



## Extensions of commutative rings

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In honor of the memory of our friend Mel Henriksen

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### ABSTRACT

In studying the minimal prime spectra of commutative rings with identity we have been able to identify several interesting types of extensions of rings. In particular, we determine what kind of ring extensions will result in a homeomorphisms of the hull-kernel and inverse topologies on the minimal prime spectra. We relate these types of extensions to other known types of extensions.

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### 1. Preliminaries

Throughout this article we make the tacit assumption that all rings are commutative, reduced, and possess an identity. For the most part we shall use  $R$  and  $S$  to denote such rings. We use the notation  $I \leq R$  to mean that  $I$  is an ideal of  $R$ . The collection of all ideals of  $R$  will be denoted by  $\mathcal{L}(R)$ . For a subset  $I \subseteq R$  we denote the annihilator of  $I$  by  $\text{Ann}_R(I) = \{a \in R : ar = 0 \text{ for all } r \in I\}$ . When  $I = \{a_1, \dots, a_n\}$  we instead write  $\text{Ann}_R(a_1, \dots, a_n)$ . When  $R$  is a subring of  $S$  (and possessing the identity) we shall write  $R \hookrightarrow S$  and call this an *extension of rings*.

The collection of all prime ideals of  $R$  is denoted by  $\text{Spec}(R)$ . The usual Zorn's Lemma argument ensures that minimal prime ideals exist and we denote the collection of these by  $\text{Min}(R)$ . There shall be occasions where we will view  $\text{Spec}(R)$  as a functor from the category of commutative rings with identity to the category of topological spaces. Recall that  $\text{Spec}(R)$  is equipped with the hull-kernel topology (a.k.a. the Zariski topology). An arbitrary open set of  $\text{Spec}(R)$  is one of the form

$$\mathcal{U}(I) = \{P \in \text{Spec}(R) \mid I \not\subseteq P\}$$

for some  $I \leq R$ . When  $I = \{a\}$ , we instead write  $\mathcal{U}(a)$ . The collection  $\{\mathcal{U}(a)\}_{a \in R}$  is a base for the hull-kernel topology on  $\text{Spec}(R)$ .

We are interested in studying rings via their space of minimal prime ideals. One of the first papers to begin this program was [7], an article to which we are greatly indebted. We therefore wish to dedicate this manuscript to the memory of Melvin Henriksen. The book by Huckaba [8] also has an excellent treatment of the subject and we mention this as our main reference. We will use the following lemmas implicitly.

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**Lemma 1.1.** (Corollary 2.2, [8]) Let  $R$  be a reduced ring and let  $P \in \text{Spec}(R)$ .  $P \in \text{Min}(R)$  if and only if for each  $x \in P$  there exists an  $r \in R \setminus P$  such that  $xr = 0$ .

**Lemma 1.2.** (Corollary 2.3, [8]) Let  $R$  be a reduced ring and let  $P \in \text{Min}(R)$ . For a finitely generated ideal  $I$  of  $R$ ,  $I \subseteq P$  if and only if  $\text{Ann}_R(I) \not\subseteq P$ .

As  $\text{Min}(R) \subseteq \text{Spec}(R)$  it follows that the collection of sets of the form  $U(a) \cap \text{Min}(R)$  is a base for the subspace topology on  $\text{Min}(R)$ . For  $I \leq R$ , we set  $U_R(I) = U(I) \cap \text{Min}(R)$ . When  $I = \{r\}$  we instead write  $U_R(r)$ . We also set  $V_R(I) = \text{Min}(R) \setminus U_R(I)$  and  $V_R(r) = \text{Min}(R) \setminus U_R(r)$ . Thus, the collection  $\{U_R(r)\}_{r \in R}$  is a base for the hull-kernel topology on  $\text{Min}(R)$ . Recall the following properties.

**Lemma 1.3.** Let  $R$  be a reduced ring and  $a, b \in R$ . Then

- (1)  $U_R(a) \cap U_R(b) = U_R(ab)$ ;
- (2)  $U_R(a) \cup U_R(b) = U_R(aR + bR)$ ;
- (3)  $U_R(a) = \emptyset$  if and only if  $a = 0$ ;
- (4)  $U_R(a) = \text{Min}(R)$  if and only if  $a$  is not a zero-divisor.

By (2) of Lemma 1.3 (and induction) it follows that the collection

$$\{V_R(I) : I \leq R \text{ is a finitely generated ideal of } R\}$$

is closed under finite intersections. Therefore, this collection forms a base for a topology on  $\text{Min}(R)$ , called the *inverse topology*. When equipped with the inverse topology we shall write  $\text{Min}(R)^{-1}$ . In general, the most that we can say about the collection  $\{V_R(r)\}_{r \in R}$  is that it is a subbase for the inverse topology. For more information and a detailed discussion of the inverse topology the reader is encouraged to read [10]. In particular we recall the following facts concerning  $\text{Min}(R)$  and  $\text{Min}(R)^{-1}$ .

A *zero-dimensional space* is one which has a base of clopen subsets. The hull-kernel topology on  $\text{Min}(R)$  is always a zero-dimensional Hausdorff topology. In particular, it follows from Lemma 1.2 that  $U_R(r) = V_R(\text{Ann}_R(r))$  for any  $r \in R$  and so each basic open is clopen. The inverse topology makes  $\text{Min}(R)^{-1}$  into a compact  $T_1$ -space (see Theorem 3.1 of [10]).

**Definition 1.4.** A ring  $R$  is said to satisfy the *annihilator condition* (or a.c. for short) if for all  $a, b \in R$  there exists a  $c \in R$  such that  $\text{Ann}_R(a, b) = \text{Ann}_R(c)$ . This has obvious cardinal generalizations. For a fixed cardinal, say  $\kappa$ ,  $R$  is said to satisfy the  $\kappa$ -*annihilator condition* if for every subset of  $R$  of cardinality less than  $\kappa$ , say  $X \subseteq R$ , there is an  $r_X \in R$  such that  $\text{Ann}_R(X) = \text{Ann}_R(r_X)$ . In this sense the annihilator condition is equivalent to the  $\aleph_0$ -annihilator condition. When  $R$  satisfies the  $\kappa$ -annihilator condition for all  $\kappa$  (or equivalently for  $|R|^+$ ), we say  $R$  satisfies the *super annihilator condition*.

A *Baer ring* is a ring  $R$  that has the property that for every subset  $X \subseteq R$  there is an idempotent  $e_X \in R$  such that  $\text{Ann}_R(X) = e_X R$ . Notice then that  $\text{Ann}_R(X) = \text{Ann}_R(1 - e_X)$  and so a Baer ring satisfies the super annihilator condition. A ring is called a *weak Baer ring* if for every  $a \in R$  there is an idempotent  $e \in R$  such that  $\text{Ann}_R(a) = \text{Ann}_R(e)$ . It follows that a Baer ring is a weak Baer ring, and a weak Baer ring satisfies the annihilator condition. Weak Baer rings are also known as Rickart rings as well as p.p. rings.

Interestingly, the annihilator condition is related to the inverse topology in the following way.

**Proposition 1.5.** Let  $R$  be a reduced ring.  $R$  satisfies the annihilator condition if and only if the collection  $\{V_R(r)\}_{r \in R}$  is closed under finite intersection. In this case, the collection is a base for the inverse topology.

**Proof.** We first assume that  $R$  satisfies the a.c. Let  $r_1, r_2 \in R$  for which  $V_R(r_1) \cap V_R(r_2) \neq \emptyset$ . Choose  $r \in R$  such that  $\text{Ann}_R(r) = \text{Ann}_R(r_1, r_2) = \text{Ann}_R(r_1) \cap \text{Ann}_R(r_2)$ .

Consider  $P \in V_R(r)$ . By Lemma 1.1  $\text{Ann}_R(r) \not\subseteq P$ . Hence, there exists  $x \in R \setminus P$  such that  $xr = 0$ . So  $xr_1 = xr_2 = 0$ . Since  $x \notin P$ , then  $r_1 \in P$  and  $r_2 \in P$ , whence  $P \in V_R(r_1) \cap V_R(r_2)$ .

As for the reverse inclusion, let  $Q \in V_R(r_1) \cap V_R(r_2)$ . Then there exist  $x, y \in R \setminus Q$  such that  $xr_1 = yr_2 = 0$ ; observe that  $xy \in R \setminus Q$ . The equation  $\text{Ann}_R(r_1, r_2) = \text{Ann}_R(r)$  yields that  $(xy)r = 0$ , and so  $r \in Q$ . Consequently,  $V_R(r_1) \cap V_R(r_2) \subseteq V_R(r)$ .

Next, suppose  $\{V_R(r)\}_{r \in R}$  is closed under finite intersections. Let  $r_1, r_2 \in R$  and consider  $\text{Ann}_R(r_1, r_2)$ . By assumption there is an  $r \in R$  such that  $V_R(r) = V_R(r_1) \cap V_R(r_2)$ . We claim  $\text{Ann}_R(r_1, r_2) = \text{Ann}_R(r)$ .

Let  $x \in \text{Ann}_R(r_1, r_2)$ . Then  $xr_1 = xr_2 = 0$ . Suppose by way of contradiction that  $xr \neq 0$ . Since  $R$  is reduced there exists  $P \in \text{Min}(R)$  with  $xr \notin P$  giving  $r, x \notin P$ . Therefore,  $P \notin V_R(r) = V_R(r_1) \cap V_R(r_2)$ . Consequently,  $r_1 \notin P$  or  $r_2 \notin P$ . Either way  $x \in P$ , a contradiction. Accordingly,  $\text{Ann}_R(r_1, r_2) \subseteq \text{Ann}_R(r)$ .

