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WEIGHTED COMPOSITION OPERATORS ON BERGMAN AND DIRICHLET SPACES

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Abstract. Let $H(\Omega)$ denote a functional Hilbert space of analytic functions on a domain Ω. Let $w : \Omega \longrightarrow \mathbf{C}$ and $\phi : \Omega \longrightarrow \Omega$ be such that $wf \circ \phi$ is in $H(\Omega)$ for every f in $H(\Omega)$. The operator wC_ϕ given by $f \longrightarrow wf \circ \phi$ is called a *weighted composition operator* on $H(\Omega)$. In this paper we characterize such operators and those for which $(wC_\phi)^*$ is a composition operator. Compact weighted composition operators on some functional Hilbert spaces are also characterized. We give sufficient conditions for the compactness of such operators on weighted Dirichlet spaces.

1. Introduction

A Hilbert space $H(\Omega)$ of analytic functions on a domain Ω is called a *functional Hilbert space* provided the point evaluation $f \longrightarrow f(x)$ is continuous for every x in Ω. The Hardy space H^2 and the Bergman space $L^2_a(\mathbf{D})$ are the well-known examples of functional Hilbert spaces. An application of the Riesz representation theorem shows that for every $x \in \Omega$ there is a vector k_x in $H(\Omega)$ such that $f(x) =< f, k_x >$ for all f in $H(\Omega)$. Let $K = \{k_x : x \in \Omega\}$. An operator T on $H(\Omega)$ is a *composition operator* if and only if K is invariant under T^* [1]. In fact, $T^* k_x = k_{\phi(x)}$, where $T = C_\phi$. It is a *multiplication operator* if and only if the elements of K are eigenvectors of T^* [2]. In this case $T^* k_x = \overline{\psi(x)} k_x$, where $T = M_\psi$ is the operator of multiplication by ψ. An operator T on $H(\Omega)$ is a *weighted composition operator* if and only if $T^* K \subset \tilde{K}$, where $\tilde{K} = \{\lambda k_x | \lambda \in \mathbf{C}, x \in \Omega\}$. In this case $T^* k_x = \overline{w(x)} k_{\phi(x)}$, where $T = wC_\phi$.

We note that the Hardy space H^2 can be identified as the space of func-

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tions f analytic in the open unit disc $\mathbf{D}$ such that

$$\|f\|^2 = \sup_{0<r<1} \int_{-\pi}^{\pi} |f(re^{i\theta})|^2 d\theta < \infty.$$

Actually, if $f \in H^2$ and $f(z) = \sum a_n z^n$ then $\|f\|^2 = \sum |a_n|^2$. Moreover, if $f \in H^2$ then

$$< f, g >= \sum a_n \overline{b_n},$$

where $g(z) = \sum b_n z^n$. For $\lambda \in \mathbf{D}$ the function $k_\lambda(z) = (1 - \overline{\lambda} z)^{-1}$ is the reproducing kernel for λ.

Let G be a bounded open subset of the complex plane $\mathbf{C}$. For $1 \le p \le \infty$, the Bergman space of G, $L^p_a(G)$ is the set of all analytic functions $f : G \longrightarrow \mathbf{C}$ such that $\int_G |f|^p dA < \infty$, where $dA(z) = 1/\pi r dr d\theta$ is the usual area measure on G. Note that $L^p_a(G)$ is closed in $L^p(G)$ and it is therefore a Banach space. When $G = \mathbf{D}$ the inner product in $L^2_a(\mathbf{D})$ is given by

$$< f, g >= \sum \frac{a_n \overline{b}_n}{n+1},$$

where $f = \sum a_n z^n$ and $g = \sum b_n z^n$. Therefore $k_\lambda(z) = (1 - \overline{\lambda} z)^{-2}$ is the reproducing kernel for the point $\lambda \in \mathbf{D}$.

