ADMISSIBLE LOCAL SYSTEMS FOR A CLASS OF LINE ARRANGEMENTS

SHAHEEN NAZIR, ZAHID RAZA

Abstract. A rank one local system \( L \) on a smooth complex algebraic variety \( M \) is admissible roughly speaking if the dimension of the cohomology groups \( H^m(M, L) \) can be computed directly from the cohomology algebra \( H^*(M, \mathbb{C}) \).

We say that a line arrangement \( \mathcal{A} \) is of type \( \mathcal{C}_k \) if \( k \geq 0 \) is the minimal number of lines in \( \mathcal{A} \) containing all the points of multiplicity at least 3. We show that if \( \mathcal{A} \) is a line arrangement in the classes \( \mathcal{C}_k \) for \( k \leq 2 \), then any rank one local system \( L \) on the line arrangement complement \( M \) is admissible. Partial results are obtained for the class \( \mathcal{C}_3 \).

1. Introduction

When \( M \) is a hyperplane arrangement complement in some projective space \( \mathbb{P}^n \), one defines the notion of an admissible local system \( L \) on \( M \) in terms of some conditions on the residues of an associated logarithmic connection \( \nabla(\alpha) \) on a good compactification of \( M \), see for instance [7], [11], [8], [9], [6]. This notion plays a key role in the theory, since for such an admissible local system \( L \) on \( M \) one has

\[
\dim H^i(M, L) = \dim H^i(H^*(M, \mathbb{C}), \alpha \wedge)
\]

for all \( i \).

Let \( \mathcal{A} \) be a line arrangement in the complex projective plane \( \mathbb{P}^2 \) and denote by \( M \) the corresponding arrangement complement. For the case of line arrangements, a good compactification as above is obtained just by blowing-up the points of multiplicity at least 3 in \( \mathcal{A} \). This explains the simple version of the admissibility definition given below, see Definition 2.1.

We say that a line arrangement \( \mathcal{A} \) is of type \( \mathcal{C}_k \) if \( k \geq 0 \) is the minimal number of lines in \( \mathcal{A} \) containing all the points of multiplicity at least 3. For instance \( k = 0 \) corresponds to nodal arrangements, while \( k = 1 \) corresponds to the case of a nodal affine arrangement, see [1]. Note that \( k = k(\mathcal{A}) \) is combinatorially defined, i.e. depends only on the associated lattice \( L(\mathcal{A}) \).

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The main result of this note is the following one, which, as explained above, is new in the case \( n = 2 \).

**Theorem 1.1.** If \( \mathcal{A} \) is a line arrangement in the classes \( \mathcal{C}_k \) for \( k \leq 2 \), then any rank one local system \( \mathcal{L} \) on \( M \) is admissible.

This result implies in particular that, for a combinatorially defined class of arrangements, the characteristic varieties are combinatorially determined by \( L(\mathcal{A}) \), see Theorem 2.3.

In section 2 we explicate first the admissibility condition in the case of line arrangements. Then we prove our Theorem and derive some consequences for the characteristic varieties of line arrangements in the classes \( \mathcal{C}_k \) for \( k \leq 2 \).

In the final section we find some sufficient conditions on a local system \( \mathcal{L} \) on the complement of a line arrangement in the class \( \mathcal{C}_3 \) which imply that \( \mathcal{L} \) is admissible, see Proposition 3.1.

The deleted \( B_3 \)-arrangement discovered by A. Suciu shows that Theorem 1.1 does not hold for \( k = 3 \), so our result is the best possible. A discussion of this example from the point of view of our paper is given in Example 3.2. Further examples conclude the paper.

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### 2. Admissible rank one local systems

Let \( \mathcal{A} = \{L_0, L_1, ..., L_n\} \) be a line arrangement in \( \mathbb{P}^2 \) and set \( M = \mathbb{P}^2 \setminus (L_0 \cup ... \cup L_n) \). Let \( \mathbb{T}(M) = \text{Hom}(\pi_1(M), \mathbb{C}^*) \) be the character group of \( M \). This is an algebraic torus \( \mathbb{T}(M) \cong (\mathbb{C}^*)^n \). Consider the exponential mapping

\[
\exp : H^1(M, \mathbb{C}) \to H^1(M, \mathbb{C}^*) = \mathbb{T}(M)
\]

induced by the usual exponential function \( \mathbb{C} \to \mathbb{C}^*, \ t \mapsto \exp(2\pi it) \), where \( i = \sqrt{-1} \).

