V, m \in M, \ n \geq 2 \}
\]
by the axiom (i) of vertex algebras. A $V$-module $M$ is called $C_2$-cofinite if $\dim M/C_2(M) < \infty$, and $V$ is called $C_2$-cofinite if it is $C_2$-cofinite as a module over itself.
Suppose that $V$ is conformal. Then a $V$-module $M$ is called $C_1$-cofinite \([Li99]\) if $M/C_1(M)$ is finite-dimensional, where

$$C_1(M) = \text{span}_C \{ \omega(0)m, a(-1)m; a \in \bigoplus_{\Delta \geq 0} V_\Delta, m \in M \}.$$ 

If $V_0 = \mathbb{C}1$, then $C_2(V)$ is a subspace of $C_1(V)$ (\([Li99]\) Remark 3.2).

### 2.2. Vertex Poisson algebras and their modules.

A vertex algebra $V$ is said to be commutative if $a(n) = 0$ in $\text{End} V$ for all $n \geq 0$, $a \in V$. This is equivalent to that

$$[a(m), b(n)] = 0 \quad \text{for} \quad a, b \in V, \quad m, n \in \mathbb{Z}.$$ 

A commutative vertex algebra is the same as a differential algebra (= a unital commutative algebra with a derivation) \([Bor86]\): the multiplication is given by $a \cdot b = a(-1)b$ for $a, b \in V$; The derivation is given by the translation operator $T$.

A commutative vertex algebra $V$ is called a vertex Poisson algebra \([FBZ04]\) if it is also equipped with a linear operation

$$Y_-(?, z) : V \to \text{Hom}(V, z^{-1}V[z^{-1}]), \quad a \mapsto a_-(z),$$

such that

(3) \quad $(Ta)(n) = -na_{(n-1)}$,

(4) \quad $a(n)b = \sum_{j \geq 0} (-1)^{n+j+1} \frac{1}{j!} T^j(b_{(n+j)}a)$,

(5) \quad $[a(m), b(n)] = \sum_{j \geq 0} \binom{m}{j} (a_{(j)}b)_{(m+n-j)}$,

(6) \quad $a(n)(b \cdot c) = (a(n)b) \cdot c + b \cdot (a(n)c)$

for $a, b, c \in V$ and $n, m \geq 0$. Here, by abuse of notation, we have set

$$a_-(z) = \sum_{n \geq 0} a(n)z^{-n-1}.$$ 

Below, for an element $a$ of a vertex Poisson algebra, we will denote by $a(n)$ with $n \leq -1$ the Fourier coefficient of $z^{-n-1}$ in the field $Y(a, z) = a(z)$, and by $a(n)$ with $n \geq 0$ the Fourier coefficient of $z^{-n-1}$ in $Y_-(a, z) = a_-(z)$.

A vertex Poisson algebra $V$ is called graded if there exists a semisimple operator $H$ on $V$ satisfying (11) for all $n \in \mathbb{Z}$.

A module over a vertex Poisson algebra $V$ is a module $M$ over $V$ as an associative algebra together with a linear map

$$Y_-^M(?, z) : V \to \text{Hom}(M, z^{-1}M[z^{-1}]), \quad a \mapsto a_-^M(z) = \sum_{n \geq 0} a(n)_nz^{-n-1},$$

such that

(7) \quad $1_M^M(z) = \text{id}_M$,

(8) \quad $(Ta)^M(n) = -na_{(n-1)}$,

(9) \quad $[a^M_{(m)}, b^M_{(n)}] = \sum_{i \geq 0} \binom{m}{i} (a_{(i)}b)^M_{(m+n-i)}$,

(10) \quad $a^M_{(n)}(b \cdot m) = (a_{(n)b}) \cdot m + b \cdot (a^M_{(n)m})$. 
for \(a, b \in V, m \in M\) and \(n \geq 0\).

A module \(M\) over a graded vertex Poisson algebra \(V\) is called graded if there exists a semisimple operator \(H^M\) on \(M\) satisfying

\[
[H^M, a^M_{(n)}] = -(n + 1)a^M_{(n)} + (Ha)^M_{(n)}
\]

for all \(a \in V, n \in \mathbb{Z}\).

If no confusion can arise below we write \(a_{(n)}\) for \(a^M_{(n)}\) and \(H\) for \(H^M\).

We call \(M\) a differential \(V\)-module if it is equipped with the linear action of \(T\) satisfying

\[
[T, a_{(n)}] = -na_{(n-1)} \quad \text{for all} \; n \in \mathbb{Z}.
\]

2.3. Functions on jet schemes of affine Poisson varieties are vertex Poisson algebras. For a scheme \(X\) of finite type we denote by \(X_m\) be the jet scheme of order \(m\) of \(X\) and by \(X_{\infty}\) the infinite jet scheme of \(X\).

Let us recall the definition of jet schemes. For general theory of jet schemes see e.g., [EM09]. The connection between jet schemes and chiral algebras goes back to Beilinson and Drinfeld [BD04]. The scheme \(X_m\) is determined by its functor of points: for every commutative \(\mathbb{C}\)-algebra \(A\), there is a bijection

\[\text{Hom}(\text{Spec} \; A, X_m) \cong \text{Hom}(\text{Spec} \; A[t]/(t^{m+1}), X).\]

If \(m > n\), we have projections \(X_m \to X_n\). This yields a projective system \(\{X_m\}\) of schemes, and the infinite jet scheme \(X_{\infty}\) is the projective limit \(\lim_{m \to \infty} X_m\) in the category of schemes.

For an affine scheme \(X = \text{Spec} \; R\), the jet scheme \(X_m\) is explicitly described. Choose a presentation \(R = \mathbb{C}[x^1, \ldots, x^r]/\langle f_1, \ldots, f_s \rangle\). Define new variables \(x^j_{(i)}\) for \(i = 1, \ldots, m + 1\) and a derivation \(T\) of the ring \(\mathbb{C}[x^j_{(i)}; i = 1, 2, \ldots, m + 1, j = 1, \ldots, r]\) by setting

\[Tx^j_{(i)} = \begin{cases} ix^j_{(i-1)} & \text{for} \; i \leq m, \\ 0 & \text{for} \; i = m + 1. \end{cases}\]

Identify \(x^j\) with \(x^j_{(-1)}\) and set

\[R_m = \mathbb{C}[x^j_{(i)}; i = 1, \ldots, m + 1, j = 1, \ldots, r]/\langle T^j f_i; i = 1, \ldots, s, j = 0, \ldots, m + 1 \rangle,\]

and we have \(X_m \cong \text{Spec} \; R_m\).

