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Local Multipliers of C^*-Algebras

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British Library Cataloguing in Publication Data
Ara, Pere
Local multipliers of C^*-algebras. - (Springer monographs in mathematics)
1. C^*-algebras
I. Title II. Mathieu, Martin
515.5'5
ISBN 1852332379

Library of Congress Cataloging-in-Publication Data
A catalog receord for this book is available from the Library of Congress

Mathematics Subject Classification (2000): 46-02, 46L05, 46L06, 46L07, 46L10, 46L40, 46L55, 46L57, 46L70, 47-02, 47A05, 47A12, 47A62, 47A65, 47B47, 47B48, 47B60, 16R20, 16R50, 16S99, 16W10, 16W80, 17B40, 17C65

Springer Monographs in Mathematics ISSN 1439-7382
ISBN 1-85233-237-9 Springer-Verlag London Berlin Heidelberg
a member of BertelsmannSpringer Science+Business Media GmbH
http://www.springer.co.uk

Typesetting: Camera-ready by the authors
... Press Ltd., Gateshead, Tyne & Wear

A les nostres famílies

Contents

Introduction

Functional Analysis, in its most fundamental and linear form, is the study of operators on infinite dimensional linear spaces. In his 1920 thesis and then, in a more comprehensive version, in his 1932 treatise, Banach, building on the work of many others, devised a beautiful framework for this endeavour. Soon Banach spaces became an established concept, and Functional Analysis quickly evolved into one of the cornerstones of 20th century mathematics.

Shortly after the inception of Banach spaces, Heisenberg in 1925 found that some parts of classical mathematics were incapable of describing the newly discovered phenomena of quantum physics adequately. Under the influence of von Neumann, operators, especially those on infinite dimensional Hilbert space, themselves became the constituents of mathematical models of quantum mechanics, and the time evolution of such systems came to be expressed in terms of operators on spaces of operators.

Such spaces, under the headings of *rings of operators*, *C^*-algebras* and others, were investigated in great detail during the second half of the 20th century. Today, there is a deep theory which even contains a complete classification of various kinds of algebras. In parallel, more and more knowledge of the behaviour of operators on, say C^*-algebras, was acquired, until it became evident that there is a fundamental relationship between properties of operators and the matricial structure of C^*-algebras. This led to the concept of completely bounded operators on operator spaces, the latter now a technical term, which was turned into another fundamental notion of Functional Analysis by the intriguing abstract characterisation due to Ruan, in 1988.

It is characteristic of this new type of Functional Analysis that the Banach spaces carry an additional structure, which is inherited from the non-commutative multiplication of a surrounding C^*-algebra. Thus the objective of this *non-commutative Functional Analysis* is the study of operators on 'non-commutative' or 'quantised' Banach spaces. Naturally, the most interesting of these operators are related to, or compatible with, the non-commutative multiplication in one way or another. More often than not, the properties of such operators are reflected in some of the qualities of the underlying C^*-algebras, and, conversely, on particularly 'nice' C^*-algebras, the operator theoretic results becoming extremely smooth.

Proof. The implication (b) $\implies$ (a) is immediate from Proposition 5.3.13 and Corollary 5.4.36 together with the fact that the norm and the *cb*-norm of each elementary operator agree on abelian C^*-algebras.

In order to prove the converse, suppose that A is not antiliminal-by-abelian. Then I_{post}, the largest postliminal ideal of A, is not abelian, and I_{post} has an essential continuous trace ideal J [**251**; 6.2.11], which is not abelian. Hence, there exists $\pi \in \mathrm{Irr}(J)$ such that $\dim H_\pi \geq 2$. Let E_{11} and E_{22} be orthogonal rank-one projections in $B(H_\pi)$. Let E_{12} be a partial isometry such that $E_{12}E_{12}^* = E_{11}$ and $E_{12}^*E_{12} = E_{22}$. By [**112**; 3.1, 3.3, 4.1], there are an open neighbourhood V of $\ker\pi$ in $\check{J}$ and elements e_{11}, e_{12}, e_{22} in J with $\pi(e_{ij}) = E_{ij}$ for $1 \leq i \leq j \leq 2$ such that $\sigma(e_{11})$ and $\sigma(e_{22})$ are rank-one projections and $\sigma(e_{12})$ is a partial isometry with initial projection $\sigma(e_{22})$ and final projection $\sigma(e_{11})$ for all $\sigma \in \mathrm{Irr}(J)$ with $\ker\sigma \in V$. Let $e_{21} = e_{12}^*$.