Let λ_α $(\alpha > -1)$ be the finite measure defined on $\mathbf{D}$ by $d\lambda_\alpha(z) = (1 - |z|^2)^\alpha dA(z)$. For $\alpha > -1$ and $0 < p < \infty$ the *weighted Bergman space* A^p_α is the collection of all functions f analytic in $\mathbf{D}$ for which $\|f\|^p_{p,\alpha} = \int_{\mathbf{D}} |f|^p d\lambda_\alpha < \infty$. The *weighted Dirichlet space* D_α $(\alpha > -1)$ is the collection of all analytic functions f in $\mathbf{D}$ for which the derivative f' belongs to A^2_α. Note that A^p_α is a Banach space for $p \ge 1$, and a Hilbert space for $p = 2$ [3]. The Dirichlet space D_α is a Hilbert space in the norm

$$\|f\|^2_{D_\alpha} = |f(0)|^2 + \int_D |f'|^2 d\lambda_\alpha.$$

For these spaces the unit ball is a normal family and the point evaluation is bounded. Also, $f(z) = \sum a_n z^n$ analytic in $\mathbf{D}$ belongs to A^2_α if and only if $\sum (n+1)^{-1-\alpha} |a_n|^2 < \infty$, and to D_α if and only if $\sum (n+1)^{1-\alpha} |a_n|^2 < \infty$. We also note that if $\alpha > -1$, then $D_\alpha \subset A^2_\alpha$ and the inclusion map is continuous.

A function ϕ on $\mathbf{D}$ is said to have an *angular derivative* at $\zeta \in \partial\mathbf{D}$ if there exist a complex number c and a point $\omega \in \partial\mathbf{D}$ such that $(\phi(z) - \omega)/(z - \zeta)$ tends to c as z tends to ζ over any triangle in $\mathbf{D}$ with one vertex at ζ. Define $d(\zeta) = \liminf_{z \to \zeta} \frac{1 - |\phi(z)|}{1 - |z|}$, where z tends unrestrictedly to ζ through $\mathbf{D}$. By [4, §5.3] the existence of an angular derivative at $\zeta \in \partial\mathbf{D}$ is equivalent to $d(\zeta) < \infty$.

For the proof of the next proposition see [5, Proposition 3.4].

Proposition 1.1. *If ϕ is analytic in $\mathbf{D}$ with $\phi(\mathbf{D}) \subset \mathbf{D}$, then C_ϕ is bounded on A^p_α for all $0 < p < \infty$ and $\alpha > -1$. Also, if $w \in H^\infty$ then wC_ϕ is bounded on A^p_α for all $0 < p < \infty$ and $\alpha > -1$.*

In this paper we characterize such operators and those for which $(wC_\phi)^*$ is a composition operator. We also study the boundedness and compactness of the weighted composition operators on A^p_α or D_α. The relationship between the compactness of such operators and a special class of measures on the unit disc, *Carleson measures*, is shown. The main result is to determine, in terms of geometric properties of ϕ and w, when wC_ϕ is a compact operator on weighted Dirichlet spaces. For Bergman spaces we attack the problem in terms of an angular derivative of ϕ and an angular limit of w. We obtain some sufficient conditions for weighted Dirichlet spaces. Finally, we would like to acknowledge the fact that we are borrowing heavily the techniques of the proofs of [5].

2. Adjoint of Weighted Composition Operators

In this section we investigate when the adjoint of a weighted composition operator on some functional Hilbert space is a composition operator.

Theorem 2.1. *Let $T = wC_\phi$ be a weighted composition operator on A^2_α, $\alpha > -1$. Then $T^* = C_\psi$ if and only if $w = k_\lambda$ and $\phi(z) = az(1-\overline{\lambda}z)^{-1}$, where $\lambda = \psi(0)$ and a is a suitable constant. In particular, ψ has the form $\psi(z) = \overline{a}z + \lambda$.*

Proof. Assume $(wC_\phi)^* = C_\psi$. Then $(wC_\phi)^* k_x = C_\psi k_x$ or $\overline{w(x)} k_{\phi(x)}(y) = k_x \circ \psi(y)$. It follows that

$$\frac{\overline{w(x)}}{(1-\overline{\phi(x)}y)^{\alpha+2}} = \frac{1}{(1-\overline{x}\psi(y))^{\alpha+2}}\ , \quad x, y \in \mathbf{D}.$$