On the other hand, let  $x \in \text{Ann}_R(r)$ . We claim  $xr_1 = xr_2 = 0$ . Suppose by way of contradiction  $xr_1 \neq 0$ . Using that  $R$  is reduced again there exists  $P \in \text{Min}(R)$  with  $xr_1 \notin P$ . So,  $x, r_1 \notin P$ , hence  $P \notin V_R(r_1)$ . Thus  $P \notin V_R(r_1) \cap V_R(r_2) = V_R(r)$ . However,  $xr = 0$  and  $x \notin P$  forces  $r \in P$ . This contradiction leads us to conclude that  $x \in \text{Ann}_R(r_1, r_2)$ . We have thus demonstrated

that  $\text{Ann}_R(r_1, r_2) = \text{Ann}_R(r)$ , whence  $R$  satisfies the a.c. Consequently, a reduced ring  $R$  satisfies the a.c. precisely when the collection  $\{V_R(r)\}_{r \in R}$  is closed under finite intersection.  $\square$

**Remark 1.6.** In Section 3 we will supply an example of a ring  $R$  for which the collection  $\{V_R(r) : r \in R\}$  forms a base for the topology on  $\text{Min}(R)^{-1}$  yet  $R$  does not satisfy the a.c.

Our next result was first proved by Mewborn [13] in the context of embedding a ring  $R$  inside its maximal ring of quotients (in the sense of Utumi) and determining when  $\text{Min}(R)$  is compact. In a more general setting it is stated as an exercise at the end of Section 1.6 of [9].

**Proposition 1.7.** *Let  $R \hookrightarrow S$  be an extension of reduced rings. For each  $P \in \text{Spec}(R)$  there exists  $Q \in \text{Min}(S)$  such that  $Q \cap R \subseteq P$ . Furthermore, if  $P \in \text{Min}(R)$ , there exists  $Q \in \text{Min}(S)$  such that  $P = Q \cap R$ .*

**Definition 1.8.** From this point on we will be interested in those extensions of rings, say  $R \hookrightarrow S$ , which have the property that for each  $P \in \text{Min}(S)$ ,  $P \cap R \in \text{Min}(R)$ . We shall refer to such an extension as an  $m$ -extension of rings. In [16] these extensions are called *minimalisant* while in [17] they are called *min* extensions. When  $R \hookrightarrow S$  is an  $m$ -extension we let  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  be the map defined by  $\Psi(P) = P \cap R$ . We continue with some examples.

First, notice that if  $S$  is a domain, then  $S$  is trivially an  $m$ -extension of any of its subrings.

Second, consider the ring homomorphism  $f : R \rightarrow R \times R$  which maps  $r$  to  $(r, r)$ . This is an  $m$ -extension as every minimal prime ideal of  $R \times R$ , say  $Q$ , has one of the forms  $P \times R$  or  $R \times P$  for some  $P \in \text{Min}(R)$ . Then  $f^{-1}(Q) = P \in \text{Min}(R)$ .

Third, the embedding of a ring  $R$  into its classical ring of quotients, which we denote by  $q(R)$ , is always an  $m$ -extension. Letting  $Q(R)$  denote the complete (a.k.a. maximal) ring of quotients of  $R$ , then it is a well-known theorem that  $R \hookrightarrow Q(R)$  is an  $m$ -extension precisely when  $\text{Min}(R)$  is compact (see Theorem 4.3 [8] for more equivalences).

**Remark 1.9.** Recall from [9] that an extension of rings, say  $R \hookrightarrow S$  is called an INC-extension if whenever  $Q_1, Q_2 \in \text{Spec}(S)$  are different primes for which  $Q_1 \cap R = Q_2 \cap R$ , then  $Q_1, Q_2$  are incomparable. One might think that an INC-extension is an  $m$ -extension, however this is not the case. For any reduced ring  $R$ , the extension  $R \hookrightarrow Q(R)$  is an INC-extension, trivially, as  $Q(R)$  is a von Neumann regular ring and therefore distinct primes are incomparable. However, we shall see later that there are examples of reduced rings  $R$  for which  $R \hookrightarrow Q(R)$  is not an INC-extension. At this point we do not know whether a Going-Up extension (or specifically, an integral extension) must be an  $m$ -extension.

**Theorem 1.10.** *The extension of reduced rings  $R \hookrightarrow S$  is an  $m$ -extension if and only if whenever  $P \in \text{Min}(S)$  and  $r \in P \cap R$ , then there exists an  $a \in R \setminus P$  such that  $ra = 0$ .*

**Proof.** The proof follows from Lemma 1.2.  $\square$

**Proposition 1.11.** *Suppose  $R \hookrightarrow S$  is an  $m$ -extension of reduced rings. Then  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is continuous with respect to both the hull-kernel topologies and the inverse topologies.*

**Proof.** Let  $I$  be a finitely generated ideal of  $R$  and let  $r \in R$ . Then

$$\Psi^{-1}(V_R(I)) = \{P \in \text{Min}(S) : I \subseteq P\} = V_S(I)$$

and

$$\Psi^{-1}(U_R(r)) = \{P \in \text{Min}(S) : r \notin P\} = U_S(r).$$

Since  $I$  is finitely generated in  $R$  it generates a finitely generated ideal of  $S$ . Since the inverse image of a basic open set is again a basic open set it follows that  $\Psi$  is simultaneously continuous with respect to both the hull-kernel topologies and inverse topologies.  $\square$

**Remark 1.12.** In [4], the author investigated exoteric extensions; in [16] they are called *faiblement de Baer*. We recall that a ring homomorphism  $f : R \rightarrow S$  is called *exoteric* if whenever  $I, J \leq R$  are finitely generated ideals of  $R$  for which  $\text{Ann}_R(I) = \text{Ann}_R(J)$ , then  $\text{Ann}_S(f(I)) = \text{Ann}_S(f(J))$ . Our next proposition states that an  $m$ -extension is an exoteric homomorphism. Its proof was originally given as Proposition 24 of [16]. We include a slightly different and more straightforward proof of this fact, for completeness sake.

**Proposition 1.13.** *If  $R \hookrightarrow S$  is an  $m$ -extension of reduced rings, then it is an exoteric homomorphism.*

**Proof.** Let  $I, J$  be finitely generated ideals of  $R$  such that  $\text{Ann}_R(I) = \text{Ann}_R(J)$ . Suppose that  $\text{Ann}_S(I) \neq \text{Ann}_S(J)$ . Without loss of generality, we can choose  $s \in \text{Ann}_S(I) \setminus \text{Ann}_S(J)$ . This means there is some  $j \in J$  such that  $sj \neq 0$ . Since  $S$  is reduced, there exists  $P \in \text{Min}(S)$  for which  $sj \notin P$ ; this means  $s \notin P$  and  $j \notin P$ . By the hypothesis,  $P \cap R \in \text{Min}(R)$ , and  $j \notin P \cap R$ . Consequently, by Lemma 1.2,  $\text{Ann}_R(J) \subseteq P \cap R$ , and so  $\text{Ann}_R(I) \subseteq P \cap R$ . On the other hand,  $s \notin P$  implies that  $\text{Ann}_S(s) \subseteq P$ . Since  $sI = 0$ , this means  $I \subseteq P \cap R \in \text{Min}(R)$ . Hence,  $\text{Ann}_R(I) \not\subseteq P \cap R$ , which is a contradiction.  $\square$

We conclude the introduction of the article by pointing out that we use  $\subseteq$  to mean subset or equal, while  $\subset$  is meant in the strict sense.

## 2. Extensions of commutative reduced rings

Let  $R \hookrightarrow S$  be an extension of rings. To make things easier we let

$$\Psi : \text{Min}(S) \rightarrow \text{Spec}(R)$$

be the contraction map defined by  $\Psi(P) = P \cap R$ . Of course  $R \hookrightarrow S$  is an  $m$ -extension precisely when  $\Psi(\text{Min}(S)) = \text{Min}(R)$ . We are interested in determining when an extension of  $R$  preserves the topological properties of hull-kernel and inverse topologies. To that end we define several important kinds of extensions.

- (i)  $S$  is a *rigid extension* of  $R$  if for each  $s \in S$  there is an  $a \in R$  such that  $\text{Ann}_S(s) = \text{Ann}_S(a)$ .
- (ii)  $S$  is an  *$r$ -extension* of  $R$  if for each  $P \in \text{Min}(S)$  and each  $s \in S \setminus P$  there exists an  $a \in R \setminus P$  such that  $\text{Ann}_S(s) \subseteq \text{Ann}_S(a)$ .
- (iii)  $S$  is an  *$r^*$ -extension* of  $R$  if for each  $P \in \text{Min}(S)$  and each  $s \in P$  there exists an  $a \in R \cap P$  such that  $\text{Ann}_S(s) \subseteq \text{Ann}_S(a)$ .

If in the above definitions one replaces the term  $a$  with a finitely generated ideal of  $R$ , then one gets the notions of *quasi rigid*, *quasi  $r$* , and *quasi  $r^*$* -extensions.

**Example 2.1.** The most common example of a rigid extension is  $R \hookrightarrow q(R)$ . In fact, any overring  $R \hookrightarrow S \hookrightarrow q(R)$  is a rigid extension. Furthermore, if  $R \hookrightarrow T$  is a rigid extension and  $R \hookrightarrow S \hookrightarrow T$ , then both  $R \hookrightarrow S$  and  $S \hookrightarrow T$  are rigid extensions. The converse is true, namely the notion of rigidity is transitive. The same holds for (quasi)  $r$ - and (quasi)  $r^*$ -extensions.