Let \(R_{\infty}\) denotes the differential algebra obtained from \(R_m\) by taking the limit \(m \to \infty\):

\[R_{\infty} = \mathbb{C}[x^j_{(-i)}; i = 1, 2, \ldots, j = 1, \ldots, ]/\langle T^j f_i; i = 1, \ldots, s, j = 0, \ldots, \rangle.\]

Then \(X_{\infty} \cong \text{Spec} \; (R_{\infty})\).

**Proposition 2.3.1.** Let \(R\) be a Poisson algebra. Then there is a unique vertex Poisson algebra structure on \(R_{\infty}\) such that

\[u^{(n)}v = \begin{cases} \{u, v\} & \text{if} \; n = 0, \\ 0 & \text{if} \; n > 0, \end{cases}\]

for \(u, v \in R \subset R_{\infty}\).
Proof. Set
\[ u_{(n)}(T^l v) = \begin{cases} \frac{n}{(l-n)} T^{l-n} \{u, v\} & \text{if } l \geq n, \\ 0 & \text{else} \end{cases} \]
for \( a, b \in R \). This extends to a well-defined linear map
\[ R \to \text{Der}(R_\infty) [[z^{-1}]] z^{-1}, \quad u \mapsto u_-(z) = \sum_{n \geq 0} u_{(n)} z^{-n-1}, \]
where \( \text{Der}(R_\infty) \) is the space of derivations on \( R_\infty \). It is straightforward to check that
\[ [T, u_-(z)] = \partial_z u_-(z) \quad \text{for } u \in R, \]
\[ u_{(n)} v = \sum_{j \geq 0} (-1)^{n+j+1} \frac{j!}{n!} T^j (v_{(n+j)} u) \quad \text{for } u, v \in R, \]
\[ [u_{(m)}, v_{(n)}] = \sum_{j \geq 0} \binom{m}{j} (u_{(j)} v)_{(m+n-j)} \quad \text{for } u, v \in R. \]

The map (11) can be extended to the linear map
\[ R_\infty \to \text{Der}(R_\infty) [[z^{-1}]] z^{-1}, \quad a \mapsto a_-(z) = \sum_{n \geq 0} a_{(n)} z^{-n-1} \]
by setting
\[ a_-(z) T^k u = \text{Sing}(e^{zT} (-\partial_z)^k u_-(z) a) \]
for \( a \in R_\infty, \ u \in R, \ k \geq 0 \). Here \( \text{Sing}(f) \) is the singular part of the formal series \( f \) \((\text{Pr}99, \text{Li}04)\). (Note that the axiom (4) is equivalent to that \( a_-(z) b = \text{Sing}(e^{zT} b_-(z) a) \).) We find from the argument of \( \text{Li}04 \) Proof of Proposition 3.10 that
\[ (Ta)_-(z) = \partial_z a_-(z) \quad \text{for } a \in R_\infty, \]
\[ a_-(z) b = \text{Sing}(e^{zT} b_-(z) a) \quad \text{for } a, b \in R_\infty. \]
This together (12) proves that (13) defines a vertex Poisson structure on \( R_\infty \) by \( \text{Li}04 \) Theorem 3.6]. The uniqueness statement is easily seen, cf. \( \text{Li}04 \) Proof of Proposition 3.10. \( \square \)

The vertex Poisson algebra structure on \( R_\infty = \mathbb{C}[X_\infty] \) given in Proposition 2.3.1 for an affine scheme \( X = \text{Spec} R \) will be called the level 0 vertex Poisson algebra structure.

Remark 2.3.2. The differential algebra \( R_\infty \) makes sense even when \( R \) is not finitely generated and Proposition 2.3.1 still holds in this case. Also, the assertion of Proposition 2.3.1 extends straightforwardly to the Poisson superalgebra cases.

2.4. Ideals of vertex Poisson algebras. Let \( V \) be a vertex Poisson algebra, \( M \) a \( V \)-module. A submodule of \( M \) is a submodule \( N \) of \( M \) as an associative algebra such that \( a_{(n)} N \subset N \) for all \( a \in V, \ n \geq 0 \). An ideal of \( V \) is a submodule \( I \) of \( V \) stable under the action of \( T \). By (4) it follows that \( u_{(n)} V \subset I \) for all \( u \in I \) and \( n \geq 0 \). Hence \( V/I \) inherits the vertex Poisson algebra from \( V \).

Lemma 2.4.1. Let \( R \) be a commutative \( \mathbb{Q} \)-algebra, \( \partial \) a derivation on \( R, \ I \) a \( \partial \)-stable ideal of \( R \). Then the radical \( \sqrt{I} \) of \( I \) is stable under the action of \( \partial \).
Proof. ([CO78]) Let \( a \in \sqrt{I} \), so that there exists \( m \in \mathbb{N} \) such that \( a^m \in I \). Because \( \partial I \subset I \), \( (\partial)^m a^m \in I \). But
\[
(\partial)^m a^m \equiv m!(\partial a)^m \pmod{\sqrt{I}},
\]
and therefore we get that \( (\partial a)^m \in \sqrt{I} \). This gives \( \partial a \in \sqrt{I} \). \( \square \)

**Corollary 2.4.2.**

(i) Let \( R \) be a Poisson algebra, \( I \) a Poisson ideal of \( R \). Then \( \sqrt{I} \) is also a Poisson ideal.

(ii) Let \( V \) be a vertex Poisson algebra, \( I \) a \( V \)-submodule of \( V \). Then \( \sqrt{I} \) is also a \( V \)-submodule of \( V \).

(iii) Let \( V \) be a vertex Poisson algebra, \( I \) a vertex Poisson algebra ideal of \( V \). Then \( \sqrt{I} \) is also a vertex Poisson algebra ideal of \( V \).