In short, $(1-\overline{\phi(x)}y)^{\alpha+2} = \overline{w(x)}(1-\overline{x}\psi(y))^{\alpha+2}$. If we put $y = 0$ and $\psi(0) = \lambda$ we have $1 = \overline{w(x)}(1-\lambda\overline{x})^{\alpha+2}$. Therefore $w = k_\lambda$. We also have $(1-\lambda\overline{x})(1-\overline{\phi(x)}y) = 1 - \overline{x}\psi(y)$ for all $x, y \in \mathbf{D}$. Hence $\overline{\phi(x)}y + \lambda\overline{x} - \lambda\overline{\phi(x)}\overline{x}y = \overline{x}\psi(y)$. Now if $xy \neq 0$, then $\overline{\phi(x)}(1-\lambda\overline{x})(\overline{x})^{-1} = (\psi(y) - \psi(0))y^{-1}$. Since the right-hand side is independent of x, it should be a constant, say, $\overline{a}$, $a \in \mathbf{C}$. Therefore $\psi(z) = \overline{a}z + \lambda$ and $\phi(z) = az(1-\overline{\lambda}z)^{-1}$.

Conversely, suppose $T = wC_\phi$, where $w = k_\lambda$ and $\phi(x) = ax(1-\overline{\lambda}x)^{-1}$, $a \in \mathbf{C}$. Then

$$\begin{aligned} T^*k_y(x) = \overline{w(y)}k_{\phi(y)}(x) &= \frac{1}{(1-\lambda\overline{y})^{\alpha+2}} \cdot \frac{1}{(1-\overline{\phi(y)}x)^{\alpha+2}} = \\ &= \frac{1}{(1-\lambda\overline{y})^{\alpha+2}} \cdot \frac{1}{(1-\overline{ay}(1-\lambda\overline{y})^{-1}x)^{\alpha+2}} = \\ &= \frac{1}{(1-\lambda\overline{y}-\overline{ay}x)^{\alpha+2}} = C_\psi k_y(x) \ , \end{aligned}$$

where $\psi(x) = \overline{a}x + \lambda$. $\square$

Remark. By an analogous proof we can show that Theorem 2.1 is also true when T is a weighted composition operator on H^2.

We use the next theorem to give a sufficient condition for the subnormality of wC_ϕ on H^2.

Theorem 2.2 ([6]). *If ϕ is a nonconstant analytic function defined on the unit disc $\mathbf{D}$ with $\phi(\mathbf{D}) \subset \mathbf{D}$ such that C_ϕ^* is subnormal on H^2 (and not normal), then there is a number c with $|c| = 1$ for which $\lim_{\rho\to 1}\phi(\rho c) = c$ and $\lim_{\rho\longrightarrow 1^-}\phi^{'}(\rho c) = s < 1$. Moreover, if ϕ is analytic in a neighborhood of c, then C_ϕ^* is subnormal on H^2 if and only if*

$$\phi(z) = \frac{(r+s)z + (1-s)c}{r(1-s)\overline{c}z + (1+sr)}$$

for some r, s with $0 \le r \le 1$ and $0 < s < 1$. Here, as above, $s = \phi^{'}(c)$.

Applying Theorem 2.2 and the above remark we obtain

Corollary 2.3. *If $w = k_\lambda$ and $\phi(z) = szk_\lambda(z)$ with $0 < s < 1$ and $\lambda = (1-s)c$, where c is the number indicated in Theorem 2.2, then wC_ϕ is subnormal on H^2.*

3. A Weighted Shift Analogy

As we shall see, for suitable w and ϕ the operator $(wC_\phi)^*$ (as well as the operator wC_ϕ) has an invariant subspace on which it is similar to a weighted shift.

We begin by defining the notions of forward and backward iteration sequences, see also [7].

Definition 3.1. A nonconstant sequence $\{z_k\}_{k=0}^\infty$ is a B-sequence for ϕ if $\phi(z_k) = z_{k-1}$, $k = 1, 2, \ldots$. A nonconstant sequence $\{z_k\}_{k=0}^\infty$ or $\{z_k\}_{k=-\infty}^\infty$ is an F-sequence for ϕ if $\phi(z_k) = z_{k+1}$ for all k.

Theorem 3.2. *If $\{z_j\}_{j=0}^{\infty}$ is a B-sequence for ϕ and*

$$\frac{1-|z_j|}{1-|z_{j-1}|} \le r < 1$$

for all j, then $\{z_j\}_{j=0}^{\infty}$ gives rise to an invariant subspace of $(wC_\phi)^*$ on which it is similar to a backward weighted shift.