**Remark 2.2.** In [1] and [2] the author investigated when an extension of frames is rigid. We prefer not to delve into these matters but we do point out the collection of all radical ideals of  $R$ , denoted  $\text{Rad}(R)$  forms a frame and in certain nice situations the extension  $R \hookrightarrow S$  can be characterized as a rigid extension in terms of the rigidity of the extensions of the  $\text{Rad}(R) \hookrightarrow \text{Rad}(S)$ .

**Proposition 2.3.** A (quasi) rigid extension is both a (quasi)  $r$ -extension and a (quasi)  $r^*$ -extension.

**Proof.** We supply a proof that a rigid extension is an  $r$ -extension and an  $r^*$ -extension. We leave the case for quasi rigid extensions to the interested reader.

For each  $s \in S$  choose  $r_s \in R$  for which  $\text{Ann}_S(r_s) = \text{Ann}_S(s)$ . Let  $P \in \text{Min}(S)$ . For  $s \in S \setminus P$ , then  $\text{Ann}_S(r_s) = \text{Ann}_S(s) \subseteq P$ . By Lemma 1.2,  $r \notin P$ . On the other hand if  $s \in P$ , then by Lemma 1.1  $\text{Ann}_S(r_s) = \text{Ann}_S(s) \not\subseteq P$ . Thus,  $r_s \in P$ .  $\square$

**Proposition 2.4.** Suppose  $R \hookrightarrow S$  is a rigid extension.  $R$  satisfies the  $\kappa$ -annihilator condition if and only if  $S$  satisfies the  $\kappa$ -annihilator condition.

**Proof.** We prove the sufficiency and leave the proof of the necessity to the interested reader. Let  $X \subseteq R$  of cardinality smaller than  $\kappa$  and consider  $\text{Ann}_S(X)$ . Since  $S$  satisfies the  $\kappa$ -annihilator condition there is an element  $e \in S$  such that  $\text{Ann}_S(X) = \text{Ann}_S(e)$ . Since  $R \hookrightarrow S$  is a rigid extension there is an  $r \in R$  such that  $\text{Ann}_S(e) = \text{Ann}_S(r)$ . From here we leave it to the interested reader to check that  $\text{Ann}_R(X) = \text{Ann}_R(r)$ .  $\square$

**Corollary 2.5.**  $R$  satisfies the a.c. if and only if  $q(R)$  satisfies the a.c.

The proof of the next lemma is straightforward and is left to the interested reader.

**Lemma 2.6.** Suppose  $R \hookrightarrow S$  is a quasi rigid extension. If  $S$  satisfies the  $\kappa$ -annihilator condition then for each subset  $X \subseteq R$  of cardinality smaller than  $\kappa$  there is a finite subset  $Y \subseteq R$  such that  $\text{Ann}_R(X) = \text{Ann}_R(Y)$ .

Our next two results demonstrate the importance of  $r$ -extensions.

**Lemma 2.7.** Let  $R \hookrightarrow S$  be an extension of reduced rings. If  $S$  is an  $r$ -extension of  $R$ , then  $\Psi$  is a bijection of  $\text{Min}(S)$  onto  $\text{Min}(R)$ . In particular, an  $r$ -extension is an  $m$ -extension.

**Proof.** Let  $P \in \text{Min}(S)$ . We first show that  $P \cap R \in \text{Min}(R)$ . Otherwise, there is a  $Q \in \text{Min}(R)$  with  $Q \subset P \cap R$ . Now by Proposition 1.7 there exists  $M \in \text{Min}(S)$  with  $M \cap R = Q$ . Choose  $s \in M \setminus P$ . By hypothesis there exists an  $r \in R \setminus P$  with  $\text{Ann}_S(s) \subseteq \text{Ann}_S(r)$ . Since  $s \in M$ , it follows that  $\text{Ann}_S(s) \not\subseteq M$ , whence  $\text{Ann}_S(r) \not\subseteq M$ . Thus,  $r \in M \cap R = Q$ . But  $Q \subseteq P$  and so  $r \in P$ , a contradiction. Therefore  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a surjective map.

Now we show  $\Psi$  is an injection. Take distinct  $P$  and  $Q$  in  $\text{Min}(S)$  and choose  $s \in P \setminus Q$ . By hypothesis there is an  $r \in R \setminus Q$  for which  $\text{Ann}_S(s) \subseteq \text{Ann}_S(r)$ . A similar argument to the one just used yields that  $r \in P$ . Therefore,  $r \in P \cap R$ , but  $r \notin Q \cap R$ . Hence  $P \cap R \neq Q \cap R$ .  $\square$

**Theorem 2.8.** Let  $R \hookrightarrow S$  be an extension of reduced rings. The following statements are equivalent.

- (1)  $S$  is an  $r$ -extension of  $R$ .
- (2)  $S$  is a quasi  $r$ -extension of  $R$ .
- (3)  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a homeomorphism (with regards to the hull-kernel topology).

**Proof.** The proof of the implication that (1) implies (2) is patent.

Suppose that  $S$  is a quasi  $r$ -extension of  $R$ . To show that  $S$  is an  $r$ -extension of  $R$  let  $P \in \text{Min}(S)$  and  $s \in S \setminus P$ . Choose  $I$ , a finitely generated ideal of  $R$ , so that  $I \not\subseteq P$  and  $\text{Ann}_S(s) \subseteq \text{Ann}_S(I)$ . Choose  $a \in I \setminus P$  and observe that  $\text{Ann}_S(I) \subseteq \text{Ann}_S(a)$ . Thus, (2) implies (1).

Next, suppose that  $S$  is an  $r$ -extension of  $R$ . We aim to show that  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a homeomorphism (with regards to the hull-kernel topology). By Lemma 2.7 and Proposition 1.11 it suffices to show that  $\Psi$  is an open map. Let  $s \in S$  and consider  $\Psi(U_S(s))$ . Note that

$$\Psi(U_S(s)) = \{P \cap R : P \in \text{Min}(S), s \notin P\}.$$

Let  $P \cap R \in \Psi(U_S(s))$ , and so since  $\Psi$  is a bijection we gather that  $s \notin P$ . Since  $R \hookrightarrow S$  is an  $r$ -extension there is an  $a \in R \setminus P$  with  $\text{Ann}_S(s) \subseteq \text{Ann}_S(a)$ . That  $a \notin P \cap R$  means that  $P \cap R \in U_R(a)$ . We claim that  $U_R(a) \subseteq \Psi(U_S(s))$  which yields that  $\Psi(U_S(s))$  is an open subset (relative to the hull-kernel topology).

Take  $M \in U_R(a)$  and choose  $Q \in \text{Min}(S)$  with  $Q \cap R = M$ . Since  $a \notin M$  it happens that  $a \notin Q$  and thus  $\text{Ann}_S(a) \subseteq Q$ . By our choice of  $a$ ,  $\text{Ann}_S(s) \subseteq \text{Ann}_S(a) \subseteq Q$ , we may apply Lemma 1.2 to conclude that  $s \notin Q$ , i.e.  $Q \in U_S(s)$ . Therefore,  $M = Q \cap R \in \Psi(U_S(s))$ , whence  $\Psi$  is an open map. Thus, (1) implies (3).

Finally, suppose that  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a homeomorphism (with regards to the hull-kernel topology). Let  $P \in \text{Min}(S)$  and let  $s \in S \setminus P$ . Then  $P \in U_S(s)$ . By hypothesis  $\Psi(U_S(s))$  is an open subset of  $\text{Min}(R)$ , and thus there is an  $r \in R$  such that  $\Psi(P) \in U_R(r) \subseteq \Psi(U_S(s))$ . That  $\Psi(P) \in U_R(r)$  means that  $P \cap R \in U_R(r)$  and so  $r \notin P$ .

Next, we demonstrate that  $\text{Ann}_S(s) \subseteq \text{Ann}_S(r)$ . Let  $a \in \text{Ann}_S(s)$  and consider  $ra \in S$ . If  $Q \in V_S(r)$ , then  $ra \in Q$ . If  $Q \in U_S(r)$ , then  $r \notin Q$ , and so  $Q \cap R \in U_R(r) \subseteq \Psi(U_S(s))$ . It follows that  $s \notin Q$  and so  $a \in Q$ . Consequently,  $ra \in Q$  for all  $Q \in \text{Min}(S)$ . Since we are assuming that  $S$  is a reduced ring, by Lemma 1.2 it follows that  $ra = 0$ , whence  $a \in \text{Ann}_S(r)$ . Thus, (3) implies (1).  $\square$

**Theorem 2.9.** Suppose  $R \hookrightarrow S$  is an  $r$ -extension of reduced rings.  $R \hookrightarrow S$  is a rigid extension if and only if  $\Psi$  maps basic open sets to basic open sets (with respect to the hull-kernel topologies).

**Proof.** Suppose  $R \hookrightarrow S$  is a rigid extension. Then for each  $s \in S$  there exists  $r_s \in R$  such that  $\text{Ann}_S(r_s) = \text{Ann}_S(s)$ . We leave it to the interested reader to check that  $\Psi(U_S(s)) = U_R(r_s)$ . From this we conclude that  $\Psi$  maps basic open sets to basic open sets.

Conversely, let  $s \in S$  and consider  $U_S(s)$ . By hypothesis, there exists  $r \in R$  such that  $\Psi(U_S(s)) = U_R(r)$ . Therefore,  $\Psi(V_S(s)) = V_R(r)$ . We now demonstrate that  $\text{Ann}_S(r) = \text{Ann}_S(s)$ .

