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**A BOUNDARY FOR THE ALGEBRAS OF BOUNDED
HOLOMORPHIC FUNCTIONS**

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Let (X, A) be a ringed space and let D be a domain in X . Let $B = B(D) = \{f \in A(D); \|f\|_D < \infty\}$. A minimal boundary for B is defined as a unique smallest subset of \bar{D} such that every function in B attains its supremum near the set. The followings are shown: If X is locally compact, D is relatively compact, and B separates the points of D then there exists a minimal boundary. Under the same assumptions, the natural projection of the Silov boundary $\partial_{\hat{B}}$ into X is the minimal boundary. If A is a maximum modulus algebra and the set of frontier points for A is the minimal boundary, then any holomorphic function which is bounded near the minimal boundary must be bounded. Finally, if D is the spectrum of B (with the compact open topology), then the topological boundary of D is the set of frontier points for B .

Introduction. Let (X, A) be a ringed space; a subsheaf of rings with identity of the sheaf of germs of continuous functions on a Hausdorff space X . Let $\Gamma(U, A)$ be the set of all sections of A over U , U is an open subset of X . Let $A(U) = \{f \in C(U): f(x) = \phi(x)(x) = {}_x f(x), x \in U\}$, where $\phi \in \Gamma(U, A)$ and ${}_x f$ is the germ of f at x . A function f in $A(U)$ is called A -holomorphic or holomorphic. Let $B(U) = \{f \in A(U): f \text{ is bounded on } U\}$. Then $B(U)$ is an algebra (over C) with identity.

Let D be an open subset of X and let \bar{D} be the closure of D in X . For $\mathcal{A} \subset \bar{D}$ let $N(\mathcal{A})$ be the filter base of open neighborhoods of \mathcal{A} in X and denote $N_0(\mathcal{A})$ be the trace of $N(\mathcal{A})$ on D .

DEFINITION. For $f \in A(D)$, define $\text{cl } t_f(\mathcal{A}) = \{\bigcap \text{cl } f(W): W \in N_0(\mathcal{A})\}$, where $\text{cl } f(W)$ is the closure of $f(W)$ in the Riemann sphere $C \cup (\infty)$, the cluster set of f at \mathcal{A} , and write $\text{cl } t_f(x)$ for $\text{cl } t_f(\{x\})$. Define $M_f(\mathcal{A}) = \sup \{|\text{cl } t_f(\mathcal{A})| \in [0, \infty]\}$, and write $M_f(x)$ for $M_f(\{x\})$.

Let $B = B(D)$. Denote B_s for B with the topology of supremum norm on D and B_c for B with the topology of uniform convergence on compact subsets of D (c.o. topology). Then B_s is a Banach algebra. Let $S(B_s)$ be the space of nonzero complex homomorphisms of B_s onto C and $S(B_c)$ be the space of nonzero continuous complex homomorphisms of B_c onto C . Then $S(B_s) \supset S(B_c)$, for, if $h \in S(B_c)$ then there exists a compact subset K_h of D such that $|h(f)| \leq \|f\|_{K_h}$ for all $f \in B$, which implies $|h(f)| \leq \|f\|_D$ for all $f \in B$, so that $h \in S(B_s)$. Endow $S(B_s)$ with the weakest topology for which each \hat{f} is continuous,

where \hat{f} is the Gelfand representation of f on $S(B_s)$ such that $\hat{f}(h) = h(f)$ for all $h \in S(B_s)$. Then $S(B_s)$ is compact. Equip $S(B_c)$ with the relative topology of $S(B_s)$. For $x \in D$ define $h_x(f) = f(x)$ for all $f \in B$ then $h_x \in S(B_s)$, moreover $h_x \in S(B_c)$, since $|h_x(f)| = |f(x)| \leq \|f\|_K$ for all $f \in B$, where K is a compact subset containing $\{x\}$. Now if B separates the points of D then it separates strongly the points of D (in the sense of [8]), since B contains constant functions. If D is locally compact and B separates the points then the natural embedding ρ of D into $S(B_s)$ is a homeomorphism (See Cor. 3.2.5 of Rickart [8]). Henceforth, we denote ρ for this homeomorphism. Let π be a continuous mapping from $S(B_s)$ into X such that $\pi|_{\rho D}$ is the inverse mapping of ρ , so that $\pi|_{\rho D}$ is a homeomorphism of ρD onto D .