Proof. Let $\{z_j\}$ be a B-sequence as in the statement of the theorem. By [7, p. 203], $\{z_j\}$ is an interpolating sequence. Let $u_j = (1-|z_j|^2)^{1/2}k_j$, where k_j denotes the reproducing kernel at z_j. We keep this notation throughout the rest of this section. Let $\mathcal{M}$ be the closed linear span of $\{u_j\}$. By [6], $\{u_j\}$ is a basic sequence in $\mathcal{M}$ equivalent to an orthonormal basis. Since

$$(wC_\phi)^* u_j = (1-|z_j|^2)^{1/2}\overline{w(z_j)}k_{j-1} = \overline{w(z_j)}\Big(\frac{1-|z_j|^2}{1-|z_{j-1}|^2}\Big)^{1/2} u_{j-1},$$

$(wC_\phi)^* \mid_{\mathcal{M}}$ is similar to a backward weighted shift with weights

$$\Big\{\Big(\frac{1-|z_{j+1}|^2}{1-|z_j|^2}\Big)^{1/2}\overline{w(z_{j+1})}\Big\}. \quad \square$$

Recall that if ϕ is analytic in $\mathbf{D}$ with $\phi(\mathbf{D}) \subset \mathbf{D}$ and ϕ is not an analytic elliptic automorphism of $\mathbf{D}$, then there is a unique fixed point a of ϕ (with $|a| \le 1$) such that $|\phi'(a)| \le 1$. We will call the distinguished fixed point a the *Denjoy–Wolff point* [8] of ϕ. We note that if $|a| = 1$ then $0 < \phi'(a) \le 1$, and if $|a| < 1$ then $0 \le |\phi'(a)| < 1$.

Corollary 3.3. *If ϕ has a Denjoy–Wolff point a in $\partial\mathbf{D}$ with $\phi'(a) < 1$ then every F-sequence for ϕ gives rise to an invariant subspace of $(wC_\phi)^*$ on which it is similar to a forward weighted shift with weights*

$$\Big\{\Big(\frac{1-|z_{j-1}|^2}{1-|z_j|^2}\Big)^{1/2}\overline{w(z_{j-1})}\Big\}.$$

Corollary 3.4. *For $0 < s < 1$ let $w = k_{1-s}$ and $\phi(z) = szk_{1-s}(z)$. Then wC_ϕ has an invariant subspace $\mathcal{M}$ such that $wC_\phi \mid_{\mathcal{M}}$ is similar to a weighted shift.*

Proof. Let $\psi(z) = sz + (1-s)$. Then 1 is a Denjoy–Wolff point for ψ. Also, $\psi'(1) = s < 1$. So by Corollary 3.3 every F-sequence for ψ gives rise to an invariant subspace of C_ψ^* on which it is similar to a weighted shift. Now by Theorem 2.1, $C_\psi^* = wC_\phi$ where $w = k_{1-s}$ and $\phi(z) = szk_{1-s}(z)$. The proof is now complete. $\square$

We note that if ϕ has a Denjoy–Wolff point a in $\partial\mathbf{D}$ with $\phi'(a) < 1$, then for real θ, C_ϕ is similar to $e^{i\theta}C_\phi$ [7]. In fact, much more is true. For the proof of the next corollary see [7].

Corollary 3.5. *If ϕ is an analytic map of the disc to itself, $\phi(1) = 1$ and $\phi'(1) < 1$, then for any function w for which wC_ϕ is bounded we have wC_ϕ similar to λwC_ϕ for $|\lambda| = 1$.*

4. Compactness on Weighted Bergman Spaces

In this section we will focus our attention on the relationship between compact weighted composition operators and a special class of measures on the unit disc. First, we will recall a few definitions.

For $0 < \delta \leq 2$ and $\zeta \in \partial\mathbf{D}$ let

$$S(\zeta, \delta) = \{z \in \mathbf{D} : |z - \zeta| < \delta\}.$$

One can show that the λ_α-measure of the semidisc $S(\zeta, \delta)$ is comparable with $\delta^{\alpha+2}$ $(\alpha > -1)$. We can now give

Definition 4.1. Let $\alpha > -1$ and suppose μ is a finite positive Borel measure on $\mathbf{D}$. We call μ an α-*Carleson measure* if

$$\|\mu\|_\alpha = \sup \mu(S(\zeta, \delta))/\delta^{\alpha+2} < \infty,$$

where the supremum is taken over all $\zeta \in \partial\mathbf{D}$ and $0 < \delta \leq 2$. If, in addition,

$$\lim_{\delta \to 0} \sup_{\zeta \in \partial\mathbf{D}} \mu(S(\zeta, \delta))/\delta^{\alpha+2} = 0,$$

then we call μ a *compact* α-Carleson measure.