2.5. **Li filtration.** Let \( V \) be a vertex algebra. Following [Li05], define \( F^p V \) to be the subspace of \( V \) spanned by the vectors
\[
a_1^{(-n_1-1)} \cdots a_r^{(-n_r-1)} b
\]
with \( a_i \in V \), \( b \in V \) \( n_i \in \mathbb{Z}_{\geq 0} \), \( n_1 + \cdots + n_r \geq p \). Then
\[
V = F^0 V \supset F^1 V \supset \cdots, \quad \bigcap_p F^p V = 0,
\]
\[
T F^p V \subset F^{p+1} V,
\]
\[
a^{(n)}_r F^q V \subset F^{p+q-n-1} V \quad \text{for } a \in F^p V, \ n \in \mathbb{Z},
\]
\[
a^{(n)}_r F^q V \subset F^{p+q-n} V \quad \text{for } a \in F^p V, \ n \geq 0.
\]
(14)

Here we have set \( F^p V = V \) for \( p < 0 \). Note that the filtration \( \{F^p V\} \) is independent of the grading of \( V \).

Let \( \text{gr}^F V = \bigoplus_p F^p V/F^{p+1} V \) be the associated graded vector space. The space \( \text{gr}^F V \) is a vertex Poisson algebra by
\[
\sigma_p(a)\sigma_q(b) = \sigma_{p+q}(a(-1)b)
\]
\[
T \sigma_p(a) = \sigma_{p+1}(Ta),
\]
\[
Y_-(\sigma_p(a), z)\sigma_q(b) = \sum_{n \geq 0} \sigma_{p+q-n}(a^{(n)}_r b) z^{-n-1},
\]
where \( \sigma_p : F^p V \to F^p V/F^{p+1} V \) is the principal symbol map.

The filtration \( \{F^p V\} \) is called the **Li filtration of** \( V \).

We have [Li05, Lemma 2.9]

(15) \( F^p V = \text{span}_\mathbb{C}\{a^{(-i-1)}_i b; a \in V, i \geq 1, b \in F^{p-i} V\} \) for all \( p \geq 1 \).

In particular
\[
F^1 M = C_2(M).
\]

Set
\[
R_V = V/C_2(V) = F^0 V/F^1 V \subset \text{gr}^F V.
\]

\(^{1}\)In [Li05] \( F^p V \) was denoted by \( E_p \).
It is known by Zhu [Zhu96] that $R_V$ is a Poisson algebra. In fact the Poisson algebra structure of $R_V$ can be understood as the restriction of the vertex Poisson structure of $\text{gr}^FV$ [Li03, Proposition 3.5]; it is given by
\[
\bar{a} \cdot \bar{b} = a_{(-1)}b,
\]
\[
\{\bar{a}, \bar{b}\} = a_{(0)}b
\]
for $a, b \in V$, where $\bar{a} = a + C_2(V)$.

By [Li03, Lemma 4.2], the embedding $R_V \hookrightarrow \text{gr}^FV$ extends to the surjective homomorphism
\[
(R_V)_\infty \rightarrow \text{gr}^FV
\]
of differential algebras.

**Proposition 2.5.1.** The surjection (10) is a homomorphism of vertex Poisson algebras, where $(R_V)_\infty$ is equipped with the level 0 vertex Poisson algebra structure.

**Proof.** From the definition we see that the vertex Poisson algebra structure coincides on the generating subspace $R_V$, that is, for $a, b \in R_V$, $a_{(0)}b = \{a, b\}$ and $a_{(n)}b = 0$ for all $n > 0$ in both $\text{gr}V$ and $(R_V)_\infty$. But then [Li04, Lemma 3.3] says that the map $(R_V)_\infty \rightarrow \text{gr}V$ must be a vertex Poisson algebra homomorphism. \qed

2.6. **Standard filtration vs Li filtration.** There is another filtration $\{G_pV; p \in \frac{1}{r_0}Z_{\geq 0}\}$ of $V$ called the *standard filtration*, which is an increasing filtration defined also by Li [Li04] by choosing a set $\{a^i; i \in I\}$ of homogeneous strong generators of $V$.

Let $G_pV$ be the linear subspace of $V$ spanned by the vectors
\[
a_{(-n_1)} \cdots a_{(-n_r)}1 \quad \text{satisfying} \quad \Delta_{a_{n_1}} + \cdots + \Delta_{a_{n_r}} \leq p,
\]
with $r \geq 0, n_i \geq 1$. Then
\[
G_pV \subset G_qV \quad \text{for} \quad p < q,
\]
\[
V = \bigcup_p G_pV,
\]
\[
TG_pV \subset G_pV,
\]
\[
a_{(n)}G_qV \subset G_{p+q}V, \quad \text{for} \quad a \in G_pV, \quad n \in Z,
\]
\[
a_{(n)}G_qV \subset G_{p+q-1}V, \quad \text{for} \quad a \in G_pV, \quad n \in Z_{>0}.
\]

It follows that $\text{gr}^G V = \bigoplus_{p \in \frac{1}{r_0}Z_{\geq 0}} G_pV/G_{p-1}V$ is naturally a vertex Poisson algebra, where we have set $G_0V = 0$ for $p < 0$.

By [Li04, Theorem 4.14] the standard filtration $\{G_pV\}$ is characterized as the finest increasing filtration of $V$ satisfying (18)-(22) such that
\[
V_\Delta \subset G_\Delta V.
\]

In particular, it is independent of the choice of a set of strong generators of $V$.

Both filtrations $\{F^pV\}$ and $\{G_pV\}$ are stable under the action of the Hamiltonian. Let $F^pV_\Delta = V_\Delta \cap F^pV$, $G_pV_\Delta = V_\Delta \cap G_pV$, so that $F^pV = \bigoplus_\Delta F^pV_\Delta$, $G_pV = \bigoplus_\Delta G_pV_\Delta$.

\[\text{In [Li04] it is assumed that } V \text{ is } Z_{\geq 0}\text{-graded and } V_0 = \mathbb{C}, \text{ but this condition can be easily relaxed, as we can see from Proposition 2.6.1.}\]
Proposition 2.6.1. We have

\[ F^p V_\Delta = G_{\Delta - p} V_\Delta \]

for all \( p \) and \( \Delta \). Moreover, the linear isomorphism

\[ \text{gr}^F V \cong \text{gr}^G V \]

is an isomorphism of vertex Poisson algebras.