Since $\check{J}$ is locally compact and Hausdorff there is a continuous function $g\colon \check{J} \to [0,1]$, supported in V, such that $g(\ker\pi) = 1$. Let $f_{ij} = g\,e_{ij}$, $1 \leq i,j \leq 2$, and define $S = \sum_{i,j=1}^{2} M_{f_{ij},f_{ij}} \in \mathcal{E}\ell(A)$. For each σ with $\ker\sigma \in \check{J}$, $S_\sigma = \sum_{i,j=1}^{2} M_{\sigma(f_{ij}),\sigma(f_{ij})}$. In particular, $S_\sigma = 0$ if $\ker\sigma \in \check{J}\setminus V$. Suppose that $P = \ker\sigma \in V$. Then

$$S_\sigma = g(P)^2 \sum_{i,j=1}^{2} M_{\sigma(e_{ij}),\sigma(e_{ij})} = g(P)^2\,\theta_\sigma \circ T \circ \theta_\sigma^{-1} \circ C_\sigma$$

where C_σ is the surjection of $K(H_\sigma)$ onto the span of $\{\sigma(e_{ij}) : 1 \leq i,j \leq 2\}$ given by

$$C_\sigma = M_{\sigma(e_{11})+\sigma(e_{22}),\sigma(e_{11})+\sigma(e_{22})},$$

θ_σ is the *-isomorphism of M_2 onto the span of $\{\sigma(e_{ij}) : 1 \leq i,j \leq 2\}$ given by $(\alpha_{ij}) \mapsto \sum_{i,j=1}^{2} \alpha_{ij}\,\sigma(e_{ij})$, and T is the transposition on M_2. The mapping C_σ is completely positive with $\|C_\sigma\|_{cb} = 1$. On the other hand, $\|T\| = 1$ but $\|T_n\| = 2$ for all $n \geq 2$ [**248**, Proposition 8.11 and Exercise 3.11]. Thus, $\|S_\sigma\| = g(P)^2 \leq 1$ while $\|(S_\sigma)_n\| = 2\,g(P)^2 \leq 2$ for all $n \geq 2$. By Theorem 5.3.12 and the fact that $g(\ker\pi) = 1$, it follows that $\|S_J\| = 1$ and $\|(S_J)_n\| = 2$ for all $n \geq 2$.

Since $f_{ij} \in J$ for all $1 \leq i,j \leq 2$, $S_B = 0$ where $B = A/J$. By Proposition 5.3.13, $\|S\| = 1$ while $\|S\|_{cb} = 2$. Thus, condition (a) fails. This proves (a) $\implies$ (b). □

We conclude this section by putting the last result together with Theorem 5.4.30.

Corollary 5.4.39. *For every elementary operator S on an antiliminal-by-abelian C^*-algebra A, the norm of S is given by $\|S\| = \|u_Z\|_{Zh}$, where $S = \theta(u)$, $u \in M(A) \otimes M(A)$ and the central Haagerup norm of u_Z is computed in $M_{\mathrm{loc}}(A) \otimes_{Zh} M_{\mathrm{loc}}(A)$.*

5.5 Notes and References

The seminal paper [**182**] by Lumer and Rosenblum started the modern investigation of elementary operators. In this paper they gave a description of the spectrum of an elementary operator S in the case when the coefficients a_j and b_j are holomorphic images of single operators a and b, respectively on some Banach space E. However, a systematic study of spectral properties of elementary operators had to await the early 1970's, with papers by Embry and Rosenblum, Davis and Rosenthal, Fialkow, Harte, Martha Smith, and many others. The two survey articles [**89**] and [**113**] contain comprehensive bibliographies until 1991 on a wealth of results concerning invertibility, compactness, and many other properties of elementary operators. The two more recent surveys [**221**] and [**222**] treat some aspects of the developments in the outgoing 20th century.

