1. Notation and preliminary results

All of the techniques and most of the results in this section are well known implicitly or explicitly, [McG], [G], [KL T] and references therein. The structure sheaf of a variety $Z$ will be denoted by $S_Z$. We will abbreviate $R(Z) = \Gamma(Z, S_Z)$.

Typically $O$ will denote the orbit of a nilpotent element $e$ in a semisimple Lie algebra $g$. The orbit is isomorphic to $G/G(e)$. Its universal cover $\tilde{O}$ is isomorphic to $G/G(e)_0$. By one of Chevalley’s theorems there is a representation $\tilde{V}$ and a vector $\tilde{e} = (e, \tilde{v}) \in g \oplus \tilde{V}$ such that its orbit under $G$ is the universal cover (in other words the stabilizer of $\tilde{v}$ is $G(e)_0$). Given any subgroup $G(e)_0 \subset H \subset G(e)$, there is a corresponding cover $\tilde{O}_H$ which can be realized in the same way as the orbit of an element $e_H = (e, v_H) \in g \oplus V_H$.

Let $\{e, h, f\}$ be a Lie triple associated to $e$. Let $g_{\geq 2}$ be the sum of the eigenvectors of ad$h$ with eigenvalue greater than or equal to 2. Let $P_e$ be the parabolic subgroup determined by $h$, i.e. the parabolic subgroup corresponding to the roots with eigenvalue greater than or equal to zero for ad$h$.

It is well known that the natural map
\begin{equation}
\{5.1\} \quad m_e : G \times P_e, g_{\geq 2} \longrightarrow \widetilde{O}, \quad (g, X) \mapsto gXg^{-1}
\end{equation}
is birational and projective. The birationality follows from [BV]. The projective property is in [McG]. Indeed let $P$ be any parabolic subgroup, $P := G/P$ and $\Sigma \subset p$ be any closed $P$-invariant subspace. Then we can embed $G \times P \Sigma \subset P \times g$ via $(g, X) \mapsto (gPg^{-1}, gXg^{-1})$. The image is $\{(gPg^{-1}, X) : g^{-1}Xg \in \Sigma\}$. It is closed because $G/P$ is complete, and this is the $G$-orbit of $\{(P, X) : X \in \Sigma\}$. Then the map $m(g, X) := gXg^{-1}$ is the composition of this embedding with the projection on the second factor.

Let $P = MN$ be an arbitrary parabolic subgroup and $O_m \subset m$ be a nilpotent orbit. A $G$-orbit $O$ is called induced from $O_m$ ([LS]), if
\begin{equation}
\{5.2\} \quad O \cap [O_m + n] \quad \text{is dense in} \quad O_m + n.
\end{equation}
Let $\Sigma := \mathcal{O}_m + n$. There is a similar moment map

$$ (3) \quad \{5.3\} \quad m : G \times_P \Sigma \longrightarrow \mathcal{O}, \quad (g, X) \mapsto gXg^{-1}, $$

It is projective for the same reason as before, but it is not always birational. Precisely, if $e \in \Sigma \cap \mathcal{O}$, then the generic fiber of $m$ is isomorphic to $G(e)/P(e)$.

We will write $\mathcal{Z}$ for $G \times_P \Sigma$ where $\Sigma = \mathcal{O}_m + n$. In general, write $A_G(e) := G(e)/G(e)_0$ (we suppress the subscript $G$ if it is clear from the context). Recall from [LS] that $G(e)_0 = P(e)_0$, so that there is an inclusion $A_P(e) \subset A_G(e)$. If $e_m \in \mathcal{O}_m$ then there is a surjection $A_P(e) \twoheadrightarrow A_M(e_m)$. Given a character $\phi$ of $A_M(e_m)$, we will denote by the same letter its inflation to $A_P(e)$.

A related result is the following. Let $e_m \in \mathcal{O}_m$ and $\lambda \in m$ be such that $C(\lambda) = m$. Let $e = e_m + n$ be a representative for the induced nilpotent. Let $\psi$ be a character of $A(\mathcal{O}_m)$ and $\Psi$ be the induced representation to $A(\mathcal{O})$. We regard them both as characters of the centralizers of the nilpotents. Choose a (noninvariant) inner product on $g$.