Proof. The second assertion is easily seen from the first. So let us prove the first assertion. First, we have by (23)

\[ \text{gr}^F V \cong \text{gr}^G V \]

Next we show the inclusion \( F^p V_\Delta \subset G_{\Delta - p} V_\Delta \) by induction on \( p \geq 0 \). Let \( p > 0 \). By (13), \( F^p V_\Delta \) is spanned by the elements

\[ a_{(-i-1)} b, \quad \text{with } a \in V_\Delta, \quad b \in F^{p-i} V_\Delta, \quad i \geq 1, \quad \Delta a + \Delta b + i = \Delta. \]

By the induction hypothesis \( F^{p-i} V_\Delta \subset G_{\Delta - p+i} V_\Delta \) for \( i \geq 1 \). Because \( a \in V_\Delta, \subset G_{\Delta a} V, \) for the vector \( a_{(-i-1)} b \) of the form (24) we have

\[ a_{(-i-1)} b \in a_{(-i-1)} G_{\Delta a - p+i} V_\Delta \subset G_{\Delta a + \Delta a - p+i} V_\Delta = G_{\Delta - p} V_\Delta. \]

Hence \( F^p V_\Delta \subset G_{\Delta - p} V_\Delta \).

It remains to show the opposite inclusion \( G_p V_\Delta \subset F^p V_\Delta \). We prove that any element \( v \) of \( G_p V_\Delta \) of the form (17) belongs to \( F^p V_\Delta \) by induction on \( r \geq 0 \). For \( r = 0 \) this is obvious. So let \( r > 0 \). Then \( v = a_{(-n_1)} w \) with \( w = a_{(-n_2)} \cdots a_{(-n_r)} 1 \), \( n_i \geq 1 \), \( \sum \Delta a_i \leq p \), \( \Delta a_i + \Delta w + n - 1 = \Delta \), where each \( a_i \) is homogeneous. Because \( w \in G_{\Delta - p} V, \) the induction hypothesis gives that \( w \in F^{\Delta a_1 + \Delta w - p} V \). Hence \( a_{n_1} \cdots a_{n_r} w \in F^{\Delta a_1 + \Delta w - p + n - 1} V_\Delta = F^{\Delta - p} V_\Delta \). This completes the proof.

From Proposition 2.6.1 we get the following well-known fact [GN03].

Corollary 2.6.2. Let \( \{ a^i; i \in I \} \) be a set of homogeneous vectors of \( V \). Then the following are equivalent:

(i) \( \{ a^i; i \in I \} \) strongly generates \( V \).
(ii) \( \{ a^i; i \in I \} \) generates \( R_V \).

In particular \( V \) is finitely strongly generated if and only if \( R_V \) is finitely generated.

Proof. Suppose that \( \{ a^i; i \in I \} \) strongly generates \( V \). By Proposition 2.6.1 \( C_2(V) = F^1 V \) is spanned by the vectors of the form (17) with \( n_1 + \cdots + n_r - r \geq 1 \), proving that \( \{ a^i; i \in I \} \) generates \( R_V \).

Conversely, suppose that \( \{ a^i; i \in I \} \) generates \( R_V \). Then by (16) \( \{ a^i \} \) generates \( \text{gr} F V \) as a differential algebra. As the principal symbol map gives the isomorphism \( V \cong \text{gr} F V \) of vector spaces, it follows that \( \{ a^i \} \) strongly generates \( V \).

2.7. Example: universal affine vertex algebras. Let \( \mathfrak{g} \) be a simple Lie algebra over \( \mathbb{C} \). \( \hat{\mathfrak{g}} = \mathfrak{g}[t, t^{-1}] \oplus \mathbb{C} K \) the Kac-Moody affinization of \( \mathfrak{g} \) with the central element \( K \). For \( k \in \mathbb{C} \), define

\[ V^k(\hat{\mathfrak{g}}) = U(\hat{\mathfrak{g}}) \otimes U(\mathfrak{g}[t] \oplus \mathbb{C} K) \mathbb{C}_k, \]

where \( \mathbb{C}_k \) is the one-dimensional representation of \( \mathfrak{g}[t] \oplus \mathbb{C} K \) on which \( \mathfrak{g}[t] \) acts trivially and \( K \) acts as the multiplication by \( k \).
There is a unique vertex algebra structure in $V^k(\mathfrak{g})$ such that $1 = 1 \otimes 1$ is the vacuum vector and

$$Y(x_{(-1)}1, z) = x(z) := \sum_{n \in \mathbb{Z}} x(n)z^{-n-1} \quad \text{for } x \in \mathfrak{g},$$

where $x(n) = x \otimes t^n$. The vertex algebra $V^k(\mathfrak{g})$ is called the universal affine vertex algebra associated with $\mathfrak{g}$ at level $k$ (see [Kac98 4.7], [FBZ04 2.4.2]).

The vertex algebra $V^k(\mathfrak{g})$ is conformal by the Sugawara construction, provided that $k \neq -h^\vee$, where $h^\vee$ is the dual Coxeter number of $\mathfrak{g}$.

**Proposition 2.7.1.** For any $k \in \mathbb{C}$ we have the following.

(i) $R_{V^k(\mathfrak{g})} \cong \mathbb{C}[\mathfrak{g}^\ast]$ as Poisson algebras, where $\mathfrak{g}^\ast$ is equipped with the Kirillov-Kostant Poisson structure.

(ii) $\text{gr}^F V^k(\mathfrak{g}) \cong \mathbb{C}[\mathfrak{g}_\infty^\ast]$ as vertex Poisson algebras, where $\mathbb{C}[\mathfrak{g}_\infty^\ast]$ is equipped with the level 0 vertex Poisson structure.

In particular $R_{V^k(\mathfrak{g})}$ and $\text{gr}^F V^k(\mathfrak{g})$ are independent of $k \in \mathbb{C}$.

**Proof.** Although Proposition is well-known (see e.g., [DLM02 DSK05 DSK06]), we include the proof for completeness.

The vertex algebra $V^k(\mathfrak{g})$ is naturally $\mathbb{Z}_{\geq 0}$-graded (see e.g., [Kac98 Example 4.9b]). We consider the corresponding standard filtration $\{G_pV^k(\mathfrak{g})\}$. We have $V^k(\mathfrak{g}) \cong U(\mathfrak{g}[t^{-1}]t^{-1})$ as vector spaces. Under this isomorphism $G_pV^k(\mathfrak{g})$ gets identified with $U_p(\mathfrak{g}[t^{-1}]t^{-1})$, where $\{U_p(\mathfrak{g}[t^{-1}]t^{-1})\}$ is the standard filtration of the enveloping algebra $U(\mathfrak{g}[t^{-1}]t^{-1})$ in the Lie theory, that is, $U_p(\mathfrak{g}[t^{-1}]t^{-1})$ is the linear span of products of at most $p$ elements in $\mathfrak{g}[t^{-1}]t^{-1}$. It follows that $\text{gr}^G V^k(\mathfrak{g}) \cong S(\mathfrak{g}[t^{-1}]t^{-1})$ as commutative rings, and thus $\text{gr}^F V^k(\mathfrak{g}) \cong S(\mathfrak{g}[t^{-1}]t^{-1})$ as commutative rings by Proposition 2.6.1.

