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ON THE ANNIHILATORS OF GENERALIZED LOCAL COHOMOLOGY MODULES

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Abstract. Let $\mathfrak{a}$ be an ideal of Noetherian ring R and M, N be two finitely generated R-modules. In this paper, we obtain some results about the annihilators of top generalized local cohomology modules. We define $T := T_R(\mathfrak{a}, M, N)$ as the largest submodule of N such that $\mathrm{cd}(\mathfrak{a}, M, T_R(\mathfrak{a}, M, N)) < \mathrm{cd}(\mathfrak{a}, M, N)$. Let $(R, \mathfrak{m})$ be a complete Gorenstein Noetherian local ring such that $\mathrm{pd}(M) = d < \infty$, $\dim N = \dim R = n < \infty$ and $\mathrm{cd}(\mathfrak{a}, M, N) = d+n$. We prove that if $\mathrm{Ass}_R(\mathrm{Ext}^d_R(M, N/T)) \subseteq \mathrm{Ass}_R R$, then $\mathrm{Ann}_R(\mathrm{H}^{d+n}_{\mathfrak{m}}(M, N)) \subseteq \mathrm{Ann}_R \mathrm{Ext}^d_R(M, N/T)$.

Keywords: Annihilator, Local cohomology, Noetherian ring.
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1. Introduction

Throughout this paper, R is a commutative Noetherian ring with identity, $\mathfrak{a}$ is an ideal of R, $M$and N are two R-modules.

For each $i \geq 0$, the i-th local cohomology module M with respect to an ideal $\mathfrak{a}$ is defined as $\mathrm{H}^i_{\mathfrak{a}}(M) = \varinjlim_n \mathrm{Ext}^i_R(R/\mathfrak{a}^n, M)$. For basic results about local cohomology we refer the reader to [6]. A Generalization of local cohomology functor has been given by J. Herzog in [10]. The i-th generalized local cohomology module of M and N with respect to $\mathfrak{a}$ is denoted by $\mathrm{H}^i_{\mathfrak{a}}(M, N) := \varinjlim_n \mathrm{Ext}^i_R(M/\mathfrak{a}^n M, N)$.

An important problem concerning local cohomology is determining the annihilators of the i-th local cohomology module $\mathrm{H}^i_{\mathfrak{a}}(M)$. This problem has been studied by several authors, see for example [2], [3], [4], [5], [9] and [11]. In [5], Bahmanpour et al. proved an intersting result about the annihilator $\mathrm{Ann}_R(\mathrm{H}^{\dim(M)}_{\mathfrak{m}}(M))$ in the case $(R, \mathfrak{m})$ is a complete local ring. In fact, in [5, Theorem 2.6], they proved that if $(R, \mathfrak{m})$ is a complete local ring then $\mathrm{Ann}_R(\mathrm{H}^{\dim(M)}_{\mathfrak{m}}(M)) = \mathrm{Ann}_R(M/T_R(M))$ where $T_R(M) = \cup\{N : N \leq M$ and $\dim N < \dim M\}$.

Atazadeh et al. in [2] generalized this main result by determining $\mathrm{Ann}_R(\mathrm{H}^{\dim(M)}_{\mathfrak{a}}(M))$ for an arbitrary Noetherian ring R. In [2, Theorem 2.3],

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by using the above main result, they showed that, if $\mathrm{H}_{\mathfrak{a}}^{\dim(M)}(M) \neq 0$, then $\mathrm{Ann}_R(\mathrm{H}_{\mathfrak{a}}^{\dim(M)}(M)) = \mathrm{Ann}_R(M/T_R(\mathfrak{a}, M))$ where $T_R(\mathfrak{a}, M) = \cup\{N : N \leq M \text{ and } \mathrm{cd}(\mathfrak{a}, N) < \mathrm{cd}(\mathfrak{a}, M)\}$.