Clearly \( \exp(H^1(M, \mathbb{C})) = \mathbb{T}(M) \) and \( \exp(H^1(M, \mathbb{Z})) = \{1\} \).

A rank one local system \( \mathcal{L} \in \mathbb{T}(M) \) corresponds to the choice of some monodromy complex numbers \( \lambda_j \in \mathbb{C}^* \) for \( 0 \leq j \leq n \) such that \( \lambda_0 \cdots \lambda_n = 1 \). And a cohomology class \( \alpha \in H^1(M, \mathbb{C}) \) is given by

\[
\alpha = \sum_{j=0}^{n} a_j \frac{df_j}{f_j}
\]

with the residues \( a_j \in \mathbb{C} \) satisfying \( \sum_{j=0}^{n} a_j = 0 \) and \( f_j = 0 \) a linear equation for the line \( L_j \). With this notation one has \( \exp(\alpha) = \mathcal{L} \) if and only if \( \lambda_j = \exp(2\pi ia_j) \) for any \( j = 0, ..., n \).

**Definition 2.1.** A local system \( \mathcal{L} \in \mathbb{T}(M) \) as above is admissible if there is a cohomology class \( \alpha \in H^1(M, \mathbb{C}) \) such that \( \exp(\alpha) = \mathcal{L} \), \( a_j \notin \mathbb{Z}_{>0} \) and, for any point
$p \in L_0 \cup \ldots \cup L_n$ of multiplicity at least 3, one has

$$a(p) = \sum_j a_j \not\in \mathbb{Z}_{>0}$$

where the sum is over all $j$'s such that $p \in L_j$. Set $b(p) = \text{Re}(a(p))$, where $\text{Re}$ denotes the real part of a complex number.

2.2. **Proof of Theorem 1.1.** We can assume that, for a line arrangement $A$ of type $C_k$, the lines in $A$ containing all the points of multiplicity at least 3 are $L_0, \ldots, L_{k-1}$.

Given $L$, we can choose $\text{Re}(a_j) \in [0, 1)$ for all $j \geq 1$. Then the relation $\sum_{j=0}^n a_j = 0$ implies that

$$\text{Re}(a_0) = -\sum_{j=1}^n \text{Re}(a_j) \leq 0.$$ 

This completes the proof in the case when $A$ is in the class $C_0$.

Consider now the case when $A$ is in the class $C_1$ and choose $p \in L_0$ as in Definition 2.1.

If the set of lines passing through $p$ is $L_0, L_{j_1}, \ldots, L_{j_k}$ for some $k \geq 2$, then one has

$$b(p) = \sum_j \text{Re}(a_j) = -\sum_k \text{Re}(a_k) \leq 0$$

where the second sum is over all $k > 0$ such that $p \not\in L_k$. This shows that any local system $L \in \mathbb{T}(M)$ is admissible in this case.

The case when $A$ is in the class $C_2$ is much more subtle. Let $m_1$ be the maximum of the real numbers $b(p)$ where $p$ is a point of multiplicity at least 3 on the line $L_1$ but not on $L_0$ such that $b(p) \not\in \mathbb{Z}_{>0}$. By convention we set $\text{max} \emptyset = 0$.

If $m_1 = 0$, then the initial choice is good, exactly as in the previous situation.

Assume now that $m_1 > 0$ and let $p_1 \in L_1$ be a multiple point with $b(p_1) = m_1$. In general this value $m_1$ can be attained at several points $p_1, p'_1, p''_1, \ldots$ on $L_1$. Any such point will be called an extremal point for $L$ on $L_1$.

Then we replace $a_1$ by $a'_1 = a_1 - m_1$ and hence $\text{Re}(a'_1) \leq 0$ if $\text{Re}(a'_1)$ is an integer. We also replace $a_0$ by $a'_0 = a_0 + m_1$, such that the total sum of the residues is still zero. Note that $\text{Re}(a'_0) \leq 0$.