The prototype of these phenomena is the following: Let D be a relatively compact domain in C^n and $B = B(D)$. Set $S = S(B_s)$. With the coordinate function z_1, z_2, \dots, z_n in B , define $\pi: S \rightarrow C^n$ by $\pi(h) = (\hat{z}_1(h), \dots, \hat{z}_n(h)), h \in S(\pi(S))$ is the joint spectrum of z_1, z_2, \dots, z_n . Then π is continuous and it is a homeomorphism on ρD . Moreover $\pi S(B_c) \subset D$ and $\pi S \supset \bar{D}$.

A minimal boundary.

PROPOSITION 1.

- (i) $M_f(\Delta) = \lim_{N_0(\Delta)} \sup \{ |f(W)| : W \in N_0(\Delta) \}$, where $\Delta \subset \bar{D}$. For $x \in D$, $M_f(x) = f(x)$. $\|f\| = \sup_{x \in D} |f(x)| = M_f(D) = M_f(\bar{D})$.
- (ii) The function $M_f(\cdot) : \bar{D} \rightarrow [0, \infty]$ is upper semi-continuous.
- (iii) For a closed subset $\Delta \subset \bar{D}$, there exists a point $p \in \Delta$ such that $M_f(\Delta) = M_f(p)$.
- (iv) $M_{f_g}(\Delta) \leq M_f(\Delta) \cdot M_g(\Delta)$, where $\Delta \subset \bar{D}$.

Proof. For (i), (ii), and (iii), see Quigley [5]. (iv) is trivial.

DEFINITION 2. Let $H \subset A(D)$. We call a subset Γ of \bar{D} an H -set if Γ is closed in \bar{D} and $\|f\| = M_f(D) = M_f(\Gamma)$ for all $f \in H$. An H -set is minimal if it properly contains no H -set. Denote Γ_H for a minimal H -set.

If $H = B = B(D)$, Γ_B is a minimal B -set.

PROPOSITION 2. If D is relatively compact then a minimal H -set exists for every $H \subset A(D)$.

Proof. See Quigley [5].

PROPOSITION 3. Let X be locally compact and B separate the points of D . Let π be a continuous mapping from $S(B_s)$ into X such that $\pi \circ \rho$ is the identity mapping on D . Let $\text{cl } \rho D$ be the closure of ρD in $S(B_s)$. Then $\pi(\text{cl } \rho D) = \bar{D}$ and $\pi(\text{cl } \rho D - \rho D) = \bar{D} - D$.

Proof. Since $\text{cl } \rho D$ is compact and $\pi(\text{cl } \rho D) \cong D, \pi(\text{cl } \rho D) \cong \bar{D}$. Let $h \in \text{cl } \rho D$ then for any net $\{h_n\} \subset \rho D$ which converges to $h, \{\pi(h_n)\}$ converges to $\pi(h)$, since π is continuous. Since $\{\pi(h_n)\} \subset D, \pi(h) \in \bar{D}$. So $\pi(\text{cl } \rho D) \subseteq \bar{D}$. Hence $\pi(\text{cl } \rho D) = \bar{D}$.