Not so much is known about the annihilators of top generalized local cohomology modules. Here, we obtain some results about them. Let $\mathfrak{a}$ be an ideal of Noetherian ring R and M, N two finitely generated R-modules. At first, we define $T_R(\mathfrak{a}, M, N)$ as the largest submodule of N such that $\mathrm{cd}(\mathfrak{a}, M, T_R(\mathfrak{a}, M, N)) < \mathrm{cd}(\mathfrak{a}, M, N)$. Then we prove the following main result:

Theorem 1.1. *Let $(R, \mathfrak{m})$ be a complete Gorenstein Noetherian local ring. Let M and N be non-zero finitely generated R-modules and $T := T_R(\mathfrak{m}, M, N)$. Assume that $\mathrm{pd}(M) = d < \infty$, $\dim N = \dim R = n < \infty$ and $\mathrm{cd}(\mathfrak{m}, M, N) = d+n$. Also, assume that $\mathrm{Ass}_R(\mathrm{Ext}_R^d(M, N/T)) \subseteq \mathrm{Ass}_R R$. Then $\mathrm{Ann}_R(\mathrm{H}_{\mathfrak{m}}^{d+n}(M, N)) \subseteq \mathrm{Ann}_R \mathrm{Ext}_R^d(M, N/T)$.*

In [13, Theorem 3.3], the author has determined the annihilators of generalized local cohomology modules. In Remark 2.9 we show that his claimed proof is invalid.

2. Main Results

Recall that, for any two R-modules M and N, the cohomological dimension of M and N with respect to an ideal $\mathfrak{a}$ of a commutative Noetherian ring R, is defined as

$$\mathrm{cd}(\mathfrak{a}, M, N) = \sup\{i \in \mathbb{N}_0 : \mathrm{H}_{\mathfrak{a}}^i(M, N) \neq 0\}.$$

For more details see [1].

We need the following result in our proofs.

Lemma 2.1. *Let R be a Noetherian ring and $\mathfrak{a}$ be an ideal of R. Let M, N, L be finitely generated R-modules such that $\mathrm{Supp}\, N \subseteq \mathrm{Supp}\, L$. Then, $\mathrm{cd}(\mathfrak{a}, M, N) \leq \mathrm{cd}(\mathfrak{a}, M, L)$.*

Proof. See [1, Theorem B]. □

We give the following definition which is a generalization of [3, Definition 2.4].

Definition 2.2. Let $\mathfrak{a}$ be an ideal of Noetherian ring R, M and N be non-zero finitely generated R-modules. We denote by $T_R(\mathfrak{a}, M, N)$ the largest submodule of N such that $\mathrm{cd}(\mathfrak{a}, M, T_R(\mathfrak{a}, M, N)) < \mathrm{cd}(\mathfrak{a}, M, N)$.

Proposition 2.3. *Let R be a Noetherian ring and $\mathfrak{a}$ be an ideal of R. Let M and N be non-zero finitely generated R-modules. Assume that $\mathrm{pd}(M) = d < \infty$ and $\dim N = n < \infty$. Then $\mathrm{H}_{\mathfrak{a}}^i(M, N) = 0$ for all $i > d + n$.*

Proof. It follows by [14, Theorem 3.7]. □

Lemma 2.4. *Let R be a Noetherian ring and $\mathfrak{a}$ be an ideal of R. Let M and N be non-zero finitely generated R-modules. Assume that $\mathrm{pd}(M) = d < \infty$,*

$\dim N = n < \infty$ *and* $\mathrm{cd}(\mathfrak{a}, M, N) = d + n$. *Assume that* $G := N/T_R(\mathfrak{a}, M, N)$. *Then*

i) $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, G) \cong \mathrm{H}^{d+n}_{\mathfrak{a}}(M, N)$ *and so* $\mathrm{cd}(\mathfrak{a}, M, G) = d + n$,

ii) G has no non-zero submodule K such that $\mathrm{cd}(\mathfrak{a}, M, K) < \mathrm{cd}(\mathfrak{a}, M, G) = d + n$,

iii) $\mathrm{Ass}\, G = \{\mathfrak{p} \in \mathrm{Supp}_R\, G | \,\mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d+n\} = \{\mathfrak{p} \in \mathrm{Ass}_R\, N | \,\mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d + n\} \subseteq \{\mathfrak{p} \in \mathrm{Spec}\, R | \,dim\, R/\mathfrak{p} = n\}$,

iv) $\dim G = n$,

v) G has no non-zero submodule of dimension less than n.