Let  $P \in \text{Min}(S)$  be arbitrary. If  $P \in U_S(s)$ , then  $P \cap R \in U_R(r)$ . Therefore, both  $\text{Ann}_S(s)$  and  $\text{Ann}_S(r)$  are subsets of  $P$ ; hence  $r \text{Ann}_S(s) \subseteq P$  and  $s \text{Ann}_S(r) \subseteq P$ . Similarly, if  $P \in V_S(s)$ , then  $P \cap R \in V_R(r)$ . So, both  $s \in P$  and  $r \in P$ . Hence,  $r \cdot \text{Ann}_S(s) \subseteq P$  and  $s \cdot \text{Ann}_S(r) \subseteq P$ . Since the rings are reduced, this implies that

$$r \cdot \text{Ann}_S(s) = 0 = s \cdot \text{Ann}_S(r).$$

Consequently  $\text{Ann}_S(s) = \text{Ann}_S(r)$ , concluding that the extension is a rigid extension.  $\square$

We now turn to quasi  $r^*$ -extensions and prove some analogous results. We shall have several occasions to use our next lemma.

**Lemma 2.10.** Let  $R \hookrightarrow S$  be an extension of reduced rings. For  $P \in \text{Min}(S)$  and  $I$  a finitely generated ideal of  $R$ . If  $I \subseteq P \cap R$ , then  $\text{Ann}_S(I) \not\subseteq P$ . The converse is also true.

**Proof.** Let  $J = \langle I \rangle_S$  be the ideal in  $S$  generated by  $I$ . Since  $I \subseteq P$ , it follows that  $J \subseteq P$ . By Lemma 1.2 ( $J$  is a finitely generated ideal of  $S$ ) it follows that  $\text{Ann}_S(J) \not\subseteq P$ . Also since  $\text{Ann}_S(J) \subseteq \text{Ann}_S(I)$ , we conclude that  $\text{Ann}_S(I) \not\subseteq P$ .

The proof of the converse is a simple application of Lemma 1.2.  $\square$

**Proposition 2.11.** *A quasi  $r^*$ -extension of reduced rings  $R \hookrightarrow S$  is an  $m$ -extension. Moreover, the map  $\Psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a bijection.*

**Proof.** Let  $P \in \text{Min}(S)$ . Since  $P \cap R \in \text{Spec}(R)$ , there exists some  $Q \in \text{Min}(R)$  such that  $Q \subseteq P \cap R$ . By Proposition 1.7 there exists  $M \in \text{Min}(S)$  such that  $M \cap R = Q$ . If  $M \neq P$  then we can choose  $s \in M \setminus P$ . By hypothesis there exists a finitely generated ideal  $I \subseteq M \cap R$  such that  $\text{Ann}_S(I) \subseteq \text{Ann}_S(s)$ . Since  $I \subseteq Q \subseteq P$ , it follows from the preceding lemma that  $\text{Ann}_S(I) \not\subseteq P$ . However,  $\text{Ann}_S(s) \subseteq P$  since  $s \notin P$ , which is a contradiction. Thus,  $M = P$ , whence  $P \cap R = Q \in \text{Min}(R)$ . Consequently,  $R \hookrightarrow S$  is an  $m$ -extension.

To show that  $\Psi$  is bijective it suffices to show that it is injective. To that end consider two distinct minimal prime ideals  $P, Q \in \text{Min}(S)$ . Choose  $s \in P \setminus Q$ . Again, using the hypothesis that  $R \hookrightarrow S$  is a quasi  $r^*$ -extension, there is a finitely generated ideal  $I \subseteq P \cap R$  such that  $\text{Ann}_S(I) \subseteq \text{Ann}_S(s)$ . Notice that  $\text{Ann}_S(I) \subseteq Q$ . Therefore, by the preceding lemma,  $I \not\subseteq Q \cap R$ . Let  $r \in I \setminus Q$ , then  $r \in (P \cap R) \setminus (Q \cap R)$ . Hence,  $P \cap R \neq Q \cap R$ .  $\square$

**Theorem 2.12.** *Suppose  $R \hookrightarrow S$  is an extension of reduced rings.  $S$  is a quasi  $r^*$ -extension of  $R$  if and only if  $\Psi : \text{Min}(S)^{-1} \rightarrow \text{Min}(R)^{-1}$  is a homeomorphism.*

**Proof.** Necessity: We have already shown in Proposition 2.11 that  $\Psi$  is a bijection. Moreover, by Proposition 1.11  $\Psi$  is a continuous map with respect to the inverse topologies. It remains to show that  $\Psi$  is an open map. Let  $s \in S$  and  $Q \in \Psi(V_S(s))$ . There exists some  $P \in V_S(s)$  with  $Q = P \cap R$ . So,  $s \in P$ . By the definition of quasi  $r^*$ -extension there exists a finitely generated ideal  $I \subseteq R$  such that  $I \subseteq P \cap R$  and  $\text{Ann}_S(I) \subseteq \text{Ann}_S(s)$ . Clearly,  $Q \in V_R(I)$ . We now show that if  $M \in V_R(I)$ , then  $M \in \Psi(V_S(s))$ . Choose  $T \in \text{Min}(S)$  for which  $T \cap R = M$ . Since  $I \subseteq M$ , then  $I \subseteq T$  and so  $\text{Ann}_S(I) \not\subseteq T$ . Furthermore,  $\text{Ann}_S(s) \not\subseteq T$  which forces  $s \in T$ . Therefore,  $T \in V_S(s)$  and so  $M = T \cap R \in \Psi(V_S(s))$ . It follows that  $\Psi(V_S(s))$  is an open set, whence  $\Psi$  is an open map.

Sufficiency: Let  $P \in \text{Min}(S)$  and  $s \in P$ . Since  $V_S(s)$  is a open subset of  $\text{Min}(S)^{-1}$  and  $\Psi$  is an open map, it follows that  $\Psi(V_S(s))$  is open in  $\text{Min}(R)^{-1}$ . So,  $P \cap R \in \Psi(V_S(s))$ . Therefore, there exists a finitely generated ideal  $I$  of  $R$  such that  $P \cap R \in V_R(I) \subseteq \Psi(V_S(s))$ ; thus  $I \subseteq P \cap R$ . We need to demonstrate that  $\text{Ann}_S(I) \subseteq \text{Ann}_S(s)$ . Let  $t \in \text{Ann}_S(I)$  and consider  $st \in S$ . Let  $Q \in \text{Min}(S)$  be an arbitrary minimal prime ideal of  $S$ . If  $s \in Q$ , then  $st \in Q$ . On the other hand, if  $s \notin Q$ , then  $Q \cap R \notin \Psi(V_S(s))$ ; observe that we are assuming that  $\Psi$  is a bijection. Therefore,  $Q \cap R \notin V_R(I)$ , i.e.  $I \not\subseteq Q \cap R$ . Then  $I \not\subseteq Q$ , and so  $\text{Ann}_S(I) \not\subseteq Q$ . Consequently,  $t \in Q$ , and thus  $st \in Q$ . Since  $Q$  was arbitrarily chosen and  $S$  is assumed to be reduced we conclude that  $st = 0$ , i.e.  $t \in \text{Ann}_S(s)$ .  $\square$

**Proposition 2.13.** *If  $R \hookrightarrow S$  is a quasi  $r^*$ -extension of reduced rings, then  $R \hookrightarrow S$  is a quasi rigid extension if and only if  $\Psi$  maps inverse basic open sets to inverse basic open sets.*

**Proof.** Suppose  $R \hookrightarrow S$  is a quasi rigid extension. In order to show that  $\Psi$  maps inverse basic open sets to inverse basic open sets, let  $J = s_1S + \dots + s_nS$  be an arbitrary finitely generated ideal of  $S$ . By hypothesis, for each  $i = 1, \dots, n$  there exists a finitely generated ideal of  $R$ , say  $I_i$ , such that  $\text{Ann}_S(I_i) = \text{Ann}_S(s_i)$ . Set  $I = I_1 + \dots + I_n$ . We claim that  $\Psi(V_S(J)) = V_R(I)$ . Let  $P \in V_S(J)$ , i.e.  $J \subseteq P$ . This means that  $s_1, \dots, s_n \in P$ . Therefore, by Lemma 2.10  $\text{Ann}_S(s_i) \not\subseteq P$ , implying that  $\text{Ann}_S(I_i) \not\subseteq P$  for all  $i$ . Therefore,  $I_i \subseteq P$  for each  $i$ . Thus  $I \subseteq P \cap R$ , whence  $P \cap R \in V_R(I)$ . This means that  $\Psi(V_S(J)) \subseteq V_R(I)$ . On the other hand, if  $P \cap R \in V_R(I)$ , then  $I \subseteq P$  and so  $I_i \subseteq P$  for all  $i$ . Therefore,  $\text{Ann}_S(I_i) \not\subseteq P$  for all  $i$ . So for all  $i$ ,  $\text{Ann}_S(s_i) \not\subseteq P$ , which says that  $s_i \in P$ . Consequently,  $J \subseteq P$ , that is,  $P \cap R \in \Psi(V_S(J))$ . This means that the reverse containment  $V_R(I) \subseteq \Psi(V_S(J))$  also holds.

Conversely, suppose that  $\Psi$  maps inverse basic open sets to inverse basic open sets and let  $s \in S$ . By the hypothesis there exists  $I \subseteq R$  a finitely generated ideal such that  $\Psi(V_S(s)) = V_R(I)$ . Therefore,  $\Psi(U_S(s)) = U_R(I)$ . We claim that  $\text{Ann}_S(I) = \text{Ann}_S(s)$ . Using a similar argument as in the preceding theorem (replace  $r$  by  $I$ ), it follows that

$$I \cdot \text{Ann}_S(s) = 0 = s \cdot \text{Ann}_S(I).$$

Hence  $\text{Ann}_S(I) = \text{Ann}_S(s)$ , which implies that the extension is a quasi rigid extension.  $\square$

Next, we consider what happens when  $R$  satisfies the a.c.