**Proposition 1.0.1.** Let $(\mu, V)$ be a representation of $G$. Then

$$ [\mu : \text{Ind}^G_M[R(\mathcal{O}_m)_\psi]] \leq [\mu : R(\mathcal{O})_\Psi] $$

where $R(\mathcal{O})_\Psi := \sum_{\rho \in A(\mathcal{O})} [\rho : \Psi] R(\mathcal{O})_{\rho}$.

**Proof.** For $n \in \mathbb{N}$, consider $\frac{1}{n} \lambda + e_m$. There is $p_n \in P$ such that $\lambda_n := \text{Ad}(p_n)(\frac{1}{n} \lambda + e_m) = \frac{1}{n} \lambda + e$. For each $n$, let $X^1_n, \ldots, X^m_n$ be an orthonormal basis of $\mathfrak{Z}(\lambda_n)$, the centralizer in $g$ of $\lambda_n$. We can extract a subsequence such that the $X^i_n$ all converge to an orthonormal basis of $\mathfrak{Z}(e)$. Now let $v^i_1, \ldots, v^i_n$ be an orthonormal basis of the space of fixed vectors of $\mathfrak{Z}(\lambda_n)$ in $V$. We can again extract a subsequence such that the $v^i_n$ all converge to an orthonormal set of vectors in $V$. Because $v^i_n$ are invariant under the action of the $X^i_n$, their limits are invariant under an orthonormal basis of $\mathfrak{Z}(e)$. Using Frobenius reciprocity, this proves the claim for the connected components of the centralizers, i.e., the corresponding statement for $R(\mathcal{O}_m)$ and $R(\mathcal{O})$. The claim of the proposition follows by a minor modification of the argument. \hfill \square

For the case of a Richardson nilpotent orbit, we can prove this type of result in a more geometric fashion. Let $P = MN$ be a parabolic subgroup with Lie algebra $\mathfrak{p} = \mathfrak{m} + \mathfrak{n}$. Denote again by $\lambda \in g$ a semisimple element whose centralizer is $\mathfrak{m}$, and which is positive on the roots of $\mathfrak{n}$. Let $e \in \mathfrak{n}$ be a representative of the Richardson induced orbit from this parabolic subalgebra, and denote its $G$ orbit by $\mathcal{O}$. As before, there is a map

$$ (4) \quad m : G \times_P \mathfrak{n} \longrightarrow \mathfrak{g}, $$

with image $\mathcal{O}$. Let $\mathcal{O}'$ be the inverse image of $\mathcal{O}$. Identify representations of $A_P(e)$ and $A_G(e)$ with representations of $G(e)$ by making them trivial on $G(e)_0$. 
Proposition 1.0.2.

\[ [\mu : \text{Ind}^G_P\text{triv}] = \sum_{\rho \in \hat{A}(e)} [\rho|_{A_P(e)} : \text{triv}] [\mu : R(\mathcal{O})_\rho]. \]

Proof. When restricted to \( \mathcal{O}' \), the fiber of \( m \) is \( A_G(e) / A_P(e) \), and

\[ R(\mathcal{O}) \cong \sum [\rho|_{A_P(e)} : \text{triv}] R(\mathcal{O})_\rho. \]

Let \( \tilde{\mathcal{O}} \) be the cover corresponding to \( A_P(e) \), and let \( \mathcal{X} \) be the normalization of \( \tilde{\mathcal{O}} \). Let \( \tilde{\mathcal{O}}_{\text{reg}} \) and \( \mathcal{X}_{\text{reg}} \) be the regular points of the respective varieties.