Let $h \in \text{cl } \rho D - \rho D$ and assume that $\pi(h) \in D$. Take any $f \in B$. Since f is continuous, we may choose, for arbitrary $\varepsilon' > 0$, a neighborhood U of $\pi(h)$; $U = \{x \in D: |f_i(x) - f_i(\pi(h))| < \varepsilon, i = 1, 2, \dots, n\}$, such that $y \in U$ implies $|f(y) - f(\pi(h))| < \varepsilon'$. Again, since \hat{f} is continuous on $S(B_s)$ and $h \in \text{cl } \rho D$, there is $y_0 \in D$ with $\rho(y_0) \in N = \{\varphi \in S(B_s): |\hat{f}_i(\varphi) - \hat{f}_i(h)| < \varepsilon, i = 1, 2, \dots, n\}$ such that $|\hat{f}(h) - \hat{f}(\rho(y_0))| < \varepsilon'$. Note that $y_0 \in U = \pi | \rho D(N)$, so $|f(y_0) - f(\pi(h))| < \varepsilon'$. Also $f(y_0) = \hat{f}(\rho(y_0))$ and $f(\pi(h)) = \hat{f}(\rho(\pi(h)))$, so it follows that $|\hat{f}(h) - \hat{f}(\rho(\pi(h)))| < 2\varepsilon'$. Since ε' is arbitrary, we have $\hat{f}(h) = \hat{f}(\rho(\pi(h)))$ for every $f \in B$. Hence $h = \rho(\pi(h)) \in \rho D$, which is absurd. Hence $\pi(\text{cl } \rho D - \rho D) = \bar{D} - D$.

THEOREM 1. *Let X be locally compact and D be relatively compact in X . If $B(D)$ separates the points of D , then the minimal B -set Γ_B is unique.*

Proof. Let Γ_1 and Γ_2 be minimal B -sets, and let $p \in \Gamma_1$ be an arbitrary point of Γ_1 . We will show that every neighborhood of p intersects Γ_2 so that $p \in \Gamma_2$. So $\Gamma_1 \subset \Gamma_2$. The same argument shows that $\Gamma_2 \subset \Gamma_1$.

Let $p \in \Gamma_1$. Let W be any neighborhood of p in \bar{D} and let $\varphi \in \text{cl } \rho D$ such that $\pi(\varphi) = p$. Take a neighborhood N of φ in $S(B_s) = S$ such that $N \subset \pi^{-1}(W)$; $N = \{h \in S: |\hat{f}_i(h) - \hat{f}_i(\varphi)| < \varepsilon, i = 1, 2, \dots, n\}$. Put $U = \{x \in D: |f_i(x) - a_i| < \varepsilon, i = 1, 2, \dots, n\}$, where $a_i = \hat{f}_i(\varphi)$. Then $U = \pi(N) \cap D \subset \pi(N)$. Let $V = \{x \in \bar{D}: M_{f_i - a_i}(x) < \varepsilon/2, i = 1, 2, \dots, n\}$. Since $M_{f_i - a_i}(x) = |f_i(x) - a_i|$ for $x \in D, V \cap D = U$. And, since $M_{f_i - a_i}$ is upper semicontinuous, V is open in \bar{D} and it is easy to see that $M_{f_i - a_i}(p) = 0$, so V is an open neighborhood of p . Note that $M_{f_i}(p) = |a_i|$. Now, since $M_{f_i - a_i}(x) < \varepsilon/2$ in V , we may choose a neighborhood G of p in \bar{D} such that $|(f_i - a_i)(x)| < \varepsilon$ for all $x \in G \cap D$ and $G \subset \pi N$. Then $V \subset G \subseteq \pi N \subset W$.

Since $\Gamma_1 - V$ is closed in \bar{D} and it is a proper subset of Γ_1 , it is not a B -set. Hence there exists $g \in B(D)$ such that $M_g(\Gamma_1 - V) < M_g(\Gamma_1) = \|g\|$. So $M_g(\Gamma_1 - V) \|g\|^{-1} < 1$. Choose m large enough such that $\{M_g(\Gamma_1 - V) \|g\|^{-1}\}^m < \varepsilon(1 + \sum_1^n \|f_i - a_i\|)^{-1} = \delta$, and set $f = g^m$. Then $M_f(\Gamma_1 - V) = M_{g^m}(\Gamma - V) \leq \{M_g(\Gamma - V)\}^m < \delta \|g\|^m = \delta \|f\|$. If $x \in V$ then $M_{f_i - a_i}(x) < \varepsilon/2$ so that

$$M_{f_i - a_i} M_f(x) = M_{f_i - a_i}(x) M_f(x) < \frac{\varepsilon}{2} M_f(\bar{D}) = \frac{\varepsilon}{2} \|f\|.$$