Proof. i) Set $T := T_R(\mathfrak{a}, M, N)$. By using the exact sequence $0 \to T \to N \to G \to 0$ we obtain

$$\cdots \to \mathrm{H}^{d+n}_{\mathfrak{a}}(M, T) \to \mathrm{H}^{d+n}_{\mathfrak{a}}(M, N) \to \mathrm{H}^{d+n}_{\mathfrak{a}}(M, G) \to 0.$$

By Definition 2.2, $\mathrm{cd}(\mathfrak{a}, M, T) < d+n$ and so $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, T) = 0$. Thus the above exact sequence implies that $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, G) \cong \mathrm{H}^{d+n}_{\mathfrak{a}}(M, N)$.

ii) Assume that, there exists a non-zero submodule $K := U/T$ of $G = N/T$ such that $\mathrm{cd}(\mathfrak{a}, M, K) < \mathrm{cd}(\mathfrak{a}, M, G)$. By Definition 2.2 and (i) we have $\mathrm{cd}(\mathfrak{a}, M, T) < \mathrm{cd}(\mathfrak{a}, M, N) = \mathrm{cd}(\mathfrak{a}, M, G)$. On the other hand, from $0 \to T \to U \to K \to 0$ and by [1, Theorem A] we have $\mathrm{cd}(\mathfrak{a}, M, U) = \mathrm{Max}\{\mathrm{cd}(\mathfrak{a}, M, T), \mathrm{cd}(\mathfrak{a}, M, K)\}$. Thus it follows that $\mathrm{cd}(\mathfrak{a}, M, U) < \mathrm{cd}(\mathfrak{a}, M, G) = \mathrm{cd}(\mathfrak{a}, M, N)$. But $T \subsetneq U$ and this is a contradiction by definition of T.

iii) By (ii) G has no non-zero submodule K such that $\mathrm{cd}(\mathfrak{a}, M, K) < \mathrm{cd}(\mathfrak{a}, M, G) = d + n$. Thus

$$\mathrm{Ass}\, G \subseteq \{\mathfrak{p} \in \mathrm{Supp}\, G : \mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d + n\}.$$

Let $\mathfrak{p} \in \mathrm{Supp}\, G$ and $\mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d + n$. Since $d + n = \mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) \leq d{+}\dim R/\mathfrak{p}$ and $d{+}\dim R/\mathfrak{p} \leq d{+}\dim N = d{+}n$ we conclude that $\dim R/\mathfrak{p} = n$. Since $\mathfrak{p} \in \mathrm{Supp}\, G \subseteq \mathrm{Supp}\, N$ and $\dim R/\mathfrak{p} = n$ it follows that $\mathfrak{p} \in \mathrm{Ass}\, N$ and so

$$\mathrm{Ass}\, G \subseteq \{\mathfrak{p} \in \mathrm{Supp}\, G : \mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d{+}n\} \subseteq \{\mathfrak{p} \in \mathrm{Ass}\, N : \mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d{+}n\}.$$

Now assume that $\mathfrak{p} \in \mathrm{Ass}\, N$ and $\mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) = d + n$. If $\mathfrak{p} \in \mathrm{Supp}\, T$, then $\mathrm{cd}(\mathfrak{a}, M, R/\mathfrak{p}) \leq \mathrm{cd}(\mathfrak{a}, M, T) < d + n$ by Lemma 2.1 which is a contradiction. Thus $\mathfrak{p} \in \mathrm{Supp}\, G$ and by the above argument $\dim R/\mathfrak{p} = n$. Therefore $\mathfrak{p} \in \mathrm{Ass}\, G$.

iv) By (iii) if $\mathfrak{p} \in \mathrm{Ass}_R\, G$, then $\dim R/\mathfrak{p} = n$. Thus $\dim G = n$.

v) Let U be a non-zero submodule of G. By (ii) we have $\mathrm{cd}(\mathfrak{a}, M, U) = d{+}n$. Now if $\dim U < n$, then $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, U) = 0$ which is a contradiction. Thus $\dim U = n$, as required. □

Proposition 2.5. *Let R be a Noetherian ring and* $\mathfrak{a}$ *be an ideal of R. Let M and N be non-zero finitely generated R-modules. Assume that* $\mathrm{pd}(M) = d < \infty$ *and* $\dim N = n < \infty$. *Then* $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, N)$ *is Artinian and* $\mathrm{H}^{d+n}_{\mathfrak{a}}(M, N) \cong \mathrm{Ext}^d_R(M, \mathrm{H}^n_{\mathfrak{a}}(N))$.