Then we have a diagram

\[ \begin{array}{ccc}
\mathcal{X}_{\tilde{\mathcal{O}}} & \longrightarrow & \mathcal{X}_{\text{reg}} \\
\downarrow & & \downarrow \theta \\
\tilde{\mathcal{O}} & \longrightarrow & \tilde{\mathcal{O}}_{\text{reg}}
\end{array} \]

where \( \mathcal{X}_{\tilde{\mathcal{O}}} \) is the inverse image of \( \tilde{\mathcal{O}} \) in \( \mathcal{X} \). The codimensions of the complements of these sets is always greater than or equal to 2, and the restriction of \( \theta \) to \( \mathcal{X}_{\text{reg}} \) is an isomorphism. This is because the morphism is finite. Because \( \mathcal{X} \) is normal, we conclude that

\[ R(\tilde{\mathcal{O}}) = R(\mathcal{X}). \]

Because \( \mathcal{Z} \) is smooth, it is also normal so there is a birational map

\[ \mathcal{Z} \longrightarrow \mathcal{X} \]

This is also a finite morphism. The rest of the proof is as in [McG].

We will use this proposition in the setting of a triangular nilpotent orbit, and the case (in the classical Lie algebras) where \( A_P(e) = \{1\} \).

We return to the case where \( P \) corresponds to the middle element of the Lie triple. In this case, \( A(\mathcal{O}) \subset P \). Let \( \chi \in \hat{A}(\mathcal{O}) \) be a (1-dimensional) character viewed as a representation of \( G(e) \) trivial on \( G(e)_0 \), and \( \xi \) be a representation of \( P \) such that \( \xi|_{G(e)} = \chi \). Then

\[ H^0(G/P, R(P \cdot f) \otimes \mathbb{C}_\xi) \subset R(\mathcal{O}, \mathcal{S}_\chi) \]

because \( \mathcal{O} \) embeds in \( \mathcal{Z} \) via \( g \cdot e \mapsto [g, e] \). The results in [McG] imply that there is equality. Indeed, if \( \phi \in R(\mathcal{O}, \mathcal{S}_\chi) \), view it as a map \( \phi : G \longrightarrow \mathbb{C} \) satisfying

\[ \phi(gx) = \chi(x^{-1})\phi(g) \]

Then define a section \( s_\phi \in H^0(G/P, R(P \cdot f)) \) by the formula

\[ s_{\phi, \xi}(p \cdot f) := \xi(p)\phi(gp). \]

The inverse map is given by

\[ s \longmapsto \phi_s(g) := s(g)(f). \]
We note that there is another inclusion

\[ \{ \text{eq:5.13} \} \]

\[ H_0(G/P, R(g \geq 2) \otimes C, \alpha) \subset H_0(G/P, R(P \cdot f) \otimes C). \]

In [McG] it is shown that when \( \chi = \text{triv} \) and \( \xi = \text{triv} \), then equality holds in (13), and in addition

\[ H^i(P, R(g \geq 2)) = (0) \quad \text{for } i > 0. \]

We make the following conjecture

**Conjecture 1.0.3.** For each \( \chi \in \hat{A}(O) \) there is a representation \( \xi \) of \( P_e \) satisfying \( \xi|_{G^e} = \chi \) such that

\[ H^i(G/P_e, R(g \geq 2) \otimes S_\xi) = \begin{cases} R(O)_\chi, & \text{if } i = 0, \\ 0 & \text{otherwise.} \end{cases} \]

A set of \( \xi \) is given in the next section in the case of classical groups. The cases when \( O \) is special and \( A(O) = \hat{A}(O) \) are called *smoothly cuspidal*. View the complex group \( G \) as a real Lie group, and let \( K \) be the maximal compact subgroup. Then \( R(O) \) can be thought of as a \( K \)-module using the identification of \( K_e \) with \( G \). We will prove the following theorem in the next section.

**Theorem 1.0.4.** Assume \( O \) is smoothly cuspidal, and let \( \chi \longmapsto L_\chi \) be the correspondence between characters of \( \hat{A}(O) \) and unipotent representations defined in [BV2]. Then

\[ L_\chi|_K \cong R(O)_\chi. \]

I conjecture that this result extends to the correspondence defined in the next section for the classical Lie algebras, and that a correspondence with these properties exists in the exceptional cases as well.

The purpose of [McG] is to show that \( R(O) \) can be expressed as a combination of modules induced from characters on Levi components. This has the effect one can express \( R(O) \) as a combination of restrictions to \( K \) of standard modules. Theorem 1.0.3 sharpens this to say that in fact \( R(O)_\chi \) equals the \( K \)-structure of an irreducible module in a natural way.