After these two changes, it is clear that $b(q) \not\in \mathbb{Z}_{>0}$ for any point $q$ of multiplicity at least 3 on the line $L_1$ but not on $L_0$. If $O = L_0 \cap L_1$ is a point of multiplicity at least 3, then

$$b(O) = \text{Re}(a'_0) + \text{Re}(a'_1) + \sum_m \text{Re}(a_m) = -\sum_k \text{Re}(a_k) \leq 0$$

where the first sum is over $m = 2, \ldots, n$ such that $O \in L_m$ and the second sum is over all $k = 2, \ldots, n$ such that $O \not\in L_k$. Note that $O$ is never an extremal point.
If now \( q \neq O \) is a point of multiplicity at least 3 on the line \( L_0 \), in the corresponding sum for \( b(q) \) we have the following terms

(i) \(-\text{Re}(a_j)\) for all \( j > 0\);
(ii) \(+\text{Re}(a_{j_0})\) for all the lines different from \( H_0 \) passing through \( q\);
(iii) \(+\text{Re}(a_{m_k})\) for all the lines passing through \( p_1 \).

(in fact the terms of type (i) come from \( \text{Re}(a_0) \), and the terms of type (iii) come from adding \( m_1 \) to \( a_0 \) to get \( a'_0 \)).

In the last two families there is at most one line in common, the line determined by \( p_1 \) and \( q \). It follows that the sum for \( b(q) \) involves some negative terms from (i) and possibly one positive term in the interval \([0, 1)\). Therefore \( b(q) < 1 \) and this concludes the proof of Theorem 1.1.

The characteristic varieties of \( M \) are the jumping loci for the cohomology of \( M \), with coefficients in rank 1 local systems:

\[
V^i_k(M) = \{ \rho \in \mathbb{T}(M) \mid \dim H^i(M, \mathcal{L}_\rho) \geq k \}.
\]

When \( i = 1 \), we use the simpler notation \( V_k(M) = V^1_k(M) \). One has the following result, see [4], Remark 2.9 (ii).

**Theorem 2.3.** If any local system in \( \mathbb{T}(M) \) is admissible, then for any \( k \) there are no translated components in the characteristic variety \( V_k(M) \).

In particular, for any irreducible component \( W \) of some characteristic variety \( V_k(M) \), the dimension of \( H^1(M, \mathcal{L}) \) is constant for \( \mathcal{L} \in W \setminus \{1\} \).

Combining this result and our Theorem 1.1 we get the following.

**Corollary 2.4.** If \( \mathcal{A} \) is a line arrangement in the classes \( \mathcal{C}_k \) for \( k \leq 2 \), then for any \( k \) there are no translated components in the characteristic variety \( V_k(M) \).

### 3. Line Arrangements in the Class \( \mathcal{C}_3 \)

In this section we discuss only the situation when the 3 lines \( L_0, L_1 \) and \( L_2 \) containing all the points of multiplicity at least 3 are concurrent. Let \( O = L_0 \cap L_1 \cap L_2 \). Let \( \mathcal{L} \in \mathbb{T}(M) \) be a rank one local system and choose the residues \( a_j \) as above. Then we have a collection \( P_1 \) of extremal points for \( \mathcal{L} \) on \( L_1 \) and a collection \( P_2 \) of extremal points for \( \mathcal{L} \) on \( L_2 \). By convention \( P_j \) is empty if the corresponding maximum \( m_j = 0 \) (see also the beginning of the proof below for the definition of \( m_j \)). Since we start with the residues \( a_j \)'s such that \( \text{Re}(a_j) \in [0, 1) \) for all \( j > 0 \), then we have as above \( O \notin P_1 \cup P_2 \). For each point \( q \in L_0 \) of multiplicity at least 3, we denote by \( \mathcal{A}_q \) the set of lines in \( \mathcal{A} \) passing through \( q \).
Proposition 3.1. With the above notation, assume that one of the following conditions hold

(i) \( P_1 = \emptyset \);

(ii) \( P_2 = \emptyset \);

(iii) for each point \( q \in L_0 \) of multiplicity at least 3, one has either

(a) \( P_1 \setminus Y_q \) and \( P_2 \setminus Y_q \) are both non-empty, where \( Y_q \) is the union of the lines in \( \mathcal{A}_q \), or

(b) one of the sets \( P_1 \setminus Y_q \) and \( P_2 \setminus Y_q \) is non-empty, say \( p_1 \in P_1 \setminus Y_q \), and there is an extremal point \( p_2 \in P_2 \) such that the line determined by \( p_1, p_2 \) is not in \( \mathcal{A} \).

Then the local system \( \mathcal{L} \) is admissible.