The next theorem is stated and proved in [5]. Since we refer to it several times, we state it without proof.

Theorem 4.2. *Fix $0 < p < \infty$ and $\alpha > -1$ and let μ be a finite positive Borel measure on $\mathbf{D}$. Then μ is an α-Carleson measure if and only if $A^p_\alpha \subset L^p(\mu)$. In this case the inclusion map $I_\alpha : A^p_\alpha \longrightarrow L^p(\mu)$ is a bounded operator with a norm comparable with $\|\mu\|_\alpha$. If μ is an α-Carleson measure, then I_α is compact if and only if μ is compact.*

In the next theorem we extend the result of [5, Corollary 4.4] by characterizing the compact weighted composition operators on the spaces A^p_α in terms of Carleson measures.

Theorem 4.3. *Fix $0 < p < \infty$ and $\alpha > -1$. Then wC_ϕ is a bounded (compact) operator on A^p_α if and only if the measure $\mu_{\alpha,p} \circ \phi^{-1}$ is an α-Carleson (compact α-Carleson) measure. Here $d\mu_{\alpha,p} = |w|^p d\lambda_\alpha$.*

Proof. We know that

$$\|(wC_\phi)f\|_{p,\alpha}^p = \int_{\mathbf{D}} |f\circ\phi|^p|w|^p d\lambda_\alpha = \int_{\mathbf{D}} |f|^p d\mu_{\alpha,p}\circ\phi^{-1},$$

for every $f \in A_\alpha^p$. By Theorem 4.2 wC_ϕ is bounded on A_α^p if and only if $\mu_{\alpha,p}\circ\phi^{-1}$ is an α-Carleson measure.

Now equip the space A_α^p with the metric of $L^p(\mu_{\alpha,p}\circ\phi^{-1})$ and call this (usually incomplete) space X. The above equation shows that wC_ϕ induces an isometry S of X into A_α^p. Thus $wC_\phi = SI_\alpha$ is compact if and only if I_α is. An application of Theorem 4.2 completes the proof. $\square$

A modification of the proof of Theorem 5.3 of [5] will give

Theorem 4.4. *Suppose $\alpha > -1$, $p > 0$.*

(a) *If wC_ϕ is a compact operator on A_α^p, then ϕ does not have an angular derivative at those points of $\partial\mathbf{D}$ at which w has a nonzero angular limit.*

(b) *Suppose w has a zero angular limit at any point of $\partial\mathbf{D}$ at which ϕ has an angular derivative; then wC_ϕ is compact.*

5. Boundedness on Weighted Dirichlet Spaces

In this section we study the relationship between the boundedness of weighted composition operators on weighted Dirichlet spaces and a special class of measures on the unit disc.

We recall that $D_1 = H^2$ and if $\alpha > 1$ then $D_\alpha = A_{\alpha-2}^2$ and the characterization of bounded (compact) weighted composition operators on D_α for $\alpha > 1$ is given in Theorem 4.3. However, for $-1 < \alpha < 1$, an obvious necessary condition for wC_ϕ to be bounded on D_α is that $w = wC_\phi 1 \in D_\alpha$. In the following, we characterize the boundedness of such operators.

Theorem 5.1. *Suppose $w \in D_\alpha$. Then wC_ϕ is bounded on D_α if the measures $\mu_\alpha\circ\phi^{-1}$ and $\nu_\alpha\circ\phi^{-1}$ are α-Carleson measures, where $d\mu_\alpha = |w'|^2 d\lambda_\alpha$ and $d\nu_\alpha = |w|^2|\phi'|^2 d\lambda_\alpha$.*