2. The complex case

Given \( \chi \in \hat{A}(O) \), denote by \( R(O)_\chi \) the regular sections of the sheaf corresponding to \( \chi \).

**Conjecture 2.0.5.** Given a nilpotent orbit \( O \), there is an infinitesimal character \( \lambda_O \) with the following property.
There is a 1-1 correspondence $\chi \leftrightarrow X_{\chi}$ between characters of the component group and irreducible $(\mathfrak{g}, K)$ modules with WF-set $\mathcal{O}$ and infinitesimal character $\lambda_{\mathcal{O}}$ with the following properties:

1. The analogous character formulas as in [BV2] hold,
2. $X_{\chi}|_K \cong R(\mathcal{O})_{\chi}$, 
3. the $X_{\chi}$ are unitary.

As evidence for this conjecture we state the following theorem which is the main result of this section. Recall Lusztig’s quotient $\overline{A(\mathcal{O})}$ of the component group.

**Theorem 2.0.6.** The conjecture is true for classical groups for nilpotent orbits such that $A(\mathcal{O}) = \overline{A(\mathcal{O})}$.

We call an orbit satisfying $A(\mathcal{O}) = \overline{A(\mathcal{O})}$ stably trivial.

We rely on [BV2] and [B1]. First, we prescribe the infinitesimal character $\lambda_{\mathcal{O}}$. The main property will be that the unipotent representations (irreducible $(\mathfrak{g}, K)$ modules whose annihilator in the universal enveloping algebra is maximal with the given infinitesimal character) are unitary and in 1-1 correspondence with the irreducible characters of the component group $A(\mathcal{O})$. The notation is as in [B1]. An orbit is called cuspidal if it is not induced from any proper Levi component. For special orbits whose dual is even, the infinitesimal character is one half the semisimple element of the Lie triple corresponding to the dual orbit. For the other orbits we need the case-by-case analysis.

**Type A.** A nilpotent orbit is determined by its Jordan canonical form. It is given by a partition i.e. a sequence of numbers in decreasing order $(n_1, \ldots, n_k)$ that add up to $n$. Let $(m_1, \ldots, m_l)$ be the dual partition. Then the infinitesimal character is

$$\left( \frac{m_1 - 1}{2}, \ldots, \frac{m_1 - 1}{2}, \ldots, \frac{m_l - 1}{2}, \ldots, \frac{m_l - 1}{2} \right)$$

The orbit is induced from the trivial orbit on the Levi component $GL(m_1) \times \cdots \times GL(m_l)$. The corresponding unipotent representation is spherical and induced irreducible from the trivial representation on the same Levi component. All orbits are stably trivial.

**Type B.** A nilpotent orbit is determined by its Jordan canonical form (in the standard representation). It is parametrized by a partition $(n_1, \ldots, n_k)$ of $2n + 1$ such that every even part occurs an even number of times. Let $(m_0, \ldots, m_{2p'})$ be the dual partition (add an $m_{2p'} = 0$ if necessary, in order to have an odd number of terms). If there are any $m_{2j} = m'_{2j+1}$ then pair them together and remove them from the partition. Then relabel the remaining columns and pair them up, the rest of the columns
The members of each pair have the same parity and \( m_0 \) is odd. Then form a parameter

\[
(m_0) \leftrightarrow \left( \frac{m_0 - 2}{2}, \ldots, 1/2 \right),
\]

\[
(m_{2j} = m_{2j+1}') \leftrightarrow \left( \frac{m_{2j} - 1}{2}, \ldots, -\frac{m_{2j} - 1}{2} \right),
\]

\[
(m_{2i-1} m_{2i}) \leftrightarrow \left( \frac{m_{2i-1}}{2}, \ldots, -\frac{m_{2i} - 2}{2} \right).
\]