If $x \in \Gamma_1 - V$ then $M_f(x) \leq M_f(\Gamma_1 - V) < \delta \|f\|$, so that again

$$M_{f_{i-a_i}} M_f(x) < \frac{\varepsilon}{2} \|f\|.$$

Since Γ_1 is a B -set it follows that $M_{f_{i-a_i}} M_f(\bar{D}) < (\varepsilon/2) M_f(\bar{D}) = (\varepsilon/2) \|f\|$. Let q be any point of Γ_2 with $M_f(q) = M_f(\bar{D}) = M_f(D) = \|f\|$. Then $M_{f_{i-a_i}}(q) M_f(q) < (\varepsilon/2) \|f\|$. Hence $M_{f_{i-a_i}}(q) < \varepsilon/2$ and this is true for all $i = 1, 2, \dots, n$. Thus $q \in V$, so $V \cap \Gamma_2 \neq \emptyset$. Hence $W \cap \Gamma_2 \neq \emptyset$. Since Γ_2 is closed, $p \in \Gamma_2$. The proof is complete.

We call the unique minimal B -set the minimal boundary for B .

Note. Let Γ_B be a minimal boundary for B then $x \in \Gamma_B$ if and only if for every neighborhood U of x there exists $f \in B$ such that $\|f\| = M_f(U) > M_f(\bar{D} - U)$.

THEOREM 2. *Let X be locally compact and D be relatively compact in X . We assume that B separates the points of D . Then $\pi \partial \hat{B}$ is a minimal boundary.*

Proof. Since $M_f(\bar{D}) = \|f\|_D = \|\hat{f}\|_{\rho D} = \|\hat{f}\|_S$ for all $f \in B$, we have $\partial \hat{B} \subset \text{cl } \rho D$. Let $x \in \pi \partial \hat{B}$ then there exists $h \in \partial \hat{B}$ such that $x = \pi h$. Now, $h \in \partial \hat{B}$ implies that for arbitrary neighborhood N of h in $S = S(B_S)$ there exists $\hat{f} \in \hat{B}$ such that $\|\hat{f}\|_S = \|\hat{f}\|_N > \|\hat{f}\|_{S-N}$. Since $S - N \supset \rho D - N \cap \rho D$, we have $\|\hat{f}\|_{S-N} \geq \|\hat{f}\|_{\rho D - N \cap \rho D}$. So $\|\hat{f}\|_{\rho D} = \|\hat{f}\|_S > \|\hat{f}\|_{S-N} \geq \|\hat{f}\|_{\rho D - N \cap \rho D}$. Hence it follows that $\|\hat{f}\|_{\rho D} = \|\hat{f}\|_{N \cap \rho D} > \|\hat{f}\|_{\rho D - N \cap \rho D}$. This is equivalent to $\|f\|_D = \|f\|_{\pi(N \cap \rho D)} > \|f\|_{D - \pi(N \cap \rho D)}$. Since $\pi(N \cap \rho D)$ is a trace of a neighborhood of $x = \pi h$ on D and a trace of any neighborhood of x on D can be written as such a form, $x = \pi h$ belongs to a minimal boundary Γ_B . So $\pi \partial \hat{B} \subset \Gamma_B$. On the other hand, if W is any open set containing $\pi \partial \hat{B}$, then by the continuity of π , there exists an open set G in S containing $\partial \hat{B}$ such that $\pi(G) \subseteq W$ and hence $\pi(G \cap \rho D) \subseteq W \cap D$. For any $f \in B$, we have

$$\|f\|_{W \cap D} \geq \|\hat{f}\|_{G \cap \rho D} = \|\hat{f}\|_{G \cap \text{cl } \rho D} = \|\hat{f}\|_{\partial \hat{B}} = \|f\|_D.$$

It follows that $M_f(\pi \partial \hat{B}) = \|f\|_D$ for all $f \in B$. Since $\pi \partial \hat{B}$ is closed, it is a B -set. Thus $\pi \partial \hat{B}$ is a minimal boundary.