Proof. Let \( m_j \), for \( j = 1, 2 \), be the maximum of the real numbers \( b(p) \) where \( p \neq O \) is a point of multiplicity at least 3 on the line \( L_j \) such that \( b(p) \in \mathbb{Z}_{>0} \). The only essentially new case is when \( m_1 > 0 \) and \( m_2 > 0 \), i.e. the case (iii) above. Then we set \( a'_j = a_j - m_j \) for \( j = 1, 2 \) and \( a'_0 = a_0 + m_1 + m_2 \). Exactly as in the proof of Theorem 1.1, this settles the case of multiple points on \( L_1 \) and \( L_2 \) distinct of \( O \). At the point \( O \) we get the following sum

\[
b(O) = \text{Re}(a'_0 + a'_1 + a'_2) + \sum_m \text{Re}(a_m) = -\sum_k \text{Re}(a_k) \leq 0
\]

where the first sum is over \( m = 3, n \) such that \( O \in L_m \) and the second sum is over all \( k = 3, n \) such that \( O \not\in L_k \).

If now \( q \neq O \) is a point of multiplicity at least 3 on the line \( L_0 \), in the corresponding sum for \( b(q) \) we have the following terms

(i) \(-\text{Re}(a_j)\) for all \( j > 0 \);

(ii) \(+\text{Re}(a_{j_k})\) for all the lines different from \( H_0 \) passing through \( q \);

(iii) \(+\text{Re}(a_{m_k})\) for all the lines passing through \( p_1 \), for a fixed choice \( p_1 \in P_1 \);

(iv) \(+\text{Re}(a_{n})\) for all the lines passing through \( p_2 \), for a fixed choice \( p_2 \in P_2 \).

(in fact the terms of type (i) come from \( \text{Re}(a_0) \), the terms of type (iii) come from adding \( m_1 \) and the terms of type (iv) come from adding \( m_2 \)).

Our assumption (iii) says exactly that there is a choice of \( p_1 \) and \( p_2 \) such that in the last 3 families of positive terms there is at most one line occurring twice (and none occurring three times). It follows that the sum for \( b(q) \) involves some negative terms from (i) and possibly one positive term in the interval \([0, 1)\). Therefore \( b(q) < 1 \) and this concludes the proof.

\( \square \)
Example 3.2. Here we analyse from the point of view of the above proof the non-admissible local systems in the case of Suciu’s arrangement, see [12].

Choose: \( L_0 : x = 0, \ L_1 : x = y, \ L_2 : y = 0, \ L_3 : x = z, \ L_4 : y = z, \ L_5 : x-y+z = 0, \ L_6 : x-y-z = 0, \ L_7 : z = 0 \) (this last one is the line at infinity).

There are 7 points of multiplicity at least 3, say, 

\[
O = L_0 \cap L_1 \cap L_2 = (0 : 0 : 1), \quad p_1 = L_1 \cap L_3 \cap L_4 = (1 : 1 : 1), \quad p_1' = L_1 \cap L_5 \cap L_6 \cap L_7 = (1 : 1 : 0), \quad p_2 = L_2 \cap L_3 \cap L_6 = (1 : 0 : 1), \quad p_2' = L_2 \cap L_4 \cap L_7 = (1 : 0 : 0), \quad q_1 = L_0 \cap L_4 \cap L_5, \quad q_2 = L_0 \cap L_3 \cap L_7 = (0 : 1 : 0). \]

It is clear that \( L_0, L_1, L_2 \) contain all the points of multiplicity at lest 3, even those at infinity.

Consider the local system \( \mathcal{L}_\rho \) which is used to define the translated component

\[
W = \rho \otimes \{(t, 1, t^{-1}, t^{-1}, t, t^{-2}, t^2, 1) \mid t \in \mathbb{C}^*\},
\]

where \( \rho = (1, -1, -1, 1, 1, 1, -1) \). The corresponding residues are

\[
a_1 = a_2 = a_3 = a_7 = 1/2, \quad a_4 = a_5 = a_6 = 0 \quad \text{and} \quad a_0 = -2.
\]

Using these residues we find out that \( m_1 = m_2 = 1, \ P_1 = \{p_1, p_1'\} \) and \( P_2 = \{p_2, p_2'\} \).

For \( q = q_2 \), both sets \( P_1 \setminus Y_q \) and \( P_2 \setminus Y_q \) are empty. Thus the condition (iii) of Proposition 3.1 is not fulfilled.