In case \( m_{2j} = m_{2j+1}' \), the nilpotent orbit is induced from a parabolic subalgebra \( p \) with Levi component \( so(*) \times gl(m_{2j}') \) with the trivial nilpotent on the \( gl \) factor. The component groups in \( G \) and \( P \) are equal. The unipotent representations are unitarily induced irreducible from similar parameters on the Levi component. Similarly if some \( m_{2i-1} = m_{2i} \), then the nilpotent is induced irreducible from a nilpotent on an \( so(*) \times gl(\frac{m_{2i-1} + m_{2i}}{2}) \) with the trivial nilpotent on the \( gl \) factor. The component groups of the centralizers in \( G \) and \( P \) coincide. The unipotent representations are again induced irreducible from the nilpotent orbit on \( so(*) \) with partition the one for \( O \) but with \( m_{2i-1}, m_{2i} \) removed. The **stably trivial** orbits are the ones such that every odd sized part appears an even number of times except for the largest size. An orbit is triangular if it has partition \( (1, 1, 3, 3, \ldots, 2m-1, 2m-1, 2m+1) \). It is induced from the trivial nilpotent orbit on \( m = gl(2) \times gl(4) \times \cdots \times gl(2m) \). The component group \( A_P \) is trivial.

**Type C.** A nilpotent orbit is determined by its Jordan canonical form (in the standard representation). It is parametrized by a partition \((n_1, \ldots, n_k)\) of \( 2n + 1 \) such that every odd part occurs an even number of times. Let \((m_0', \ldots, m_{2p}')\) be the dual partition (add a \( m_{2p}' = 0 \) if necessary in order to have an odd number of terms). If there are any \( m_{2j-1}' = m_{2j}' \) pair them up and remove them from the partition. Then relabel and pair up the remaining columns \((m_0 m_1) \cdots (m_{2p-2} m_{2p-1}) (m_{2p})\). The members of each pair have the same parity. The last one, \( m_{2p} \), is always even. Then form a parameter

\[
(m_{2j-1} = m_{2j}') \leftrightarrow \left( \frac{m_{2j} - 1}{2}, \ldots, -\frac{m_{2j} - 1}{2} \right),
\]

\[
(m_{2i} m_{2i+1}) \leftrightarrow \left( \frac{m_{2i}}{2}, \ldots, -\frac{m_{2i+1} - 2}{2} \right),
\]

\[
m_{2p} \leftrightarrow \left( \frac{m_{2p}}{2}, \ldots, 1 \right).
\]

The nilpotent orbits and the unipotent representations have the same properties with respect to these pairs as the corresponding ones in type B. The **stably trivial** orbits are the ones such that every even sized part appears an even number of times. An orbit is called triangular if it corresponds to the partition \((2, 2, 4, 4, \ldots, 2m, 2m)\). It is induced from the trivial orbit on \( m = sp(2m) \times gl(1) \times \cdots \times gl(2m - 1) \). The component group \( A_P \) is trivial.

**Type D.** A nilpotent orbit is determined by its Jordan canonical form (in the standard representation). It is parametrized by a partition \((n_1, \ldots, n_k)\)
of $2n$ such that every even part occurs an even number of times. Let 
\( (m'_0, \ldots, m'_{2p-1}) \) be the dual partition (add a \( m'_{2p-1} = 0 \) if necessary). If 
there are any \( m'_{2j} = m'_{2j+1} \) pair them up and remove from the partition. 
Then pair up the remaining columns \( (m_0m_{2p})(m_1, m_2) \ldots (m_{2p-2}m_{2p-1}) \). 
The members of each pair have the same parity and \( m_0, m_{2p-1} \) are even. 
Then form a parameter 
\[
(m'_{2j} = m'_{2j+1}) \leftrightarrow \left( \frac{m'_{2j} - 1}{2}, \ldots, \frac{m'_{2j} - 1}{2} \right)
\]
\[
(m_0m_{2p-1}) \leftrightarrow \left( \frac{m_0 - 2}{2}, \ldots, \frac{m_{2p-1}}{2} \right),
\]
\[
(m_{2i-1}m_{2i}) \leftrightarrow \left( \frac{m_{2i-1}}{2}, \ldots, \frac{m_{2i} - 2}{2} \right).
\]
The nilpotent orbits and the unipotent representations have the same properties with respect to these pairs as the corresponding ones in type B. An exception occurs when the partition is formed of pairs \( (m'_{2j} = m'_{2j+1}) \) only. In 
this case there are two nilpotent orbits corresponding to the partition. There 
are also two nonconjugate Levi components of the form \( gl(m'_0) \times gl(m'_2) \times \ldots \times gl(m'_{2p-2}) \) of parabolic subalgebras. There are two unipotent representations each induced irreducible from the trivial representation on the corresponding Levi component. The stably trivial orbits are the ones such that 
every even sized part appears an even number of times. A nilpotent orbit is 
triangular if it corresponds to the partition \( (1, 1, 3, 3, \ldots, 2m - 1, 2m - 1) \). 
It is induced from the trivial orbit in the Levi component \( m = gl(2) \times \cdots \times gl(2m - 2) \). The component group \( A_F \) is trivial.