For instance: Let D be the unit open disc in C and let $B(D) = H^\infty$. Define a natural continuous mapping π of S into the closed unit disc \bar{D} by $\pi(h) = h(z)$, $h \in S$ and z is the coordinate function. Then the minimal boundary Γ_B is the unit circle and the Šilov boundary $\partial \hat{B}$ on S is a proper closed subset of $\text{cl } \rho D - \rho D$ which is totally disconnected. The image of $\partial \hat{B}$ under π is the unit circle.

Next, we have a question that whether a function f with $M_f(\Gamma_B) < \infty$ is bounded.

PROPOSITION 4. *Suppose $A = A(D)$ and $B = B(D)$ have the unique minimal boundaries Γ_A and Γ_B respectively. If $\Gamma_A \neq \Gamma_B$ then there exists a function $f \in A$ which is bounded near Γ_B (i.e., $M_f(\Gamma_B) < \infty$), but not in B .*

Proof. In general, $\Gamma_A \supset \Gamma_B$. Take $x \in \Gamma_A - \Gamma_B$ and choose a neighborhood U of x in \bar{D} such that $M_f(U) = \|f\| > M_f(\bar{D} - U)$ and $U \cap \Gamma_B = \emptyset$. Then $M_f(\Gamma_B) < \infty$ but $f \notin B$.

DEFINITION. A point $x \in \bar{D}$ is a frontier point of D for $H \subset A(D)$ if for each compact subset K of D with $x \notin K$ there exists $f \in H$ such that $M_f(x) > \|f\|_K$. Let F_H be the set of all frontier points of D for H . Denote F_A for $A(D)$ and F_B for $B(D)$ respectively.

We introduce a generalized form of a theorem in Bochner and Martin [2] (see Theorem 1, Ch. V) as follows:

PROPOSITION 5. *Let X be locally compact, D be a subset of X which is countable at ∞ , and let $\bar{D} - D$ be first countable. Let $A = A(D)$ be a maximum modulus algebra and c.o. complete. Then $x \in F_A$ if and only if there is a function $f \in A$ such that $M_f(x) = \infty$. In fact, there is a single function f such that $M_f(x) = \infty$ for all $x \in F_A$.*

Proof. Use the analogous argument as in Bochner and Martin [2].

THEOREM 3. *Let X be locally compact, D be countable at ∞ , and $\bar{D} - D$ be first countable. Let A be a maximum modulus algebra and c.o. complete. Suppose Γ_B is a minimal boundary and $F_A = \Gamma_B$ then every function $f \in A$ with $M_f(\Gamma_B) < \infty$ belongs to B .*

Proof. Assume that f is unbounded then there exists a sequence $\{x_n\} \subset D$ such that $|f(x_n)| \rightarrow \infty$ and $n \rightarrow \infty$. Let $x_n \rightarrow x$ then by Proposition 5, $x \in F_A$ and so $x \in \Gamma_B$. Thus $\infty = M_f(x) \leq M_f(\Gamma_B) < \infty$, which is absurd. Hence $f \in B$.

We observe that $h \in S(B_s) - S(B_c)$ if and only if for any compact subset K of D there exists $f \in B$ (f may depend on K) such that $|h(f)| > \|f\|_K$.

THEOREM 4. *Let X be locally compact and B separate the points of D . Let F_B be the set of all frontier points for B . If $\rho D = S(B_c)$ then $\bar{D} - D = F_B$.*

Proof. Let $\text{bdry } S(B_s) = \text{cl } S(B_c) - S(B_c)$. By Proposition 3, $\pi(\text{bdry } S(B_c)) = \text{bdry } D$. Now if $h \in \text{bdry } S(B_c)$, then for any com-

pact subset K of D , there exists $f \in B$ such that $|h(f)| > \|f\|_K$. We claim $M_f(\pi(h)) > \|f\|_K$: Suppose $M_f(\pi(h)) = \|f\|_K = r$, then there exists a net $\{x_n\} \subset D$ such that $\|f(x_n) - r\| < 1/n$ as $x_n \rightarrow \pi(h)$. So $|f(x_n)| \rightarrow r$. Now, let $h_{x_n} \rightarrow h$. Since \hat{f} is continuous, $\hat{f}(h_{x_n}) \rightarrow \hat{f}(h)$. So $f(x_n) \rightarrow h(f)$. In particular, $|f(x_n)| \rightarrow |h(f)|$. Then it follows that $|h(f)| = r = \|f\|_K$. This is absurd. Hence $M_f(\pi(h)) > \|f\|_K$. So $\text{bdry } D = F_B$.