Proof. Assume $\mu_\alpha\circ\phi^{-1}$ and $\nu_\alpha\circ\phi^{-1}$ are α-Carleson measures. Then, for every f in D_α we have $f' \in A_\alpha^2 \subset L^2(\nu_\alpha\circ\phi^{-1})$ by Theorem 4.2. For every f in D_α we have $(wC_\phi f)' = w' f\circ\phi + w(f\circ\phi)'$. We now have

$$\begin{aligned}\|w(f\circ\phi)'\|_{2,\alpha}^2 &= \int |w|^2|\phi'|^2|f'\circ\phi|^2\, d\lambda_\alpha = \\ &= \int |f'\circ\phi|^2\, d\nu_\alpha = \\ &= \int |f'|^2\, d\nu_\alpha\circ\phi^{-1} < \infty,\end{aligned}$$

therefore, $w(f \circ \phi)^{'} \in A^2_\alpha$. Note also that

$$\int |w'|^2 |f \circ \phi|^2 d\lambda_\alpha = \int |f \circ \phi|^2 d\mu_\alpha = \int |f|^2 d\mu_\alpha \circ \phi^{-1}.$$

Since $f \in D_\alpha \subset A^2_\alpha \subset L^2(\mu_\alpha \circ \phi^{-1})$, we have $\int |w'|^2 |f \circ \phi|^2 d\lambda_\alpha < \infty$. Combining these two observations we conclude that $(wC_\phi f)' \in A^2_\alpha$ for every f in D_α. Therefore $wC_\phi f \in D_\alpha$ and wC_ϕ is bounded on D_α. $\square$

6. Compactness on Dirichlet Spaces

The main result of this section concerns sufficient conditions for the compactness of weighted composition operators on Dirichlet spaces D_α. We would like to investigate whether an analogue of Theorem 4.3, the Carleson measure characterization of compact weighted composition operators, holds for Dirichlet spaces.

Theorem 6.1. *If $\mu_\alpha \circ \phi^{-1}$ and $\nu_\alpha \circ \phi^{-1}$ are compact α-Carleson measures, where $d\mu_\alpha = |w^{'}|^2 d\lambda_\alpha$ and $d\nu_\alpha = |w|^2 |\phi^{'}|^2 d\lambda_\alpha$, then wC_ϕ is compact on D_α for $\alpha > -1$.*

Proof. Let X denote the space D_α taken in the metric induced by $\|.\|_1$ defined by

$$\|f\|_1^2 = (\|f\|_2 + \|f\|_3)^2 + |w(0) f \circ \phi(0)|^2,$$

where $\|f\|_2^2 = \int_{\mathbf{D}} |f|^2 d\mu_\alpha \circ \phi^{-1}$ and $\|f\|_3^2 = \int_{\mathbf{D}} |f^{'}|^2 d\nu_\alpha \circ \phi^{-1} \quad (f \in D_\alpha)$. Let $I : D_\alpha \longrightarrow X$ be the identity map and define $S : X \longrightarrow D_\alpha$ by $Sf = wf \circ \phi$. So $wC_\phi = SI$. To show that S is a bounded operator let $f \in X$. Then

$$\|Sf\|^2_{D_\alpha} = \int_{\mathbf{D}} |(wf \circ \phi)^{'}|^2 d\lambda_\alpha + |w(0) f \circ \phi(0)|^2 \leq$$
$$\leq (\|w^{'} f \circ \phi\|_{2,\alpha} + \|w\phi^{'}(f^{'} \circ \phi)\|_{2,\alpha})^2 + |w(0) f \circ \phi(0)|^2.$$

We use the change of variable formula to get

$$\int_{\mathbf{D}} |w^{'}|^2 |f \circ \phi|^2 d\lambda_\alpha = \int_{\mathbf{D}} |f|^2 d\mu_\alpha \circ \phi^{-1} = \|f\|_2^2$$

and

$$\int_{\mathbf{D}} |w|^2 |\phi^{'}|^2 |f^{'} \circ \phi|^2 d\lambda_\alpha = \int_{\mathbf{D}} |f^{'}|^2 d\nu_\alpha \circ \phi^{-1} = \|f\|_3^2.$$

Thus we have

$$\|Sf\|^2_{D_\alpha} \leq (\|f\|_2 + \|f\|_3)^2 + |w(0) f \circ \phi(0)|^2 = \|f\|_1^2.$$

Hence $\|S\| \leq 1$ and S is bounded. If we show that I is compact, then $wC_\phi = SI$ is compact and the proof is complete.