**Theorem 2.14.** *Let  $R \hookrightarrow S$  be an extension of reduced rings and suppose that  $R$  satisfies the a.c. The following statements are equivalent.*

- (1)  $R \hookrightarrow S$  is a quasi  $r^*$ -extension.

- (2)  $\Psi : \text{Min}(S)^{-1} \rightarrow \text{Min}(R)^{-1}$  is a homeomorphism.  
 (3)  $R \hookrightarrow S$  is an  $r^*$ -extension.

**Proof.** That (1) and (2) are equivalent is Theorem 2.12. Clearly, (3) implies (1).

Suppose  $R \hookrightarrow S$  is a quasi  $r^*$ -extension and that  $R$  satisfies the a.c. By Proposition 1.5  $\{V_R(r) : r \in R\}$  is a base for the inverse topology on  $\text{Min}(R)^{-1}$ . To show that the extension is an  $r^*$ -extension, let  $P \in \text{Min}(S)^{-1}$  and  $s \in P$ . Since  $\Psi$  is an open map,  $\Psi(V_S(s))$  is open in  $\text{Min}(R)^{-1}$ . Thus, there exists some  $r \in R$  such that  $P \cap R \in V_R(r) \subseteq \Psi(V_S(s))$ ;  $r \in P \cap R$ . We aim to show that  $\text{Ann}_S(r) \subseteq \text{Ann}_S(s)$ ; let  $t \in \text{Ann}_S(r)$ .

Observe that for any  $Q \in \text{Min}(S)^{-1}$  if  $s \notin Q$ , then  $r \notin Q$  because  $\Psi$  is injective. Therefore,  $t \in Q$  and hence so is  $st \in Q$ . In the case that  $s \in Q$  then so is  $st$ . Since  $S$  is reduced it follows that  $ts = 0$ . Consequently,  $R \hookrightarrow S$  is an  $r^*$ -extension.  $\square$

We end this section by considering the extension  $R \hookrightarrow R[x]$ . First, a useful lemma.

**Lemma 2.15.** *Suppose  $R \hookrightarrow S$  is a quasi rigid extension and  $R$  satisfies the a.c. Then the extension is a rigid extension.*

**Proof.** Let  $s \in S$  and choose  $r_1, \dots, r_n \in R$  such that

$$\text{Ann}_S(s) = \text{Ann}_S(r_1, \dots, r_n).$$

Next, choose  $r \in R$  such that

$$\text{Ann}_R(r_1, \dots, r_n) = \text{Ann}_R(r).$$

We aim to prove that  $\text{Ann}_S(s) = \text{Ann}_S(r)$ .

Let  $x \in \text{Ann}_S(s)$ . Choose  $a_1, \dots, a_m \in R$  such that

$$\text{Ann}_S(x) = \text{Ann}_S(a_1, \dots, a_m).$$

Then  $sa_1 = \dots = sa_m = 0$  and so  $a_1, \dots, a_m \in \text{Ann}_S(s) = \text{Ann}_S(r_1, \dots, r_n)$ . It follows that each  $a_i \in \text{Ann}_R(r_1, \dots, r_n) = \text{Ann}_R(r)$ . Therefore,

$$r \in \text{Ann}_S(a_1, \dots, a_m) = \text{Ann}_S(x).$$

In other words,  $x \in \text{Ann}_S(r)$ . Therefore,  $\text{Ann}_S(s) \subseteq \text{Ann}_S(r)$ .

Next, let  $x \in \text{Ann}_S(r)$  and suppose  $\text{Ann}_S(x) = \text{Ann}_S(a_1, \dots, a_m)$  for  $a_1, \dots, a_m \in R$ . So  $r \in R \cap \text{Ann}_S(a_1, \dots, a_m) = \text{Ann}_R(a_1, \dots, a_m)$ . Switching it around,  $a_1, \dots, a_m \in \text{Ann}_S(r_1, \dots, r_n) = \text{Ann}_S(s)$ . Therefore,  $s \in \text{Ann}_S(a_1, \dots, a_m) = \text{Ann}_S(x)$ . Therefore,  $x \in \text{Ann}_S(s)$ .  $\square$

**Proposition 2.16.** *Suppose  $R$  is a reduced ring. The extension  $R \hookrightarrow R[x]$  is a quasi rigid extension (and therefore an  $m$ -extension).*

**Proof.** Let  $f(x) \in R[x]$  and set  $f(x) = a_0 + a_1x + \dots + a_nx^n$ . Set  $I = Ra_0 + \dots + Ra_n$ , a finitely generated ideal of  $R$ . By Proposition B of [5],

$$\text{Ann}_{R[x]}(f(x)) = (\text{Ann}_R(I))[x].$$

It follows that if  $g(x) \in (\text{Ann}_R(I))[x]$ , then  $g(x)a_k = 0$  for each  $k = 0, \dots, n$ , whence  $(\text{Ann}_R(I))[x] \subseteq \text{Ann}_{R[x]}(a_k)$  for each  $k$ . Conversely, if  $a_k g(x) = 0$  for each  $k$ , then every coefficient of  $g(x)$  annihilates each  $a_k$ . Therefore,

$$\text{Ann}_{R[x]}(f(x)) = (\text{Ann}_R(I))[x] = \text{Ann}_{R[x]}(a_0, \dots, a_n). \quad \square$$

**Corollary 2.17.** *Suppose  $R$  is a reduced ring and  $x_1, x_2, \dots, x_n$  is a finite number of indeterminates. Then  $R \hookrightarrow R[x_1, \dots, x_n]$  is a quasi rigid extension.*

**Proposition 2.18.** *Suppose  $R$  is a reduced ring.  $R \hookrightarrow R[x]$  is a rigid extension if and only if  $R$  satisfies the a.c.*

**Proof.** The proof of the statement consists of a simple application of Proposition 2.4 and Lemma 2.15, together with the known fact (see Corollary 2.9 of [8]) that  $R[x]$  always satisfies the a.c. when  $R$  is a reduced ring.  $\square$

**Remark 2.19.** Observe that if  $R$  is reduced ring that does not satisfy the a.c., then  $R \hookrightarrow R[x]$  is an example that shows we cannot generalize Proposition 2.4 to quasi rigid extensions.

### 3. Compact minimal prime spectra

In the last section we looked at extensions  $R \hookrightarrow S$  and described the relationships involving rigid,  $r$ -, and  $r^*$ -extensions (and their quasi counterparts). We also had several occasions to consider what happens when you assume that the base ring  $R$  satisfies the a.c. In this section we turn our attention to when our desired extension satisfies the added hypothesis that either  $\text{Min}(R)$  or  $\text{Min}(S)$  is compact. We begin by recalling a very useful theorem characterizing this situation.

**Proposition 3.1.** (Proposition 3.2 [10]) *For a reduced ring  $R$ , the following statements are equivalent.*

- (1)  $\text{Min}(R)$  is compact.
- (2)  $\text{Min}(R) = \text{Min}(R)^{-1}$ .
- (3) For each  $a \in R$  there exists a finitely generated ideal  $I \leq R$ , such that  $I \leq \text{Ann}_R(a)$  and  $\text{Ann}_R(aR + I) = 0$ .

We remark that when we write  $\text{Min}(R) = \text{Min}(R)^{-1}$  we mean that the hull-kernel and inverse topologies are the same. Since the hull-kernel topology is finer than the inverse this is also equivalent to saying that the inverse topology generates the hull-kernel topology. If  $R$  is a ring for which  $\text{Min}(R)$  is compact yet  $R$  does not satisfy the a.c., then the collection  $\{V_R(r) : r \in R\}$  forms a base for the topology while not being closed under intersection. This addresses Remark 1.6.

To give a flavor of the style of theorems we aim to prove we next demonstrate that when  $\text{Min}(R)$  is compact then Proposition 1.13 can be strengthened.

**Proposition 3.2.** (Proposition 24 [16]) *Let  $R \hookrightarrow S$  be an extension of reduced rings and suppose that  $\text{Min}(R)$  is compact.  $R \hookrightarrow S$  is an exoteric homomorphism if and only if it is an  $m$ -extension.*

**Proposition 3.3.** *Suppose that  $R$  is reduced and  $\text{Min}(R)$  is compact. For any extension of reduced rings, say  $R \hookrightarrow S$ , the extension is an  $r$ -extension if and only if it is a quasi rigid extension.*

**Proof.** To prove the sufficiency recall that a quasi rigid extension is a quasi  $r$ -extension. Theorem 2.8 states that a quasi  $r$ -extension is an  $r$ -extension. Therefore, a quasi rigid extension is an  $r$ -extension.

Conversely, suppose that  $\text{Min}(R)$  is compact and that  $R \hookrightarrow S$  is an  $r$ -extension of reduced rings. Let  $s \in S$ . By Theorem 2.8,  $\psi : \text{Min}(S) \rightarrow \text{Min}(R)$  is a homeomorphism and thus an open map. So  $\Psi(U_S(s)) \subseteq \text{Min}(R)$  is a closed, and hence compact, open subset. Therefore, there is a finite set  $r_1, \dots, r_n \in R$  such that

$$\Psi(U_S(s)) = U_R(r_1) \cup \dots \cup U_R(r_n) = U_R(I)$$

where  $I$  is the ideal generated by  $r_1, \dots, r_n$ . We claim that  $\text{Ann}_S(s) = \text{Ann}_S(I)$ .