Example 3.3. Here is an example of an arrangement in \( \mathcal{C}_3 \) of the type discussed above for which all local systems are admissible. Let \( \mathcal{A} \) be the arrangement in \( \mathbb{C}^2 \) consisting of the following 10 lines:

Choose \( L_0 : x = 0, \ L_1 : y = 1/2(x + 3), \ L_2 : y = -1/2(x - 3) \)
\[
L_3 : y = x + 1, \ L_4 : y = -(x - 1), \quad L_5 : y = 2(x + 1), \ L_6 : y = -2(x - 1), \quad L_7 : y = 3/2(x + 3), \ L_8 : y = -3/2(x + 3), \quad L_9 : y = 5/2(x - 3) \quad \text{and} \quad L_{10} : y = -5/2(x - 3).
\]
There are 5 triple points, 3 on the line \( L_0 \) namely \( O = L_1 \cap L_2 \cap L_0 = (0, \frac{3}{2}) \), \( q_1 = L_0 \cap L_3 \cap L_4 = (0, 1) \) and \( q_2 = L_0 \cap L_5 \cap L_6 = (0, 2) \), the other 2 being \( p_1 = L_1 \cap L_7 \cap L_8 = (−3, 0) \) and \( p_2 = L_2 \cap L_9 \cap L_{10} = (3, 0) \). Any local system is admissible by Proposition 3.1. Indeed, if we suppose that \( P_1 \) and \( P_2 \) are both non-empty, then both sets \( P_1 \backslash Y_q = P_1 \) and \( P_2 \backslash Y_q = P_2 \) are again non-empty, for \( q = q_1 \) and \( q = q_2 \).

**Example 3.4.** Here is an example of an arrangement in \( C_3 \) of the type discussed above for which Proposition 3.1 does not apply, but still most (perhaps all) local systems are admissible. Let \( A \) be the arrangement in \( C^2 \) consisting of the following 7 lines:

\[
L_0 : x = 0, \quad L_1 : y = -2(x - 1), \quad L_2 : y = 2(x + 1), \quad L_4 : y = x + 1, \quad L_5 : y = -1/3(x + 1), \quad L_3 : y = -(x - 1), \quad L_6 : y = 1/3(x - 1).
\]

The line at infinity is denoted by \( L_7 \).
Here are 5 points of multiplicity at least 3 which are on the lines $L_0$, $L_1$ and $L_2$: $O = L_0 \cap L_1 \cap L_2 = (0, 2)$, $p_1 = L_1 \cap L_3 \cap L_6 = (0, 1)$, $p_2 = L_2 \cap L_4 \cap L_5 = (-1, 0)$, $q_1 = L_0 \cap L_5 \cap L_6 = (0, -\frac{1}{3})$, $q_2 = L_0 \cap L_3 \cap L_4 = (0, 1)$.

Assume that we have a local system $\mathcal{L}$ such that $P_1$ and $P_2$ are both non-empty. Then one has

$$m_1 = \text{Re}(a_2 + a_4 + a_5) \in \{1, 2\}$$

and

$$m_2 = \text{Re}(a_1 + a_3 + a_6) \in \{1, 2\}.$$  

In this case the new residue along $L_0$ is

$$a'_0 = a_0 + m_1 + m_2 = -\sum_{k=1,7} a_k + m_1 + m_2 = -a_7 - i \cdot \text{Im}(\sum_{k=1,6} a_k)$$

where $\text{Im}$ denotes the imaginary part of a complex number. When we compute the residue along the exceptional curve $E_1$ created by blowing-up the point $q_1$, we get

$$r_1 = a'_0 + a_5 + a_6 = a_5 + a_6 - a_7 - i \cdot \text{Im}(\sum_{k=1,6} a_k).$$

Similarly we get

$$r_2 = a_3 + a_4 - a_7 - i \cdot \text{Im}(\sum_{k=1,6} a_k)$$

for the point $q_2$. In this case Proposition 3.1 does not apply, since for $q = q_1, q_2$ both sets $P_1 \setminus Y_q$ and $P_2 \setminus Y_q$ are empty. However, as soon as $r_j$ for $j = 1, 2$ are not strictly positive integers, we know that the corresponding local system $\mathcal{L}$ is admissible.
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SCHOOL OF MATHEMATICAL SCIENCES, GOVERNMENT COLLEGE UNIVERSITY, 68-B NEW MUSLIM TOWN LAHORE, PAKISTAN.

E-mail address: shaheen.nazeer@gmail.com

ZAHID RAZA, SCHOOL OF MATHEMATICAL SCIENCES, GOVERNMENT COLLEGE UNIVERSITY, 68-B NEW MUSLIM TOWN LAHORE, PAKISTAN.

E-mail address: zahidsms@gmail.com