Proof. By [8, Proposition 2.2]. □

Proposition 2.6. *Let $(R,\mathfrak{m})$ be a Cohen-Macaulay Noetherian local ring and for every $\mathfrak{p}\in \operatorname{Ass}_R R$ the zero-dimensional local ring $R_{\mathfrak{p}}$ is Gorenstein. Let M be a finitely generated R-module such that $\operatorname{Ass}_R M \subseteq \operatorname{Ass}_R R$. Then there is an exact sequence $0\to M\to \oplus_{i=1}^{n} R$ for some positive integer n.*

Proof. By [7, Theorem 3.5]. □

In the following, we prove the main result of this paper.

Theorem 2.7. *Let $(R,\mathfrak{m})$ be a complete Gorenstein Noetherian local ring. Let M and N be non-zero finitely generated R-modules and $T := T_R(\mathfrak{m}, M, N)$. Assume that $\operatorname{pd}(M) = d < \infty$, $\dim N = \dim R = n < \infty$ and $\operatorname{cd}(\mathfrak{m}, M, N) = d+n$. Also, assume that $\operatorname{Ass}_R \operatorname{Ext}_R^d(M, N/T) \subseteq \operatorname{Ass}_R R$. Then $\operatorname{Ann}_R \operatorname{H}_{\mathfrak{m}}^{d+n}(M,N) \subseteq \operatorname{Ann}_R \operatorname{Ext}_R^d(M, N/T)$.*

Proof. By Lemma 2.4 (i), $\operatorname{H}_{\mathfrak{m}}^{d+n}(M,N)\cong \operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T)$. Thus we must show that $\operatorname{Ann}_R \operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T) \subseteq \operatorname{Ann}_R \operatorname{Ext}_R^d(M,N/T)$. By Proposition 2.6 there exists a monomorphism

$$f : \operatorname{Ext}_R^d(M,N/T) \to \oplus_{i=1}^{t} R,$$

for some positive integer t. We claim

$$\operatorname{Ann}_R(\operatorname{Hom}_R(\operatorname{Ext}_R^d(M,N/T), \oplus_{i=1}^{t} R) = \operatorname{Ann}_R \operatorname{Ext}_R^d(M,N/T).$$

If $r \in \operatorname{Ann}_R(\operatorname{Hom}_R(\operatorname{Ext}_R^d(M,N/T), \oplus_{i=1}^{t} R)$, then $rf = 0$. Thus $f(r\operatorname{Ext}_R^d(M,N/T)) = 0$. Since f is a monomorphism, it follows that $r\operatorname{Ext}_R^d(M,N/T) = 0$ and so $r \in \operatorname{Ann}_R \operatorname{Ext}_R^d(M,N/T)$. On the other hand, since $\operatorname{Ext}_R^d(M,-)$ is a right exact functor we have $\operatorname{Ext}_R^d(M,N/T) \simeq \operatorname{Ext}_R^d(M,R)\otimes N/T$. Thus by using Proposition 2.5 we have

$$\begin{aligned}
&\operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))\\
&\cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M, \operatorname{H}_{\mathfrak{m}}^{n}(N/T)), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))\\
&\cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M,R)\otimes \operatorname{H}_{\mathfrak{m}}^{n}(N/T), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))\\
&\cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M,R)\otimes \operatorname{H}_{\mathfrak{m}}^{n}(R)\otimes N/T, \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))\\
&\cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M,R)\otimes N/T, \operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{n}(R), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m})))\\
&\cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M,N/T), \operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{n}(R), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))).
\end{aligned}$$

Since R is a Gorenstein ring by [6, Lemma 11.2.3] it follows that $\operatorname{H}_{\mathfrak{m}}^{n}(R)\cong \operatorname{E}(R/\mathfrak{m})$ and since R is complete by [6, Theorem 10.2.11] we conclude that

$$\operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{n}(R), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m})) \cong \oplus_{i=1}^{t} R.$$

Thus we have

$$\operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m})) \cong \operatorname{Hom}_R(\operatorname{Ext}_R^d(M,N/T), \oplus_{i=1}^{t} R).$$