First, let  $t \in \text{Ann}_S(I)$ . By means of contradiction assume that  $t \notin \text{Ann}_S(s)$ , i.e.  $ts \neq 0$ . Since  $S$  is reduced there is a minimal prime ideal  $P \in \text{Min}(S)$  such that  $ts \notin P$ . It follows that  $P \in U_S(s)$  and so  $P \cap R \in \Psi(U_S(s)) = U_R(I)$ . This means that  $I \not\subseteq P$ , whence  $\text{Ann}_S(I) \leq P$ . Since  $t \in \text{Ann}_S(I)$ , we conclude that  $t \in P$ , hence  $st \in P$ , contradicting that  $st \notin P$ . This contradiction forces  $t \in \text{Ann}_S(s)$ . Since  $t$  was arbitrarily chosen we conclude that  $\text{Ann}_S(I) \subseteq \text{Ann}_S(s)$ .

To show the reverse containment let  $t \in \text{Ann}_S(s)$ , and once again assume, by means of contradiction, that  $t \notin \text{Ann}_S(I)$ . It follows that for some  $i = 1, \dots, n$   $tr_i \neq 0$ . Since  $S$  is reduced there is some  $P \in \text{Min}(S)$  such that  $tr_i \notin P$ , thus  $t \notin P$ . Next, since  $ts = 0$ , we gather that  $s \in P$ , whence  $P \notin U_S(s)$ . By Theorem 2.8  $\Psi$  is a bijection and so  $P \cap R \notin \Psi(U_S(s)) = U_R(I)$ . Equivalently, this last statement means that  $I \not\subseteq P \cap R$ . Therefore,  $r_i \in P$  and so  $tr_i \in P$ , yielding the desired contradiction. We are forced to conclude that  $t \in \text{Ann}_S(I)$ , and since  $t$  was arbitrary we obtain the reverse containment  $\text{Ann}_S(s) \subseteq \text{Ann}_S(I)$ .  $\square$

**Corollary 3.4.** *Let  $S$  be a reduced ring for which  $\text{Min}(S)$  is compact. For any subring  $R$  of  $S$ , the extension  $R \hookrightarrow S$  is an  $r$ -extension if and only if it is a quasi rigid extension.*

**Proof.** If the extension is an  $r$ -extension, then  $\text{Min}(S)$  is homeomorphic to  $\text{Min}(R)$ . Hence, the hypothesis implies  $\text{Min}(R)$  is compact and so Proposition 3.3 applies.  $\square$

**Proposition 3.5.** *Let  $S$  be a reduced ring for which  $\text{Min}(S)$  is compact. For any subring  $R$  of  $S$ , the extension  $R \hookrightarrow S$  is an (quasi)  $r^*$ -extension if and only if it is a (quasi) rigid extension.*

**Proof.** First of all we recall that Proposition 2.3 states that in general a rigid extension is an  $r^*$ -extension. Next, we supply a proof that whenever  $\text{Min}(S)$  is compact then an  $r^*$ -extension is a rigid extension, leaving the quasi case for the interested reader. Let  $s \in S$  and suppose that  $R \hookrightarrow S$  is an  $r^*$ -extension. For each  $P \in V_S(s)$  choose  $r_P \in P \cap R$  such that  $\text{Ann}_S(r_P) \subseteq \text{Ann}_S(s)$ . It follows that the collection  $\{V_S(r_P) : P \in V_S(s)\}$  is an open cover of  $V_S(s)$ . Since  $\text{Min}(S)$  is compact  $V_S(s)$  is a compact open subset and so there is a finite collection  $r_{P_1}, \dots, r_{P_n} \in P \cap R$  such that

$$V_S(s) = V_S(r_{P_1}) \cup \dots \cup V_S(r_{P_n}) = V_S(r_{P_1} \cdots r_{P_n}).$$

It follows that  $\text{Ann}_S(s) = \text{Ann}_S(r_{P_1} \cdots r_{P_n})$ , whence  $R \hookrightarrow S$  is a rigid extension.  $\square$



Two standard examples of classes of rings whose minimal prime ideal spaces are compact are the Baer ring and von Neumann regular rings. This leads to our next corollary.

**Corollary 3.6.** *A Baer ring is an  $r^*$ -extension if and only if it is a rigid extension of any of its subrings. The same is true for a von Neumann regular ring.*

**Theorem 3.7.** *Let  $R \hookrightarrow S$  be an extension of reduced rings. Suppose that  $\text{Min}(S)$  is compact and  $R$  satisfies the a.c. The following are equivalent.*

- (1)  $S$  is an  $r$ -extension of  $R$ .
- (2)  $S$  is an  $r^*$ -extension of  $R$ .
- (3)  $S$  is a rigid extension of  $R$ .

**Proof.** That (2) and (3) are equivalent and that (3) implies (1) follows from Proposition 2.3 and Lemma 3.4. To get that (1) implies (3) use Proposition 3.3 and Lemma 2.15.  $\square$

**Example 3.8.** Recall that if  $X$  is a topological space,  $C(X)$  (resp.  $C(X, \mathbb{Z})$ ) denotes the ring of continuous real valued (resp. integer-valued) functions on  $X$ . In Example 3.18 of [1], the author proved that if  $X$  is a compact zero-dimensional  $F$ -space, then  $C(X, \mathbb{Z}) \leq C(X)$  is an  $r^*$ -extension. Furthermore, this extension is a rigid extension precisely when  $X$  is basically disconnected. What is interesting is that in this case  $\text{Min}(C(X, \mathbb{Z}))$  is homeomorphic to  $X$  and hence is compact, however in general  $\text{Min}(C(X))$  is not compact.

Now, the space  $\beta\mathbb{N} \setminus \mathbb{N}$  is a compact zero-dimensional  $F$ -space which is not basically disconnected. It follows that

$$C(\beta\mathbb{N} \setminus \mathbb{N}, \mathbb{Z}) \leq C(\beta\mathbb{N} \setminus \mathbb{N})$$

is an example of an  $r^*$ -extension which is not a rigid extension. This shows that Proposition 3.5 cannot be generalized to the case that  $\text{Min}(R)$  is compact.

#### 4. Essential extensions

In a category the characterization of the epimorphisms (i.e. a morphism  $f$  for which  $m \circ f = n \circ f$  implies  $m = n$ ) is an important pursuit. In many categories the epimorphisms are precisely the surjective maps, however in the category of commutative rings this is not the case. The standard example of a non-surjective epimorphism is that of the embedding of a ring into its classical ring of quotients. Study of epimorphisms of algebras began in earnest by Isbell in a series of papers titled *Epimorphisms and dominions*. For commutative rings much credit should be given to Storrer [21].

Storrer showed that for a given reduced commutative ring  $R$  there is a largest epimorphic essential extension. What this means is that for a reduced commutative ring  $R$  there exists an extension  $R \hookrightarrow E(R)$  which is both an essential and epimorphic extension, and such that whenever  $R \hookrightarrow S$  is another essential epimorphic extension, then there is an embedding of  $S$  into  $E(R)$  which restricts to the identity on  $R$ . Nowadays, such an extension is known as the *epimorphic hull* of  $R$ .  $E(R)$  can be described as the intersection of the set of von Neumann regular rings lying intermediate between  $R$  and  $Q(R)$ ; it itself is a von Neumann regular ring. It is also described as the subring of  $Q(R)$  generated by  $R$  and the quasi-inverses of elements of  $R$ .

Since  $R \hookrightarrow q(R)$  is an essential epimorphic extension we gather that  $R \hookrightarrow q(R) \hookrightarrow E(R)$ . What distinguishes the extensions  $R \hookrightarrow q(R)$  and  $R \hookrightarrow E(R)$  is that the former is always a flat epimorphism (that is, an extension  $R \hookrightarrow S$  for which  $S$  is a flat  $R$ -module). Several authors have been instrumental in showing that a maximal flat epimorphic essential extension exists. We let  $M(R)$  denote the maximal flat epimorphic ring of quotients of  $R$ . Observe that

$$R \hookrightarrow M(R) \hookrightarrow E(R) \hookrightarrow Q(R).$$

In this section we consider the rigidity of these extensions. We shall also have occasion to consider the *Baer hull* of a reduced ring  $R$ . Recall that from Proposition 2.5 of [14] the intersection of all Baer subrings of  $Q(R)$  containing  $R$  is the subring of  $Q(R)$ , denoted  $B(R)$ , generated by  $R$  and the idempotents of  $Q(R)$ . Mewborn proved that  $B(R)$  is a Baer ring and thus called  $B(R)$  the Baer hull of  $R$ .

**Remark 4.1.** For a detailed discussion of the epimorphic hull and maximal flat epimorphic essential extension including a list of references the reader is directed to [20] and [19]. Other sources on the epimorphic hull the reader might find useful are [19] and [3].

**Remark 4.2.** In [6], the authors investigated when for a reduced  $f$ -ring  $R$ , the extension  $R \hookrightarrow Q(R)$  is a rigid extension. Some care must be taken to read the article as the language is couched in the terminology from the theory of lattice-ordered groups and function-rings. In a strong sense Theorem 4.3 is a generalization of their theorem to the general case of commutative reduced rings, so no surprise that our proof models theirs with the appropriate modifications.

We first look at when  $R \hookrightarrow Q(R)$  is a rigid extension. Recall that this extension of rings is an  $m$ -extension precisely when  $\text{Min}(R)$  is compact (Theorem 4.3 [8]). Therefore, it is necessary that  $\text{Min}(R)$  be compact for  $R \hookrightarrow Q(R)$  to be a rigid extension. We can say more.

When  $R$  is reduced then  $Q(R)$  is a von Neumann regular Baer ring. It follows that  $\text{Min}(Q(R))$  is a compact extremally disconnected space; a space is called extremally disconnected if the closure of every open set is clopen (Proposition 2.1 [14]). Thus, if  $R \hookrightarrow Q(R)$  is a quasi rigid extension then  $\text{Min}(R)$  is also compact extremally disconnected by Proposition 2.3 and Theorem 2.8. Furthermore, if the extension is rigid then we also know that  $R$  satisfies the a.c. by the fact that  $Q(R)$  satisfies the a.c. and Proposition 2.4. We presently show that these properties characterize when  $R \hookrightarrow Q(R)$  is a rigid extension.