Now, we use the idea of [5, Theorem 4.3] to prove that I is compact. It is enough to show that each sequence (f_n) in D_α that converges uniformly to zero on compact subsets of $\mathbf{D}$ must be norm convergent to zero in X. Fix $0 < \delta < 1$ and let μ_δ and ν_δ be the restriction of the measures $\mu_\alpha \circ \phi^{-1}$ and $\nu_\alpha \circ \phi^{-1}$ to the annulus $1 - \delta < |z| < 1$. Observe that the α-Carleson norm of μ_δ and ν_δ satisfy

$$\|\mu_\delta\|_\alpha \leq c_1 \sup \mu_\alpha \circ \phi^{-1}(S(\zeta, r))/r^{\alpha+2},$$

and

$$\|\nu_\delta\|_\alpha \leq c_2 \sup \nu_\alpha \circ \phi^{-1}(S(\zeta, r))/r^{\alpha+2},$$

where the supremum is taken over all $0 < r < \delta$ and $\zeta \in \partial\mathbf{D}$, and c_1 , c_2 are positive constants which depend only on α. Since $\mu_\alpha \circ \phi^{-1}$ and $\nu_\alpha \circ \phi^{-1}$ are compact α-Carleson measures, the right-hand sides of the above two inequalities, which we denote by $\epsilon_1(\delta)$ and $\epsilon_2(\delta)$, respectively, tend to zero as $\delta \to 0$. So we have

$$\begin{aligned} \|f_n\|_2^2 &= \int_{|z|<1-\delta} |f_n|^2 d\mu_\alpha \circ \phi^{-1} + \int_{\mathbf{D}} |f_n|^2 d\mu_\delta \leq \\ &\leq o(1) + k_1 \epsilon_1(\delta) \|f_n\|_{2,\alpha}^2, \end{aligned}$$

and in the same manner

$$\|f_n\|_3^2 \leq o(1) + k_2 \epsilon_2(\delta) \|f_n^{'}\|_{2,\alpha}^2,$$

where k_1 and k_2 are constants depending only on α. We recall that the estimate of the first terms comes from the uniform convergence of (f_n) to zero on $|z| \leq 1 - \delta$, and the estimate of the second terms comes from the first part of [6, Theorem 4.3]. Since $\epsilon_i(\delta) \to 0$ as $\delta \to 0$, $i = 1, 2$, and $w(0) f_n \circ \phi(0) \to 0$, we have $\|f_n\|_1 \to 0$, which completes the proof. $\square$

We now characterize compact weighted composition operators in terms of an angular derivative of ϕ and angular limit of w,$w^{'}$.

Theorem 6.2. *If $w^{'}$ has a zero angular limit at any point of $\partial\mathbf{D}$ at which ϕ has an angular derivative, then $\mu_\alpha \circ \phi^{-1}$ is a compact α-Carleson measure. Here $d\mu_\alpha = |w^{'}|^2 d\lambda_\alpha$.*

Proof. Suppose $w^{'}$ has a zero angular limit at those points of $\partial\mathbf{D}$ at which ϕ has an angular derivative. Choose $0 < \gamma < \alpha$ with $r = 2 - (\alpha - \gamma) > 0$. For $0 < \delta < 2$ define

$$\epsilon(\delta) = \sup \Big\{ \frac{(1 - |z|^2)|w^{'}(z)|}{1 - |\phi(z)|^2} : 1 - |z| \leq \delta \Big\}.$$

Since $w^{'}$ has a zero angular limit at those points of $\partial\mathbf{D}$ at which ϕ has an angular derivative we have $\lim_{\delta\to 0}\epsilon(\delta)=0$. With no loss of generality assume that $\phi(0)=0$. Fix $S=S(\zeta,\delta)$. By the Schwartz Lemma and definition of $\epsilon(\delta)$ we have

$$|w^{'}(z)|(1-|z|^2)\leq(1-|\phi(z)|^2)\epsilon(\delta)\leq 2\delta\epsilon(\delta)$$

whenever $\phi(z)\in S$. So we have

$$\mu_\alpha\circ\phi^{-1}(S)=\int\limits_{\phi^{-1}(S)}|w^{'}(z)|^2(1-|z|^2)^\alpha d\lambda(z)\leq$$

$$\leq(2\delta\epsilon(\delta))^{\alpha-\gamma}\int\limits_{\phi^{-1}(S)}|w^{'}(z)|^r(1-|z|^2)^\gamma d\lambda(z)\times$$

$$\times(2\epsilon(\delta))^{\alpha-\gamma}\delta^{\alpha-\gamma}\mu_{r,\gamma}\circ\phi^{-1}(S).$$

Here $d\mu_{r,\gamma}(z)=|w^{'}(z)|^r d\lambda_\gamma(z)$. Now by Proposition 1.1 and Theorem 4.2, $\mu_{r,\gamma}\circ\phi^{-1}$ is a γ-Carleson measure. Thus there exists a constant k independent of ζ, δ such that $\mu_{r,\gamma}\circ\phi^{-1}(S)\leq k\delta^{\gamma+2}$.