Now $S(\mathfrak{g}[t^{-1}]t^{-1})$ is naturally isomorphic to $S(\mathfrak{g})_\infty = \mathbb{C}[\mathfrak{g}_\infty^\ast]$ as commutative rings, and we get the isomorphism

$$\Phi : \mathbb{C}[\mathfrak{g}_\infty^\ast] \to \text{gr}^F V^k(\mathfrak{g}),$$

which is easily seen to be an isomorphism of differential algebras. It remains to prove that $\Phi$ is a homomorphism of vertex Poisson algebras. For this, it is sufficient to check that $\Phi(x_{(n)}) = \Phi(x)_{(n)}$ only for $x \in \mathfrak{g}$ by [Li04 Lemma 3.3]. For $n > 0$ this follows immediately from the definition, and for $n = 0$ this is equivalent to (i) of Proposition, which is easy to see. \qed

3. Associated Varieties of Vertex Algebras and Their Modules

For the rest of the paper we will assume that $V$ to be finitely strongly generated. Thus, in particular, $R_V$ is finitely generated (Corollary 2.6.2).

3.1. Filtration of V-modules. Let $M$ be a $V$-module. A compatible filtration $\{\Gamma^pM\}$ of $M$ is a decreasing filtration $M = \Gamma^0M \supset \Gamma^1M \supset \cdots$ satisfying

$$a_{(n)}\Gamma^qM \subset \Gamma^{p+q-n-1}M, \quad \text{for } a \in F^pV, \ n \in \mathbb{Z},$$

$$a_{(n)}\Gamma^qM \subset \Gamma^{p+q-n}M \quad \text{for } a \in F^pV, \ n \geq 0,$$

$$H\Gamma^qM \subset \Gamma^qM,$$

where $\{F^pV\}$ is the Li filtration of $V$. The associated graded space $\text{gr}^F M = \bigoplus \Gamma^pM/\Gamma^{p+1}M$ is naturally a module over the vertex Poisson algebra $\text{gr}^F V$. Here
we have set $\Gamma^p M = M$ for $p < 0$. Note that each subspace $\Gamma^p M/\Gamma^{p+1} M$ of $\text{gr}^p M$

is a submodule over $R_V = V/C(2)$. A compatible filtration $\{\Gamma^p M\}$ is good\footnote{The definition of a “good” filtration in this note is different form the one given in [Li05].} if it is separated (i.e. $\bigcap \Gamma^p M = 0$) and $\text{gr}^p M$ is finitely generated over the ring $\text{gr} V$.

Remark 3.1.1. Let $\{\Gamma^p M\}$ be a compatible filtration of a $V$-module $M$. Then $\bigcap_p \Gamma^p M$ is a submodule of $M$. Hence, if $M$ is simple, we have either $\bigcap \Gamma^p M = 0$ or $\bigcap \Gamma^p M = M$.

Lemma 3.1.2. Let $V$ be a conformal vertex algebra, $M$ a $V$-module, $\{\Gamma^p M\}$ a compatible filtration. Then $\text{gr}^p M$ is a differential $\text{gr}^F V$-module.

Proof. Let $\omega$ be the Virasoro element of $V$. Then the derivation $\Gamma^p M/\Gamma^{p+1} M \to \Gamma^{p-1}/\Gamma^p M$, $\sigma_p(m) \to \sigma_{p-1}(\omega(0)m)$, defines an action of $T$ with the desired property. \hfill \□

Let $F^p M$ be a subspace of $M$ spanned by the vectors

$$a_1^{(-n_1-1)} \cdots a_r^{(-n_r-1)} m$$

with $a^i \in V$, $m \in M$, $n_i \in \mathbb{Z}_{\geq 0}$, $n_1 + \cdots + n_r \geq p$. Then $\{F^p M\}$ is a compatible filtration [Li05]. It is separated because $M$ is lower truncated by our assumption, see (the proof of) [Li05] Lemma 2.1.4. The filtration $\{F^p M\}$ is called the Li filtration of a $V$-module $M$. Note that

$$F^1 M = C_2(M).$$

The $\text{gr} V$-module structure of $\text{gr}^F M$ gives a $R_V$-module structure on $M/C_2(M)$:

$$\tilde{a}.\tilde{m} = \underline{a_{(-1)}} m, \quad a \in V, \ m \in M,$$

where $\tilde{a} = a + C_2(V)$, $\tilde{m} = m + C_2(M)$. Note that $M/C_2(M)$ is also a module over $R_V$ viewed as a Lie algebra by the assignment $\tilde{a} \mapsto L_{\tilde{a}}$, where

$$L_{\tilde{a}} \tilde{m} = \underline{a_{(0)}} \tilde{m}, \quad a \in V, \ m \in M.$$

These two actions are compatible in the sense that

$$L_{\tilde{a}} \tilde{b}.\tilde{m} = \{\tilde{a}, \tilde{b}\} \tilde{m} + \tilde{b}. L_{\tilde{a}} \tilde{m}. \tag{27}$$

Lemma 3.1.3 ([Li05] Lemma 4.2). For a $V$-module $M$, the $\text{gr}^F V$-module $\text{gr}^F M$

is generated by the subspace $M/C_2(M) = F^0 M/F^1 M$.

Lemma 3.1.4. Let $\{a^i; i \in I\}$ be a set of strong generators of $V$. Then

$$C_2(M) = \text{span}_C \{a_i^{(-n)} m; i \in I, \ n \geq 2, \ m \in M\}. \tag{26}$$

Proof. Let $\{F^p C_2(V)\}$ be the induced filtration. Then we have $\text{gr}^F C_2(V) = \bigoplus_{p \geq 1} F^p M/F^{p+1} M$ and

$$\text{gr}^F C_2(M) = \text{span}_C \{a_i^{(-n)} \tilde{m}; i \in I, \ n \geq 2, \ m \in M\}$$

by [10], Corollary 2.6.2 and Lemma 3.1.3 where $\tilde{m}$ is the image of $m$ in $\text{gr}^F M$. This proves the assertion. \hfill \□

We call $M$ finitely strongly generated over $V$ if $M/C_2(M)$ is finitely generated over $R_V$. 