**Theorem 4.3.** *Let  $R$  be a reduced commutative ring with identity. The following statements are equivalent.*

- (1)  $R \hookrightarrow Q(R)$  is a rigid extension.
- (1')  $R \hookrightarrow Q(R)$  is an  $r^*$ -extension.
- (2)  $R \hookrightarrow B(R)$  is a rigid extension.
- (2')  $R \hookrightarrow B(R)$  is an  $r^*$ -extension.
- (3)  $\text{Min}(R)$  is a compact extremally disconnected space and  $R$  satisfies the a.c.
- (4)  $q(R)$  is a Baer ring.
- (5)  $q(R)$  and  $Q(R)$  have the same idempotents.

**Proof.** That (1) and (1') are equivalent and (2) and (2') are equivalent follows from Corollary 3.6. The proof that statement (1) implies (2) is patent.

If  $R \hookrightarrow B(R)$  is a rigid extension, then as we mentioned above, since  $B(R)$  is a Baer ring,  $\text{Min}(B(R))$  is a compact extremally disconnected and hence by rigidity so is  $\text{Min}(R)$  (Proposition 2.3 and Theorem 2.8). Furthermore, since  $B(R)$  is a von Neumann regular ring it satisfies the a.c. and thus rigidity implies that  $R$  satisfies the a.c. by Theorem 2.4. This means that (2) implies (3).

Suppose that  $\text{Min}(R)$  is a compact extremally disconnected space and  $R$  satisfies the a.c. First, by Theorem 4.5 of [8] we gather that  $q(R)$  is a von Neumann regular ring. Moreover,  $\text{Min}(q(R))$  is compact extremally disconnected. By Proposition 2.1 of [14] it follows that  $q(R)$  is a Baer ring. Thus, (3) implies (4).

If  $q(R)$  is a Baer ring, it follows that  $B(R) \leq q(R)$  and so  $q(R)$  and  $Q(R)$  share the same idempotents. Hence (4) implies (5).

Finally, suppose  $q(R)$  and  $Q(R)$  have the same idempotents. Let  $a \in Q(R)$ . Then there is some idempotent  $e \in Q(R)$  such that  $aQ(R) = eQ(R)$ . By hypothesis  $e \in q(R)$  and so  $e = \frac{r}{s}$  for some  $r, s \in R$ . Then it is straightforward to check that

$$\text{Ann}_{Q(R)}(a) = \text{Ann}_{Q(R)}(e) = \text{Ann}_{Q(R)}(r)$$

and so  $R \hookrightarrow Q(R)$  is a rigid extension. Consequently, (5) implies (1).  $\square$

It ought to be apparent by now that when weakening the condition of rigid to quasi rigid the arguments in Theorem 4.3 apply with slight modification. We include a proof of this for completeness sake.

**Theorem 4.4.** *Let  $R$  be a reduced commutative ring with identity. The following statements are equivalent.*

- (1)  $R \hookrightarrow Q(R)$  is a quasi rigid extension.
- (2)  $R \hookrightarrow B(R)$  is a quasi rigid extension.
- (3)  $\text{Min}(R)$  is a compact extremally disconnected space.
- (4)  $\text{Min}(q(R))$  is a compact extremally disconnected space.
- (5)  $\text{Min}(R)$  is compact and every annihilator ideal of  $R$  is the annihilator of a finitely generated ideal of  $R$ .

**Proof.** If  $R \hookrightarrow Q(R)$  is a quasi rigid extension, then so is  $R \hookrightarrow S$  for any subring  $S$  of  $Q(R)$  containing  $R$ . Therefore, in this case  $R \hookrightarrow B(R)$  is a quasi rigid extension. Thus (1) implies (2).

Suppose that  $R \hookrightarrow B(R)$  is a quasi rigid extension. It follows from Proposition 2.3 and Theorem 2.8 that  $\text{Min}(R)$  is homeomorphic to  $\text{Min}(B(R))$ . Since  $B(R)$  is a Baer ring  $\text{Min}(B(R))$ , and hence  $\text{Min}(R)$ , is a compact extremally disconnected space. Thus (2) implies (3).

It is always the case that  $\text{Min}(R)$  and  $\text{Min}(q(R))$  are homeomorphic. Thus (3) and (4) are equivalent.

To show that (3) and (5) are equivalent we shall use of the following lemma.

**Lemma 4.5.** *Suppose  $T$  is a reduced commutative ring with identity. For any ideal  $I$  of  $T$  the closure of  $U(I)$  in  $\text{Min}(T)$  equals  $V(\text{Ann}_T(I))$ . Moreover, for any pair of ideals  $I$  and  $J$ ,  $V(\text{Ann}_T(I)) = V(\text{Ann}_T(J))$  if and only if  $\text{Ann}_T(I) = \text{Ann}_T(J)$ .*

**Proof.** Suppose  $P \in \text{Min}(T)$  and  $I \not\subseteq P$ . Then  $\text{Ann}_T(I) \subseteq P$ . Therefore,  $\overline{U(I)} \subseteq V(\text{Ann}_T(I))$ . Conversely, let  $P \in \text{Min}(T)$  and suppose that  $\text{Ann}_T(I) \subseteq P$ . Let  $t \in T$  and suppose that  $P \in U(t)$ . This means that  $t \notin P$ . If it were the case that  $U(t) \cap U(I) = \emptyset$ , then this would mean that  $tI = 0$  since  $T$  is assumed to be reduced. It would then follow that  $t \in \text{Ann}_T(I)$  and hence  $t \in P$ . This apparent contradiction means that  $U(t) \cap U(I) \neq \emptyset$ . Since  $t$  was arbitrarily chosen we conclude that every basic open set around  $P$  meets  $U(I)$  and so  $P \in \overline{U(I)}$  showing the reverse containment.

As for the second statement, if  $V(\text{Ann}_T(I)) = V(\text{Ann}_T(J))$  but  $\text{Ann}_T(I) \neq \text{Ann}_T(J)$ , then there would exist, without loss of generality, an  $x \in \text{Ann}_T(I) \setminus \text{Ann}_T(J)$ . This means that there is some  $j \in J$  such that  $xj \neq 0$  and so (since  $T$  is reduced) there is some  $P \in \text{Min}(T)$  such that  $xj \notin P$ , hence  $x \notin P$ . But then  $I \subseteq P$ , i.e.  $P \in V(I)$ . By assumption  $V(I) = V(J)$  so that  $J \subseteq P$ , a contradiction.  $\square$

Notice that if  $\text{Min}(R)$  is a compact extremally disconnected space then for any ideal  $I$  of  $R$ ,  $\overline{U(I)} = V(\text{Ann}_R(I))$  is a clopen subset and hence compact and open. It follows that  $V(\text{Ann}_R(I)) = V(\text{Ann}_R(J))$  for some finitely generated ideal  $J$  of  $R$  (use (2) of Lemma 1.3). By the just-proved lemma  $\text{Ann}_R(I) = \text{Ann}_R(J)$ .

Conversely, if every annihilator ideal is the annihilator of a finitely generated ideal, then since any open subset of  $\text{Min}(R)$  is of the form  $U(I)$  for some ideal the lemma implies that  $\overline{U(I)} = V(\text{Ann}_R(I))$ . The hypothesis implies that  $\text{Ann}_R(I) = \text{Ann}_R(J)$  for some finitely generated ideal  $J$  of  $R$ . Since  $V(\text{Ann}_R(J))$  is clopen we conclude that  $\text{Min}(R)$  is extremally disconnected. Thus, (3) and (5) are equivalent.

Finally, suppose that  $\text{Min}(R)$  is compact and that the annihilator of every ideal of  $R$  is the annihilator of a finitely generated ideal. To show that  $R \hookrightarrow Q(R)$  is a quasi rigid extension we need to recall the construction of  $Q(R)$  (see [11]). An arbitrary element of  $Q(R)$  is an equivalence class of  $R$ -module homomorphisms defined on a dense ideal of  $R$  with values in  $R$ . Two such modules are equivalent if they agree on the product of their domains. Given  $[\phi], [\psi] \in Q(R)$  where  $\phi : I \rightarrow R$  and  $\psi : J \rightarrow R$  ( $I, J$  dense ideals of  $R$ ),  $[\phi][\psi] = [\alpha]$  where  $\alpha : IJ \rightarrow R$  is the  $R$ -module homomorphism which maps  $ij$  to  $\phi(i)\psi(j)$  for all  $i \in I$  and  $j \in J$ .

Given  $s \in Q(R)$ , set  $s = [\phi]$  for  $\phi : I \rightarrow R$ ,  $I$  a dense ideal. We leave it to the interested reader to show that  $\phi(I)$  is an ideal of  $R$ . By hypothesis there is a finitely generated ideal of  $R$ , say  $J = r_1R + \cdots + r_nR$ , such that  $\text{Ann}_R(\phi(I)) = \text{Ann}_R(J)$ . We claim that

$$\text{Ann}_{Q(R)}(s) = \text{Ann}_{Q(R)}(r_1, \dots, r_n)$$

from which it will follow that  $R \hookrightarrow Q(R)$  is a quasi rigid extension. Let  $t \in \text{Ann}_{Q(R)}(s)$  and set  $t = [\tau]$  for some  $R$ -module homomorphism  $\tau : Z \rightarrow R$  where  $Z$  is a dense ideal of  $R$ . Then given  $[\alpha] = [\phi][\tau]$ , where  $\alpha$  is defined as above, we observe that for all  $z \in Z$  and  $i \in I$ ,  $0 = \alpha(iz) = \phi(i)\tau(z)$ . Thus,  $\tau(Z)\phi(I) = 0$  and so  $r_i\tau(Z) = 0$  for each  $i = 1, \dots, n$ . Thus,  $t \in \text{Ann}_{Q(R)}(r_1, \dots, r_n)$ . We have shown that  $\text{Ann}_{Q(R)}(s) = \text{Ann}_{Q(R)}(r_1, \dots, r_n)$ . We leave the proof of the reverse containment to this interested reader.  $\square$

Next, we consider when the embedding of  $R$  into its epimorphic hull is a rigid extension. Since  $E(R)$  is a von Neumann regular ring  $R \hookrightarrow E(R)$  is an  $m$ -extension if and only if  $E(R)$  is a flat  $R$ -module. This yields the following result. (See Corollary 3.3 and Theorem 4.5 of [8] for more equivalences.)