Since all these results are clear for type A, we deal with types B, C, D only. Consider a stably trivial nilpotent orbit \( O \subset g(n) \). Let \( m = g(n) + gl(k_1) \times \cdots \times gl(k_r) \) be a Levi component of a parabolic subalgebra in \( g^+ := g(n + k_1 + \cdots + k_r) \). There are \( k_1, \ldots, k_r \) such that the orbit 
\[
O^+ = Ind_m^{g(n')} [O \times \text{triv} \times \cdots \times \text{triv}]
\]
is triangular. Let \( m^+ \) be the Levi component corresponding to the semisimple element of the Lie triple of \( O^+ \). By \( \left[ 1.0.1 \right] \), the unipotent representations attached to \( O^+ \)
\[
X^+_\nu = R(O^+)\nu - Y^+_\nu.
\]
where \( Y^+_\nu \) is a genuine K-module. Adding over \( \nu \) and using \( \left[ \text{BVI} \right] \), we find
\[
R(\tilde{O}^+) = R(\tilde{O}^+) - Y^+,
\]
so \( X^+_\nu = R(O^+)\nu \).

By \( \left[ \text{B3} \right] \) and \( \left[ \text{V} \right] \), for each unipotent representation \( X_\psi \) there is a representation \( \psi' \) of the centralizer of a representative of the orbit \( O \), and a K-representation \( Y_\psi \) such that 
\[
X_\psi = R(O)\psi - Y_\psi.
\]
In addition, \( Y_\psi \) is supported on strictly smaller orbits. We need to show that \( Y_\psi = 0 \) and \( \psi = \psi' \). Consider the induced modules
\[
I_\psi^+ = \text{Ind}_{\mathfrak{m}}^G [X_\psi \otimes \text{triv}].
\]
Let \( \Psi \) be the character induced from \( \psi \) and write \( X_\Psi^+ \) for the corresponding combination of \( X_\nu^+ \). By \([\text{BV}]\)
\[
I_\psi^+ = X_\Psi^+.
\]
By \((1.0.1)\), the module induced from \( R(\mathcal{O})\psi' \) is contained in \( R(\mathcal{O}^+)\psi' \). Thus
\[
I_\psi^+ = R(\mathcal{O}^+)\psi' - Z_\psi^+,
\]
where \( Z_\psi^+ \) is a genuine module (containing the induced from \( Y_\psi \)). Again by \([\text{BV}]\), summing both sides over \( \psi \) we get
\[
R(\tilde{\mathcal{O}}^+) = \sum R(\mathcal{O}^+)\psi' - Z^+,
\]
where \( Z^+ = \sum Z_\psi^+ \) is a genuine module supported on smaller orbits. Unless
\[
R(\tilde{\mathcal{O}}^+) = \sum R(\mathcal{O}^+)\psi' \text{ and } Z^+ = 0,
\]
this contradicts the linear independence of the \( R(\mathcal{O})\nu \) in \([\text{V}]\). Thus the \( Y_\psi = 0 \) and the correspondence \( \psi \leftrightarrow \psi' \) is 1-1.

Remains to show that \( \psi = \psi' \). Suppose not. Equation \((19)\) now reads
\[
I_\psi^+ = I_\psi^+.
\]
The claim follows from the linear independence of the \( R(\mathcal{O}^+)\nu \) as \( K \)-modules.

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