In [**198**], an important algebraic property was added to the picture. It was noted that the requirement on the C^*-algebra A to be prime — and in the more general framework of a Banach algebra A, the assumption of A being *ultraprime* — had strong implications on the behaviour of elementary operators on A. Subsequently, see e. g. [**207**] and [**209**], it was observed that a number of structural questions are related to the ambiguity in the choice of the coefficients of an elementary operator and, thus, lead to the problem when $\sum_{j=1}^{n} a_j x b_j = 0$ for all $x \in A$. This problem had been addressed by Fong and Sourour in their influential paper [**117**] for $A = B(H)$ but their methods were restricted to primitive C^*-algebras containing the compact operators. As it was noted in [**198**], see also [**15**] and [**200**, Part I], that prime C^*-algebras are centrally closed, the connection to the extended centroid was made and its significance for the solution of the above-mentioned problem became evident (through the fundamental paper by Martindale [**195**]). In this way, the aim to understand various parts of the theory of elementary operators in the setting of general C^*-algebras gave a strong impetus to the development of local multipliers of C^*-algebras. The question is finally settled in Theorem 5.2.1, building on the results in Section 5.1. This purely algebraic section is based on ideas in [**17**], which in particular contains Theorem 5.1.5.

Akemann and Wright undertook a thorough study of compact actions and (weakly) compact derivations of C^*-algebras [**5**], [**6**]. Theorem 5.3.30 and the necessary preparatory work appears in [**6**]. (It is in fact easy to see that every weakly compact, not necessarily *-preserving homomorphism from a C^*-algebra into a Banach algebra must be of finite rank [**203**].) The goal to unify these results with descriptions when derivations on C^*-algebras are compact or weakly compact [**5**], products of derivations on C^*-algebras are compact or weakly compact [**205**], and of (weakly) compact elementary operators [**200**, Part II], [**204**] (our Corollary 5.3.23, Theorem 5.3.25, and Corollary 5.3.26) stimulated the study of central bimodule homomorphisms. In fact, the terminology is introduced in [**205**] and Theorem 5.3.18 is stated.

Proposition 5.3.17 is an adaptation of [**5**, Lemma 3.2] to the present context. Theorem 5.3.31 is obtained for derivations in [**5**, Theorem 3.3].

In [**117**] Fong and Sourour characterised compact elementary operators on $B(H)$ (compare Theorem 5.3.25). On the basis of this, they stated the following conjecture [**117**, p. 856]. Let H be separable. Then there is no non-zero compact elementary operator on the Calkin algebra $C(H)$. This conjecture was subsequently confirmed in independent works and with different methods by Apostol and Fialkow [**11**], by Magajna [**183**], and in [**200**, Part II] (see also [**198**]). Corollary 5.3.20 states the answer to this conjecture in a concise way and a far more general setting, but Corollary 5.3.19 reveals that it is actually the compatibility with the ideal structure in conjunction with weak compactness that determine the result. The *generalised Fong–Sourour conjecture* asks for a characterisation of those Banach spaces E for which there are no non-zero weakly compact elementary operators on $C(E)$. Saksman and Tylli recently made some deep contributions to this problem in [**274**], see below.

A C^*-algebra A with the property that $K(A) = A$ is called *weakly compact.* Every such C^*-algebra is an ideal in A'', which itself is an atomic C^*-algebra. A C^*-algebra is weakly compact if and only if it is the C^*-direct sum of a family of C^*-algebras of compact operators. See [**303**, Exercise III.5.3 and III.5.4].

The bulk of Section 5.3 is taken from [**211**], apart from the results mentioned above and Proposition 5.3.13, which is obtained (for elementary operators) in [**31**]. Lemma 5.3.4 is a reformulation of a transitivity theorem for algebras of elementary operators on C^*-algebras obtained in [**185**, Theorem 2.1]. These ideas are further developed in [**186**] and [**188**]. For special classes of central bimodule homomorphisms more detailed information on their spectra than in Corollary 5.3.15 is available. Elementary operators are treated in [**196**] and [**200**, Part I], compare also [**89**]. Akemann and Ostrand [**2**] obtained a formula for the spectrum of a *-derivation on a C^*-algebra [**2**]; see also [**172**].