**Theorem 4.6.** *Let  $R$  be a reduced commutative ring with identity. Then the following statements are equivalent.*

- (1)  $R \hookrightarrow E(R)$  is a rigid extension.
- (2)  $\text{Min}(R)$  is compact and  $R$  satisfies the a.c.
- (3)  $q(R)$  is von Neumann regular.
- (4)  $q(R) = E(R)$ .
- (5)  $q(R)$  is a weak Baer ring.

**Proof.** That (2) is equivalent to (3) is part of Theorem 4.5 of [8]. Since  $E(R)$  is the smallest von Neumann regular subring of  $Q(R)$  containing  $R$  and  $q(R) \subseteq E(R)$  it follows that (3) and (4) are equivalent. That (3) and (5) are equivalent is well known; one may look at the remark after Definition 2.10 of [10]. This (2), (3), (4), and (5) are all equivalent statements.

That (1) implies (2) follows from the fact that  $E(R)$  is a von Neumann regular ring together with the appropriate applications to Proposition 2.3, Proposition 2.4, and Theorem 2.8. Clearly (4) implies (1).  $\square$

We now turn to the embedding  $R \hookrightarrow M(R)$ . We begin by recalling the most useful characterization of a flat epimorphism (see [20]). Proposition 4.7 strengthens the fact that a flat epimorphism is an  $m$ -extension (see the remarks after Definition 3 of [16]).

**Theorem 4.7.** *The extension  $R \hookrightarrow S$  is a flat epimorphism if and only for all  $s \in S$  there exists  $r_1, \dots, r_n \in R$  such that  $r_i s \in R$  and  $r_1 s + \cdots + r_n s = s$ .*

**Proposition 4.8.** *If the extension  $R \hookrightarrow S$  is a flat epimorphism, then it is a quasi rigid extension.*

**Proof.** The second statement follows from the first statement and Lemma 2.15. As for the first let  $b \in S$  and choose  $r_1, \dots, r_n \in R$  for which  $r_1S + \dots + r_nS = S$  and  $r_k b \in R$  for each  $k = 1, \dots, n$ . Choose  $s_1, \dots, s_n \in S$  for which  $1 = r_1s_1 + \dots + r_ns_n$ . We leave it to the interested reader to check that  $\text{Ann}_S(b) = \text{Ann}_S(r_1b, \dots, r_nb)$ .  $\square$

**Remark 4.9.** Notice that the above proof carries through if we just assume that  $r_1S + \dots + r_nS$  is a dense ideal of  $S$ .

**Corollary 4.10.** For any reduced ring  $R$ , the extension  $R \hookrightarrow M(R)$  is a quasi rigid extension.

Next, we give a new characterization of when  $M(R)$  is von Neumann regular. That conditions (5) and (6) are equivalent was first proved by Quentel [18] and Olivier [15].

**Theorem 4.11.** Let  $R$  be a reduced commutative ring with identity. Then the following statements are equivalent.

- (1)  $R \hookrightarrow E(R)$  is a quasi rigid extension.
- (2)  $R \hookrightarrow E(R)$  is an  $r$ -extension.
- (3)  $R \hookrightarrow E(R)$  is an  $m$ -extension.
- (4)  $M(R) = E(R)$ .
- (5)  $M(R)$  is a von Neumann regular ring.
- (6)  $\text{Min}(R)$  is compact.

**Proof.** By Proposition 2.3, a quasi rigid extension is a quasi  $r$ -extension. Applying Theorem 2.8 yields that a quasi rigid extension is an  $r$ -extension. Thus, (1) implies (2). That an  $r$ -extension is an  $m$ -extension is the contents of Lemma 2.7. Thus, (2) implies (3).

Suppose  $R \hookrightarrow E(R)$  is an  $m$ -extension.  $E(R)$  is von Neumann regular, and thus  $R \hookrightarrow E(R)$  is an  $m$ -extension if and only if  $E(R)$  is a flat  $R$ -module (see Proposition 1.14 of [12]). Therefore,  $E(R)$  is a flat (epimorphic) extension of  $R$ . It follows that  $M(R) = E(R)$ . This proves that (3) implies (4).

If  $M(R) = E(R)$ , then since  $E(R)$  is von Neumann regular so is  $M(R)$ . Hence (4) implies (5).

Suppose  $M(R)$  is a von Neumann regular ring. Corollary 4.10 states that  $R \hookrightarrow M(R)$  is a quasi rigid extension. Hence, by applying Proposition 2.3 and Theorem 2.8, we conclude that  $\text{Min}(R)$  and  $\text{Min}(M(R))$  are homeomorphic. Since  $M(R)$  is von Neumann,  $\text{Min}(M(R))$  is compact and hence so is  $\text{Min}(R)$ . Therefore, (5) implies (6).

Finally, suppose  $\text{Min}(R)$  is compact. Then  $R \hookrightarrow Q(R)$  is an  $m$ -extension. It follows that  $R \hookrightarrow E(R)$  is an  $m$ -extension and so  $E(R) = M(R)$  is a quasi rigid extension of  $R$ . Consequently, (6) implies (1).  $\square$

**Remark 4.12.** Theorem 2.3 of [4] states that for any reduced ring  $R$ , the extension  $R \hookrightarrow E(R)$  is an exoteric homomorphism. It follows by Theorem 4.11 that if  $\text{Min}(R)$  is not compact, then  $R \hookrightarrow E(R)$  is an exoteric homomorphism which is not an  $m$ -extension.

At this point we are unable to characterize when  $R \hookrightarrow M(R)$  is a rigid extension. If  $R$  satisfies the a.c. then by Proposition 2.4 and Corollary 4.10 it is a rigid extension. However, there are cases when  $q(R) = M(R)$ , and hence it is a rigid extension, without having  $R$  satisfy the a.c. We wonder whether  $R \hookrightarrow M(R)$  is a rigid extension if and only if  $q(R) = M(R)$ .

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## References

- [1] P. Bhattacharjee, Rigid extensions of algebraic frames, *Algebra Universalis* 62 (1) (2010) 133–149.
- [2] P. Bhattacharjee, Minimal prime element space of an algebraic frame, Dissertation, Bowling Green State University, 2009.
- [3] D.E. Dobbs, G. Picavet, Weak Baer going-down rings, *Houston J. Math.* 29 (2003) 559–581.
- [4] M. Evans, Exoteric homomorphisms, *J. Pure Appl. Algebra* 49 (1987) 117–131.
- [5] R. Gilmer, Polynomial rings over a commutative von Neumann regular ring, *Proc. Amer. Math. Soc.* 49 (2) (1975) 294–296.
- [6] A.W. Hager, J. Martinez, Fraction-dense algebras and spaces, *Canad. J. Math.* 45 (5) (1993) 977–996.
- [7] M. Henriksen, M. Jerison, The space of minimal prime ideals of a commutative ring, *Trans. Amer. Math. Soc.* 115 (1965) 110–130.
- [8] J. Huckaba, *Commutative Rings with Zero Divisors*, Pure Appl. Math., vol. 117, Marcel Dekker, New York, 1988.
- [9] I. Kaplansky, *Commutative Rings*, Allyn and Bacon, Boston, 1970.
- [10] M. Knox, R. Levy, W.Wm. McGovern, J. Shapiro, Generalizations of complemented rings with applications to rings of functions, *J. Algebra Appl.* 7 (6) (2008) 1–24.
- [11] J. Lambek, *Lectures on Rings and Modules*, 2nd ed., Chelsea Publishing Co., New York, 1976.
- [12] E. Matlis, The minimal prime spectrum of a reduced ring, *Illinois J. Math.* 27 (1983) 353–391.
- [13] A.C. Mewborn, Some conditions on commutative semiprime rings, *J. Algebra* 13 (1969) 422–431.
- [14] A.C. Mewborn, Regular rings and Baer rings, *Math. Z.* 121 (1971) 211–219.

- [15] J.P. Olivier, Anneaux absolument plats universels et epimorphismes d'anneaux, *C. R. Acad. Sci. Paris Sér. A* 266 (1968) 317–318.
- [16] G. Picavet, Ultrafiltres sur un espace, *Math. Scand.* 46 (1980) 23–53.
- [17] G. Picavet, Universally going-down rings, 1-split rings, and absolute integral closure, *Comm. Algebra* 31 (10) (2003) 4655–4685.
- [18] Y. Quentel, Sur la compacité du spectre minimal d'un anneau, *Bull. Soc. Math. France* 99 (1971) 265–272.
- [19] R. Raphael, R.G. Woods, The epimorphic hull of  $C(X)$ , *Topology Appl.* 105 (2000) 65–88.
- [20] B. Stenström, *Rings and Modules of Quotients*, Lecture Notes in Math., vol. 237, Springer-Verlag, Berlin–New York, 1971.
- [21] H.H. Storrer, Epimorphismen von kommutativen Ringen, *Comment. Math. Helv.* 43 (1968) 378–401.