Therefore by Lemma 2.4 (i) we have

$$\begin{aligned}
\operatorname{Ann}_R \operatorname{H}_{\mathfrak{m}}^{d+n}(M,N) &= \operatorname{Ann}_R \operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T)\\
&\subseteq \operatorname{Ann}_R(\operatorname{Hom}_R(\operatorname{H}_{\mathfrak{m}}^{d+n}(M,N/T), \oplus_{i=1}^{t} \operatorname{E}(R/\mathfrak{m}))
\end{aligned}$$

$$= \operatorname{Ann}_R(\operatorname{Hom}_R(\operatorname{Ext}^d_R(M, N/T), \oplus^t_{i=1}R)) \subseteq \operatorname{Ann}_R \operatorname{Ext}^d_R(M, N/T)$$

and the proof is complete. □

Corollary 2.8. *Let $(R, \mathfrak{m})$ be a complete Gorenstein Noetherian local ring. Let M and N be non-zero finitely generated R-modules and $T := T_R(\mathfrak{m}, M, N)$. Assume that* $\operatorname{pd}(M) = d < \infty$, $\dim N = \dim R = n < \infty$ *and* $\operatorname{cd}(\mathfrak{m}, M, N) = d + n$. *Then*

i) If $\operatorname{Ass}_R \operatorname{Ext}^d_R(M, N/T) \subseteq \operatorname{Ass}_R R$, *then*

$$\sqrt{\operatorname{Ann}_R \operatorname{H}^{d+n}_{\mathfrak{m}}(M, N)} \subseteq \cap_{\mathfrak{p} \in \operatorname{Ass}_R \operatorname{Ext}^d_R(M,N/T)}\mathfrak{p}.$$

ii) If $\operatorname{Ass}_R \operatorname{Ext}^d_R(M, N/T) \subseteq \{\mathfrak{p} \in \operatorname{Spec} R | \, dim\, R/\mathfrak{p} = n\}$, *then*

$$\operatorname{Ann}_R \operatorname{H}^{d+n}_{\mathfrak{m}}(M, N) \subseteq \operatorname{Ann}_R \operatorname{Ext}^d_R(M, N/T).$$

iii) If $\operatorname{Ass}_R \operatorname{Ext}^d_R(M, N/T) \subseteq \operatorname{Ass}_R N/T$, *then*

$$\operatorname{Ann}_R \operatorname{H}^{n+d}_{\mathfrak{m}}(M, N) \subseteq \operatorname{Ann}_R \operatorname{Ext}^d_R(M, N/T).$$

iv) Let $\operatorname{Ext}^d_R(M, N/T)$ *be a Cohen-Macaulay R-module of dimension n. Then*

$$\operatorname{Ann}_R \operatorname{H}^{n+d}_{\mathfrak{m}}(M, N) \subseteq \operatorname{Ann}_R \operatorname{Ext}^d_R(M, N/T).$$

v) Assume that M is projective. Then

$$\operatorname{Ann}_R \operatorname{H}^{n}_{\mathfrak{m}}(M, N) \subseteq \operatorname{Ann}_R \operatorname{Hom}_R(M, N/T).$$

Proof. i) The result follows by Theorem 2.7.

ii) Since $\{\mathfrak{p} \in \operatorname{Spec} R | \dim R/\mathfrak{p} = n\} \subseteq \operatorname{Ass}_R R$, the result follows by Theorem 2.7.

iii) By assumption and Lemma 2.4 (iii) we conclude that

$$\operatorname{Ass}_R \operatorname{Ext}^d_R(M, N/T) \subseteq \{\mathfrak{p} \in \operatorname{Spec} R | \dim R/\mathfrak{p} = n\},$$

and so the result follows by (ii).

iv) By assumption and [12, Theorem 17.3 (i)] we conclude that $\operatorname{Ass}_R \operatorname{Ext}^d_R(M, N/T) \subseteq \{\mathfrak{p} \in \operatorname{Spec} R | \dim R/\mathfrak{p} = n\}$. Thus the result follows by (ii).

v) By assumption $d = \operatorname{pd} M = 0$. We have

$$\operatorname{Ass}_R \operatorname{Hom}_R(M, N/T) = \operatorname{Supp}_R M \cap \operatorname{Ass}_R N/T \subseteq \operatorname{Ass}_R N/T.$$

Thus Part (iii) completes the proof. □

Remark 2.9. In [13, Theorem 3.3], the author has determined the annihilators of generalized local cohomology modules. But he has made an error in the proof. In fact, for a system of ideals Φ in a Noetherian ring R and two non-zero finitely generated R-modules M, N such that $c := \operatorname{cd}_\Phi(M, N)$, when one apply the functor $\operatorname{H}_\Phi(M, -)$ to the map $N \to xN$ where $x \in R$, the result will not be multiplication by x. But applyig the local cohomology functor to $N \to N$ which is multiplication by x will be again multiplication by x.

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