Lemma 3.1.5. A $V$-module $M$ is finitely strongly generated if and only if there exists a good filtration of $M$.

Proof. Suppose that $M/C_2(M)$ is finitely generated over $R_V$. Then the Li filtration of $M$ is good by Lemma 3.2.8.

Let us show the opposite direction. Suppose that there exists a good filtration $\{F^pM\}$ of $M$, so that $\text{gr}^F M$ is finitely generated over $\text{gr}^F V$. Let $v_1, \ldots, v_r$ elements of $M$ such that there images $\bar{v}_1, \ldots, \bar{v}_r$ generate $\text{gr}^F M$ as a $\text{gr}^F V$-module. Then it follows that $M$ is spanned by the vectors of the form $(T^j a_1) \cdots (T^j a_r) v_i$ with $a_s \in V$, $j_s \in \mathbb{Z}_{\geq 0}$, $s = 1, \ldots, r$. This means that the images of $v_i$’s generate $\text{gr}^F M$ as well, and the assertion follows.

□

Lemma 3.1.6. Suppose that $V$ is conformal and $V_0 = \mathbb{C}$. Then for a $V$-module $M$, $M$ is finitely strongly generated over $V$ if and only if $M$ is $C_1$-cofinite.

Proof. Observe that the grading on $V$ induces a grading on $R_V$ such that

\[
R_V = \bigoplus_{\Delta \in \mathbb{Z}_{\geq 0}} (R_V)_{\Delta}, \quad (R_V)_0 = \mathbb{C}.
\]

The inclusion $C_2(M) \hookrightarrow C_1(M)$ gives the surjection

\[
\eta: M/C_2(M) \twoheadrightarrow M/C_1(M).
\]

As easily seen $\eta$ is a homomorphism of $R_V$-modules, where $M/C_1(M)$ is considered as a trivial $R_V$-module, and we have $\ker \eta = R_V^* (M/C_2(M))$, where $R_V^*$ is the argumentation ideal of $R_V$:

\[
R_V^* = \bigoplus_{\Delta > 0} (R_V)_{\Delta}.
\]

□

3.2. Associated varieties of vertex algebras and their modules.

Lemma 3.2.1. Let $M$ be a $V$-module.

(i) The annihilator $\text{Ann}_{R_V}(M/C_2(M))$ of $M/C_2(M)$ in $R_V$ is a Poisson ideal of $R_V$.

(ii) Let $\{F^pM\}$ be a compatible filtration. Then $\text{Ann}_{(R_V)_\infty} (\text{gr}^F M)$ is a $(R_V)_\infty$-submodule of $(R_V)_\infty$. If $V$ is conformal, then $\text{Ann}_{(R_V)_\infty} (\text{gr}^F M)$ is a vertex Poisson algebra ideal of $(R_V)_\infty$.

Proof. (i) follows from (27). (ii) By (3), $\text{Ann}_{\text{gr}^F V} (\text{gr}^F M)$ is a submodule of $\text{gr}^F V$. Because $(R_V)_\infty$ acts on $\text{gr}^F M$ via the surjective homomorphism $\Phi: (R_V)_\infty \twoheadrightarrow \text{gr}^F V$ of vertex Poisson algebras, $\text{Ann}_{(R_V)_\infty} (\text{gr}^F M) = \Phi^{-1} (\text{Ann}_{\text{gr}^F V} (\text{gr}^F M))$ is a submodule of $(R_V)_\infty$. If $V$ is conformal then $\text{gr}^F M$ is a differential $\text{gr}^F V$-module by Lemma 3.1.2. It follows that $\text{Ann}_{\text{gr}^F V} (\text{gr}^F M)$ is an ideal and hence so is $\text{Ann}_{(R_V)_\infty} (\text{gr}^F M)$.

□

Define the associated variety $X_V$ of $V$ by

\[
X_V = \text{Spec } R_V.
\]
More generally, for a finitely strongly generated $V$-module $M$, define the associated variety $X_M$ of $M$ by

$$X_M = \text{supp}_{R_V}(M/C_2(M))$$

$$= \{ p \in \text{Spec } R_V; p \supset \text{Ann}_{R_V}(M/C_2(M)) \}. $$

By Lemma 3.2.1, $X_M$ is a Poisson subvariety of $X_V$. The following assertion is clear.

**Lemma 3.2.2.** Let $M$ be a finitely strongly generated $V$-module. Then the following are equivalent:

(i) $M$ is $C_2$-cofinite.

(ii) dim $X_M = 0$.

**Remark 3.2.3.** Let $V$ be as in Lemma 3.1.6. Then by (28) the variety $X_V$ is conical. If $M$ is a graded $V$-module then $X_M$ is also conical. Hence

$$M \text{ is } C_2\text{-cofinite } \iff X_M = \{0\} \text{ (as topological spaces)}.$$ 

This is equivalent to that, for any homogeneous element $a \in V$ with $\Delta_a > 0$, $a + C_2(V)$ acts nilpotently on $M/C_2(M)$.

### 3.3. Singular support of $V$-modules.

Let $M$ be a finitely strongly generated $V$-module, $\{F^pM\}$ a good filtration of $M$. Define the singular support $SS(M)$ of $M$ by

$$SS(M) = \text{supp}_{(R_V)_{\infty}}(\text{gr}^F M)$$

$$= \{ p \in \text{Spec } (R_V)_{\infty}; p \supset \text{Ann}_{(R_V)_{\infty}}(\text{gr}^F M) \}. $$

Then $SS(M)$ is a closed subscheme of the infinite jet scheme $(X_V)_{\infty} = \text{Spec } (R_V)_{\infty}$. It is well-known that $SS(M)$ is independent of the choice of a good filtration of $M$.

Let

$$\pi_m : (X_V)_{\infty} \to (X_V)_m$$

be the natural projection.

**Lemma 3.3.1.** Let $M$ be a finitely strongly generated $V$-module.

(i) We have $X_M = \pi_0(SS(M))$.

(ii) If $V$ is conformal then $SS(M) \subset (X_M)_{\infty}$.