Hence $\mu_\alpha\circ\phi^{-1}(S)\leq k(2\epsilon(\delta))^{\alpha-\gamma}\delta^{\alpha+2}$. Since $\epsilon(\delta)\to 0$ as $\delta\to 0$, $\mu_\alpha\circ\phi^{-1}$ is therefore a compact α-Carleson measure and the proof is complete. □

To state our main result we need

Theorem 6.3. *Suppose w has a zero angular limit at any point of $\partial\mathbf{D}$ at which ϕ has an angular derivative. If, in addition, for some $-1<\gamma<\alpha$, the measure $\eta_\gamma\circ\phi^{-1}$ is a γ-Carleson measure, where $d\eta_\gamma=|w|^{2-\alpha+\gamma}|\phi^{'}|^2 d\lambda_\gamma$, then $\nu_\alpha\circ\phi^{-1}$ is a compact α-Carleson measure ($d\nu_\alpha=|w|^2|\phi^{'}|^2 d\lambda_\alpha$).*

Proof. For $0<\delta<2$ define

$$\rho(\delta)=\sup\Big\{\frac{(1-|z|^2)|w(z)|}{1-|\phi(z)|^2}:1-|z|\leq\delta\Big\}.$$

By the argument of the proof of Theorem 6.2 $\lim_{\delta\to 0}\rho(\delta)=0$. Also, we have $|w(z)|(1-|z|^2)\leq(1-|\phi(z)|^2)\rho(\delta)\leq 2\delta\rho(\delta)$, whenever $\phi(z)\in S(\zeta,\delta)$. Thus

$$\nu_\alpha\circ\phi^{-1}(S)=\int\limits_{\phi^{-1}(S)}|w|^2|\phi^{'}(z)|^2(1-|z|^2)^\alpha d\lambda(z)\leq$$

$$\leq(2\delta\rho(\delta))^{\alpha-\gamma}\int\limits_{\phi^{-1}(S)}|w|^{2-\alpha+\gamma}|\phi^{'}(z)|^2(1-|z|^2)^\gamma d\lambda(z)=(2\rho(\delta))^{\alpha-\gamma}\eta_\gamma\circ\phi^{-1}(S).$$

Now we use the hypothesis that $\eta_\gamma\circ\phi^{-1}$ is a γ-Carleson measure; so there exists a constant k independent of ζ and δ such that $\eta_\gamma\circ\phi^{-1}(S)\leq k\delta^{\gamma+2}$.

Thus $\nu_\alpha \circ \phi^{-1}(S) \le k(2\rho(\delta)^{\alpha-\gamma})\delta^{\alpha+2}$. Since $\rho(\delta) \to 0$ as $\delta \to 0$, $\nu_\alpha \circ \phi^{-1}$ is therefore a compact α-Carleson measure, and the proof is complete. $\square$

Now we state the main theorem.

Theorem 6.4. *Let $w' \in H^\infty$ and $\phi \in D_\alpha$. Assume w and w' have a zero angular limit at any point of $\partial\mathbf{D}$ at which ϕ has an angular derivative. If, in addition, for some $-1 < \gamma < \alpha$ the measure $\eta_\gamma \circ \phi^{-1}$ is a γ-Carleson measure, then wC_ϕ is compact on D_α. Here $d\eta_\gamma = |w|^{2-\alpha+\gamma}|\phi'|^2 d\lambda_\gamma$.*

Proof. By Theorems 6.2 and 6.3, the measures $\mu_\alpha \circ \phi^{-1}$ and $\nu_\alpha \circ \phi^{-1}$ are compact α-Carleson measures. Thus Theorem 6.1 shows that wC_ϕ is compact on D_α. $\square$

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