It was shown in [**197**] that a positive two-sided multiplication $M_{a,b}$ can be written as $M_{a,b} = M_{c^*,c}$ and thus is completely positive, compare Example 5.2.15. This initiated the quest for a complete characterisation of completely positive elementary operators. The unpublished manuscript [**169**], and [**198**], contain Lemma 5.2.12 and Corollary 5.2.14, albeit with a different proof. The new Theorem 5.2.13 is based on the more general discussion in Section 5.2, extending the results in the case of prime C^*-algebras (obtained in [**198**] and [**200**, Part I]) to the general case. The necessity of using local multipliers is illustrated not only in the proofs of these results but in addition by Example 5.2.17.

Let S be an elementary operator on a C^*-algebra with minimal length $\ell(S) \geq 1$. It was proved independently in [**179**] and [**216**] that S is completely positive if it is n-positive with $n \geq \frac{\ell(S)-1}{2}$, improving Corollary 5.2.14. Timoney showed in [**305**] that it suffices to assume that $n > \sqrt{\ell(S)} - 1$ and also provided an example showing that this is the best lower bound. Li showed in [**178**] that *every* positive elementary operator on the Calkin algebra is already completely positive, and this result was recovered in [**216**] with a simplified proof. In fact, the latter methods imply that this phenomenon persists for every antiliminal C^*-algebra. In analogy to Theorem 5.4.38 it was shown in [**31**, Theorem 6] that a C^*-algebra A is antiliminal-by-abelian if and only if every positive elementary operator on A is completely positive. In fact, for A to be an extension of this kind, it suffices that every positive elementary operator is 2-positive [**31**, p. 616]. Once again, Timoney took up the discussion and refined these results in terms of k-positivity [**307**].

Antiliminal-by-abelian C^*-algebras are characterised in [**30**] as those for which every factorial state is a weak*-limit of pure states. The terminology is coined in [**31**], where Theorem 5.4.38 is proved. The somewhat surprising Theorem 5.4.34 is due to Magajna [**187**, Theorem 3.1], and Lemma 5.4.33 is obtained by Smith in [**286**, Theorem 2.1] in a more general formulation. Lemma 5.4.12 is also found in [**187**] (with the proof presented here) but had been obtained earlier by Lazar, see [**42**, Proposition 3 and Added Note]; compare also [**110**, Proposition 3.1]. Elementary operators defined on the Calkin algebra have some more unexpected properties; for an overview on these see [**222**]. Using Voiculescu's non-commutative Weyl–von Neumann theorem, Apostol and Fialkow proved that the norm and the essential norm of every elementary operator on $C(\ell^2)$ coincide [**11**]. By means of this, they solved the original Fong–Sourour conjecture (see above). Saksman and Tylli extended their results to $C(\ell^p)$, $1 < p < \infty$ and indeed to Banach spaces with 1-unconditional bases in [**274**].

Theorem 5.4.7 lays the foundation for Section 5.4. It is obtained in Haagerup's unpublished manuscript [**131**] with the proof presented here and is put into print for the first time, with the kind permission of the author. In [**131**], Haagerup introduced the tensor product defined in Definition 5.4.1, calling it the α-tensor product. The term *Haagerup tensor product* goes back to the paper [**102**] by Effros and Kishimoto, where they established the characterisation of the dual of the Haagerup tensor product given in Lemma 5.4.3 (which is [**131**, Proposition 4]). See also the discussion in [**86**, Section 4] and the article by Kaijser and Sinclair [**160**]. As is noted in [**199**], Haagerup's theorem combined with the injectivity of the Haagerup norm (which is due to Paulsen and Smith [**249**]) and the first part of Lemma 5.4.12 yield Proposition 5.4.11. Independently of these results, Smith in [**286**, Theorem 4.3] proved Theorem 5.4.7 by different means and used this to obtain a commutant theorem for the Haagerup tensor product. Chatterjee and Sinclair [**82**] extended Smith's result to factors on separable Hilbert space, using several non-trivial facts on injective subfactors. Smith introduced the central Haagerup tensor product of von Neumann algebras and obtained the isometric property of θ_Z (as stated in Corollary 5.4.27) for von Neumann algebras on separable Hilbert space; the latter assumption was removed in [**83**]. Chatterjee and Smith in addition established the isometric property on unital C^*-algebras with Hausdorff spectrum and provided an example of a (necessarily not boundedly centrally closed) C^*-algebra such that θ_Z is injective but not isometric. Our Lemma 5.4.21 is extracted from the proofs of [**83**, Lemma 2.3 and Theorem 2.4].