Note. If D is a Stein manifold of bounded type then $\rho D = S(B_\circ)$ (see Kim [3]).

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William George Bade, <i>Complementation problems for the Baire classes</i>	1
Ian Douglas Brown, <i>Representation of finitely generated nilpotent groups</i>	13
Hans-Heinrich Brungs, <i>Left Euclidean rings</i>	27
Victor P. Camillo and John Cozzens, <i>A theorem on Noetherian hereditary rings</i>	35
James Cecil Cantrell, <i>Codimension one embeddings of manifolds with locally flat triangulations</i>	43
L. Carlitz, <i>Enumeration of up-down permutations by number of rises</i>	49
Thomas Ashland Chapman, <i>Surgery and handle straightening in Hilbert cube manifolds</i>	59
Roger Cook, <i>On the fractional parts of a set of points. II</i>	81
Samuel Harry Cox, Jr., <i>Commutative endomorphism rings</i>	87
Michael A. Engber, <i>A criterion for divisoriality</i>	93
Carl Clifton Faith, <i>When are proper cyclics injective</i>	97
David Finkel, <i>Local control and factorization of the focal subgroup</i>	113
Theodore William Gamelin and John Brady Garnett, <i>Bounded approximation by rational functions</i>	129
Kazimierz Goebel, <i>On the minimal displacement of points under Lipschitzian mappings</i>	151
Frederick Paul Greenleaf and Martin Allen Moskowitz, <i>Cyclic vectors for representations associated with positive definite measures: nonseparable groups</i>	165
Thomas Guy Hallam and Nelson Onuchic, <i>Asymptotic relations between perturbed linear systems of ordinary differential equations</i>	187
David Kent Harrison and Hoyt D. Warner, <i>Infinite primes of fields and completions</i>	201
James Michael Hornell, <i>Divisorial complete intersections</i>	217
Jan W. Jaworowski, <i>Equivariant extensions of maps</i>	229
John Jobe, <i>Dendrites, dimension, and the inverse arc function</i>	245
Gerald William Johnson and David Lee Skoug, <i>Feynman integrals of non-factorable finite-dimensional functionals</i>	257
Dong S. Kim, <i>A boundary for the algebras of bounded holomorphic functions</i>	269
Abel Klein, <i>Renormalized products of the generalized free field and its derivatives</i> ...	275
Joseph Michael Lambert, <i>Simultaneous approximation and interpolation in L_1 and $C(T)$</i>	293
Kelly Denis McKennon, <i>Multipliers of type (p, p) and multipliers of the group L_p-algebras</i>	297
William Charles Nemitz and Thomas Paul Whaley, <i>Varieties of implicative semi-lattices. II</i>	303
Donald Steven Passman, <i>Some isolated subsets of infinite solvable groups</i>	313
Norma Mary Piacun and Li Pi Su, <i>Wallman compactifications on E-completely regular spaces</i>	321
Jack Ray Porter and Charles I. Votaw, <i>$S(\alpha)$ spaces and regular Hausdorff extensions</i>	327
Gary Sampson, <i>Two-sided L_p estimates of convolution transforms</i>	347
Ralph Edwin Showalter, <i>Equations with operators forming a right angle</i>	357
Raymond Earl Smithson, <i>Fixed points in partially ordered sets</i>	363
Victor Snaith and John James Ucci, <i>Three remarks on symmetric products and symmetric maps</i>	369
Thomas Rolf Turner, <i>Double commutants of weighted shifts</i>	379
George Kenneth Williams, <i>Mappings and decompositions</i>	387