**Proof.** We may take the Li filtration $\{F^pM\}$ as a good filtration. By Lemma 3.1.3,

$$\text{Ann}_{\text{gr}^F V}(\text{gr}^F M) \cap R_V = \text{Ann}_{R_V}(M/C_2(M))$$

Hence $X_M = \pi_0(SS(M))$. Next assume that $V$ is conformal. By Lemma 3.2.1,

$$\text{Ann}_{(R_V)_{\infty}}(\text{gr}^F M)$$

is $T$-stable. Thus from (30) it follows that $\text{Ann}_{\text{gr}^F V}(\text{gr}^F M)$ contains the defining ideal of $(X_M)_{\infty}$, that is, the minimal $T$-stable ideal of $C[(X_V)_{\infty}]$ containing $\text{Ann}_{R_V}(M/C_2(M))$. This shows that $SS(M) \subset (X_M)_{\infty}$.

A $V$-module $M$ is called lisse if $M$ is finitely strongly generated and $SS(M)$ is zero-dimensional, or equivalently, $\pi_m(SS(M))$ is zero-dimensional for all $m \geq 0$. A vertex algebra $V$ is called lisse if it is lisse as a module over itself.

**Remark 3.3.2.** Suppose that $V$ is $Q_{>0}$-graded and $V_0 = C$. Then as in Remark 3.2.3, we see that a $C_1$-cofinite $V$-module $M$ is lisse if and only if $SS(M) = \{0\}$, or equivalently, for any homogeneous element $a$ with $\Delta_a > 0$, its principal symbol $\sigma_p(a)$ acts nilpotently on in $\text{gr}^F M$. 


Theorem 3.3.3. The following are equivalent.

(i) V is $C_2$-cofinite.
(ii) V is lisse.

Proof. The direction (ii) $\Rightarrow$ (i) immediately follows from Lemma 3.3.1. The direction (i) $\Rightarrow$ (ii) follows from the fact that $SS(V) \subset (X_V)_\infty$ and the jet scheme of 0-dimensional variety is 0-dimensional. □

The same assertion holds for the modules provided that $\text{gr}^V M$ is a differential $\text{gr}^V V$-module for a good grading $\{\Gamma^p M\}$. This is the case when V is conformal:

Theorem 3.3.4. Suppose that V is conformal and M is a finitely strongly generated $V$-module. Then the following are equivalent.

(i) M is $C_2$-cofinite, or equivalently, $\dim X_M = 0$.
(ii) M is lisse.

Proof. By Lemma 3.1.2 the assertion follows from in the same manner as Theorem 3.3.3. □

3.4. Example: Virasoro vertex algebras. Let $L = \bigoplus_{n \in \mathbb{Z}} \mathbb{C}L_n \oplus \mathbb{C}c$ be the Virasoro algebra, with the commutation relation

$$[L_m, L_n] = (m-n)L_{m+n} + \frac{(m^3 - m)}{12} \delta_{m+n,0} c,$$

$$[c, L] = 0.$$

Define the subalgebras $L_{\geq 0} = \bigoplus_{n \in \mathbb{Z}} \mathbb{C}L_n \oplus \mathbb{C}c$, $L_{< 0} = \bigoplus_{n < 0} \mathbb{C}L_n$, so that $L = L_{< 0} \oplus L_{\geq 0}$. For $c \in \mathbb{C}$, denote by $C_c$ the one-dimensional representation of $L_{\geq 0}$ on which $L_n$ acts trivially and $c$ acts as the multiplication by $c$. Define $M_c = U(L)\otimes U(L_{\geq 0})C_c$. Then $L_{-1}(1 \otimes 1) \in M_c$ is annihilated by all $L_n$ with $n > 0$. Set $Vir_c = M_c/U(L)L_{-1}(1 \otimes 1)$.

As is well-known there is a unique vertex algebra structure on $Vir_c$ such that the image of $1 \otimes 1$ is the vacuum vector $1$ and

$$Y(L_{-2}1, z) = L(z) := \sum_{n \in \mathbb{Z}} L_n z^{-n-2}.$$

The vertex algebra $Vir_c$ is called the universal Virasoro vertex algebra with central charge $c$. Any $L$-module with central charge $c$ (i.e., $c$ acts as the multiplication by $c$) on which $L(z)$ is a field can be considered as a $Vir_c$-module.

We have

$$(31) \quad R_{Vir_c} \cong \mathbb{C}[x]$$

(with the trivial Poisson structure), where $x$ is the image of $L_{-2}1$. Let $N_c$ its unique maximal submodule of $Vir_c$, and $Vir_c = Vir_c/N_c$ its unique simple quotient.

Proposition 3.4.1. The following are equivalent.

(i) $Vir_c$ is $C_2$-cofinite.
(ii) $Vir_c$ is reducible.
(iii) $c = 1 - 6(p - q)^2/pq$ for some $p, q \in \mathbb{Z}_{>2}$ such that $(p, q) = 1$. (These are precisely the central charges of the minimal series representations of $L_c$.)
Proof. It is known that the image of $N_c$ in $V_{ir^c}$ is nonzero if $N_c \neq 0$ (see e.g. [Wan93, Lemma 4.2 and Lemma 4.3] or [GK07, Proposition 4.3.2]). Therefore $X_{V_{ir^c}} = \{0\}$ if and only if $V_{ir^c}$ is not irreducible. This happens if and only if the central charge is of the form in (iii) ([Kac74, FF84, GK07]). □

We now compare the $C_2$-cofiniteness condition with the zero singular support condition of Beilinson, Feigin and Mazur [BFM]. Let $\{U_p(\mathcal{L})\}$ be the standard filtration of $U(\mathcal{L})$ as in Introduction. Then the associated graded algebra $\text{gr} U(\mathcal{L})$ is isomorphic to the symmetric algebra $S(\mathcal{L})$. Let $\mathcal{L}$ be a highest weight representation of $\mathcal{L}$ with central charge $c$, $v$ the highest weight vector of $\mathcal{M}$. Then $\{U_p(\mathcal{L})v\}$ defines an increasing filtration of $\mathcal{M}$ compatible with the standard filtration of $U(\mathcal{L})$. (Note that $U_p(\mathcal{L})v = U_p(\mathcal{L}_c)v$.) Let $gr^{Lie}_M$ denote the associated graded space $\bigoplus_p U_p(\mathcal{L})v / U_{p+1}(\mathcal{L})v$. Then $gr^{Lie}_M$ is an $S(\mathcal{L})$-module generated by the image of $v$. The singular support $SS^{BFM}(M)$ defined in [BFM] is by definition the support $\text{supp}_{S(\mathcal{L})} \text{gr}^{Lie}_M$. Clearly, we have $SS^{BFM}(M) \subset \mathcal{L}_c$.