The central Haagerup tensor product for C^*-algebras (Definition 5.4.14 and Remark 5.4.16) was defined in [**22**], where Theorems 5.4.20, 5.4.22, and 5.4.26 are proved. In fact, to this end, the bounded central closure of a C^*-algebra was introduced and much of the basic theory of boundedly centrally closed C^*-algebras, see Chapter 3, was developed in [**22**]. The injectivity of the central Haagerup tensor product in Corollary 5.4.25 is new and allows for a smoother formulation of the subsequent results. A more general injectivity property is discussed in [**187**]. On the basis of [**22**], the *cb*-norm, and thus the norm, of an inner derivation on a C^*-algebra was computed in [**212**], see our Theorem 4.1.20, Corollary 4.1.24 and Example 5.4.31. Our Example 5.4.32.3 combines Corollaries 8 and 9 from [**131**]. Using an approach similar to ours, but with the Glimm ideal space rather than the primitive spectrum, Somerset showed in [**293**] that the canonical mapping θ_Z is an isometry on the central Haagerup tensor product for every unital C^*-algebra with the property that every Glimm ideal is primal. By Remark 3.5.8, this extends Theorem 5.4.26 but the precise characterisation of θ_Z being an isometry appears to remain unknown.

The paper [**221**] contains a survey on the state-of-the-art of the norm problem for elementary operators. This problem has recently attracted some attention, see e.g. [**60**], [**78**], [**296**], [**297**], [**306**] and [**308**], but a full solution currently seems to be out of reach. So far, in each instance where the norm of $S \in \mathcal{E}\ell(A)$ has been computed, it coincides with the *cb*-norm of S. The main result in [**189**] contains a formula for the norm of $M_{a^*,b} + M_{b^*,a} \in \mathcal{E}\ell(B(H))$, where $a, b \in B(H)$ are arbitrary, and it implies, together with Theorem 5.3.12, that

$$\|M_{a^*,b} + M_{b^*,a}\| = \|M_{a^*,b} + M_{b^*,a}\|_{cb} \qquad (a, b \in M(A))$$

for an arbitrary C^*-algebra A. On the other hand, it is shown in [**190**, Theorem 2.1] that the *cb*-norm of $M_{a,b} + M_{b,a}$ is at least $\|a\|\,\|b\|$ whenever $a, b \in B(H)$. This answers a question posed in [**205**] for the operator norm in place of the *cb*-norm. Magajna and Turnšek also provide an example of 2×2 matrices a and b with the property that

$$1 = \|a\|\,\|b\| = \|M_{a,b} + M_{b,a}\| < \|M_{a,b} + M_{b,a}\|_{cb} = \sqrt{2}.$$

All these investigations rest on Haagerup's theorem (5.4.7).

There are other possible approaches to elementary operators. An axiomatic one has been proposed in [**75**] and [**74**]. Another natural setting would be a complex normed A-B-bimodule E, where A and B are complex normed algebras, and the two-sided multiplications $M_{a,b}$ are defined by $M_{a,b}x = axb$, $x \in E$ and $a \in A$, $b \in B$. This covers a number of situations studied in the literature such as $A = B = B(H)$ and E a symmetrically normed ideal of $B(H)$, or $A = B(X)$, $B = B(Y)$ for some Banach spaces X and Y and $E = B(Y, X)$. However, there does not seem to be a systematic theory available at present.

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