**Proposition 3.4.2.** Let $\mathcal{M}$ be a highest weight representation of $\mathcal{L}$ with central charge $c$. Then the following are equivalent.

(i) $\mathcal{M}$ is $C_2$-cofinite.

(ii) $SS^{BFM}(\mathcal{M}) = \{0\}$.

Proof. First, by Lemma 3.1.3 we have

$$C_2(\mathcal{M}) = \text{span}_C \{L_{-n}m; m \in \mathcal{M}, n \geq 3\}$$

because $V_{ir^c}$ is strongly generated by $L_{-2}1$. It follows that $\mathcal{M}/C_2(\mathcal{M})$ is spanned by the images of the vectors of the form $L_{-n}^m L_{-1}^n v$ with $m, n \geq 0$, where $v$ is the highest weight vector of $\mathcal{M}$. In particular $\mathcal{M}/C_2(\mathcal{M})$ is generated by the image of the vectors $L_{-n}^m v$ with $n \geq 0$ over $V_{ir^c}$ by (31).

Suppose that $SS^{BFM}(\mathcal{M}) = \{0\}$. We then have $L_{-1}^p v \in U_{p-1}(\mathcal{L}_{<0})v$ for a sufficiently large $p$. By considering the $L_0$-eigenvalue we find that this is equivalent to $L_{-1}^p v \in \sum_{n \geq 2} L_n U(\mathcal{L}_{<0})v$. This happens if and only if $\mathcal{M}/C_2(\mathcal{M})$ is finitely generated over $R_{V_{ir^c}}$. We also have $L_{-2}^p v \in U_{p-1}(\mathcal{L}_{<0})v$ for a sufficiently large $p$

By taking account of the $L_0$-eigenvalue it follows that this is equivalent to $L_{-2}^p v \in \sum_{n \geq 3} L_n U(\mathcal{L}_{<0})v = C_2(\mathcal{M})$. Therefore $\mathcal{M}$ is $C_2$-cofinite.

Conversely, suppose that $\mathcal{M}$ is $C_2$-cofinite. From the above argument it follows that $L_{-1}$ and $L_{-2}$ act nilpotently on $gr^{Lie}_M$. Then $SS^{BFM}(\mathcal{M})$ must be $\{0\}$, because $L_{-1}$ and $L_{-2}$ generates $\mathcal{L}_{<0}$ and $\sqrt{\text{Ann}_{S(\mathcal{L}_{<0})} \text{gr}^{Lie}_M}$ is involutive by Gabber’s theorem. □

By Proposition 3.4.2 a result of [BFM] can be read as follows.

**Theorem 3.4.3 (BFM).** Let $\mathcal{M}$ be an irreducible highest weight representation of $\mathcal{L}$ with central charge $c$. Then the following are equivalent.

(i) $\mathcal{M}$ is $C_2$-cofinite.

(ii) $\mathcal{M}$ is isomorphic to one of the minimal series representations of $\mathcal{L}$.

3.5. **Example: affine vertex algebras.** Let $\hat{\mathfrak{g}}, \mathfrak{g}, V^k(\mathfrak{g})$ be as in Example 2.7.

For a weight $\lambda$ of $\hat{\mathfrak{g}}$, let $L(\lambda)$ be the irreducible (graded) representation of $\hat{\mathfrak{g}}$ of highest weight $\lambda$. If $\lambda$ is of level $k$, that is, if $\lambda(K) = k$, then $L(\lambda)$ can be naturally considered as a (simple) module over $V^k(\mathfrak{g})$. In particular $L(k\Lambda_0)$ (in the notation of [Kac90]) is isomorphic to the unique simple graded quotient of $V^k(\mathfrak{g})$. 
Let $\lambda(K) = k$. Because
\[ C_2(L(\lambda)) = \text{span}_{\mathbb{C}} \{ x_{(n)}m : x \in \mathfrak{g}, \; m \in L(\lambda), \; n \geq 2 \} \]
by Lemma 3.1.4, it follows that $L(\lambda)$ is finitely strongly generated over $V^k(\mathfrak{g})$ if and only if the highest weight vector of $L(\lambda)$ generates a finite-dimensional $\mathfrak{g}$-module, or equivalently, the restriction of $\lambda$ to the Cartan subalgebra of $\mathfrak{g}$ is integral dominant. This happens if and only if $L(\lambda)$ is a direct sum of finite-dimensional $\mathfrak{g}$-modules. In this case $X_{L(\lambda)}$ is a $\text{Ad}G$-invariant, conic, Poisson subvariety of $\mathfrak{g}^*$.

We give a simple proof of the following well-known assertion (cf. [Zhu96]).

**Proposition 3.5.1.** Let $\lambda$ be a weight of $\hat{\mathfrak{g}}$, and set $k = \lambda(K)$. Then $L(\lambda)$ is a $C_2$-cofinite $V^k(\mathfrak{g})$-module if it is an integrable representation of $\hat{\mathfrak{g}}$. In particular the simple affine vertex algebra $L(K_0)$ is $C_2$-cofinite if $k \in \mathbb{Z}_{\geq 0}$.

**Proof.** Suppose that $L(\lambda)$ is integrable and set $J = \text{Ann}_{V^k(\mathfrak{g})} L(\lambda)/C_2(L(\lambda))$. Let $x_\alpha$ be any root vector of $\mathfrak{g}$. Because $(x_\alpha)(-1)$ acts locally nilpotently on $L(\lambda)$, its image $x_\alpha \in \mathbb{C}[\mathfrak{g}] = R_{V^k(\mathfrak{g})}$ belongs to $\sqrt{J}$. As $\sqrt{J}$ is a Poisson ideal of $\mathbb{C}[\mathfrak{g}]$ by Corollary 2.4.2 and Lemma 3.2.1, $\sqrt{J}$ contains $\{ \mathfrak{g}, x_\alpha \} = \mathfrak{g}$, proving that $X_{L(\lambda)} = \{ 0 \}$. \hfill \Box

One can show that the converse of Proposition 3.5.1 is also true, that is, $L(\lambda)$ is $C_2$-cofinite if and only if it is integrable, see [DM00], [Ara].

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