Regularity of the Bergman Projection on Variants of the Hartogs Triangle

Liwei Chen
Washington University in St. Louis

Follow this and additional works at: https://openscholarship.wustl.edu/art_sci_etds

Part of the Mathematics Commons

Recommended Citation
https://openscholarship.wustl.edu/art_sci_etds/461

This Dissertation is brought to you for free and open access by the Arts & Sciences at Washington University Open Scholarship. It has been accepted for inclusion in Arts & Sciences Electronic Theses and Dissertations by an authorized administrator of Washington University Open Scholarship. For more information, please contact digital@wumail.wustl.edu.
Regularity of the Bergman Projection on Variants of the Hartogs Triangle

by

Liwei Chen

A dissertation presented to the
Graduate School of Arts & Sciences
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

May 2015
St. Louis, Missouri
# Table of Contents

Acknowledgments ................................................. iv  

ABSTRACT OF THE DISSERTATION ............................. vi  

1 Introduction ....................................................... 1  
   1.1 Setup and Background History .............................. 1  
   1.2 Problems and Results ........................................ 3  
   1.3 Outline and Organization .................................... 13  
   1.4 Future Directions ........................................... 15  
      1.4.1 The two-weight inequality ................................ 15  
      1.4.2 Non-smooth domains ....................................... 15  
      1.4.3 Smooth domains ............................................ 16  
      1.4.4 Biholomorphic mappings .................................. 16  

2 The Notion of Inflation ......................................... 18  
   2.1 Preliminaries and Basic Definitions ....................... 18  
   2.2 The Inflation Theorem ........................................ 19  

3 The $L^p$ Regularity ............................................. 24  
   3.1 The Punctured Disk .......................................... 24  
   3.2 The Hartogs Triangle ......................................... 34  
   3.3 The $n$-dimensional Hartogs Triangle ....................... 35  

4 The Two-weight Inequality ...................................... 39  
   4.1 Preliminaries and Basic Definitions ....................... 39  
   4.2 The Properties of the Operator $E$ ......................... 41  
   4.3 Analysis on Variants of $A_p$ Class ....................... 44  
   4.4 Proof of Theorem 6. .......................................... 48  

5 A Wider Class of Weights ........................................ 53  
   5.1 Alternative Proof of Theorem 2 and Its Extension .......... 53  
   5.2 A Two-weight Estimate on the Hartogs Triangle ............ 61  

6 More Analysis on the $A_p^+(\mathbb{R}^2)$ Class ................ 63  
   6.1 Preliminaries and Basic Definitions ....................... 63  
   6.2 Properties of the Special Maximal Function Operator ........ 65  

7 Twisted-Weighted Projections .................................. 74
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Preliminaries and Basic Definitions</td>
<td>74</td>
</tr>
<tr>
<td>7.2</td>
<td>The $L^p$ Regularity</td>
<td>76</td>
</tr>
<tr>
<td>8</td>
<td>The $L^p$ Sobolev Regularity</td>
<td>79</td>
</tr>
<tr>
<td>8.1</td>
<td>Preliminaries and Basic Definitions</td>
<td>79</td>
</tr>
<tr>
<td>8.2</td>
<td>Transfer to the Product Model</td>
<td>81</td>
</tr>
<tr>
<td>8.3</td>
<td>Convert the Differential Operators on $\mathbb{D}^*$</td>
<td>83</td>
</tr>
<tr>
<td>8.4</td>
<td>Proof of Theorem 13</td>
<td>86</td>
</tr>
<tr>
<td>8.5</td>
<td>Generalization to $n$-dimensional Hartogs Triangle</td>
<td>91</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>94</td>
</tr>
</tbody>
</table>
Acknowledgments

I would like to express my sincerest gratitude and appreciation to my thesis advisor, Professor Steven G. Krantz, whose guidance taught me how to become a mathematician. I am also greatly thankful to his constant encouragement, support and enlightening discussions on my research for all these years in Washington University in St. Louis.

I would like to give my greatest thanks to Professor Quo-Shin Chi, Professor Renato Feres, and Professor Xiang Tang for their guidance on my graduate studies.

I would like to thank Professor Carl M. Bender from the Physics Department for being part of my dissertation committee.

I would like to thank Professor Emil Straube from Texas A&M University for very helpful comments and suggestions on my thesis work.

I would like to thank Professor Shiu-chun Wong from Zhejiang University for his guidance on my early stage mathematics studies.

I am grateful to my parents and my friends for always being with me.

Last but not least, my thanks to Yiwenn for her endless love and support, especially on my toughest days.
Dedicated to My Family.
ABSTRACT OF THE DISSERTATION

Regularity of the Bergman Projection on Variants of the Hartogs Triangle

by

Liwei Chen

Doctor of Philosophy in Mathematics,
Washington University in St. Louis, 2015.
Professor Steven G. Krantz, Chair

The Bergman projection is the orthogonal projection from the space of square integrable functions onto the space of square integrable holomorphic functions on a domain. Initially, the projection is defined on the $L^2$ space, but its behavior on other function spaces, e.g. $L^p$, Sobolev and Hölder spaces, is of considerable interest.

In this dissertation, we focus on the Hartogs triangle which is a classical source of counterexamples in several complex variables, and generalize it to higher dimensions. We investigate the $L^p$ mapping properties of the weighted Bergman projections on these Hartogs domains. As applications, we obtain the $L^p$ regularity of the twisted-weighted Bergman projections and the weighted $L^p$ Sobolev regularity of the ordinary Bergman projection on the corresponding domains.
1. Introduction

1.1 Setup and Background History

The Bergman theory has been a seminal part of geometric analysis and partial differential equations since its invention by Stefan Bergman in 1922. It is based on a very simple idea: suppose $\Omega$ is a domain in $\mathbb{C}^n$; the set of square integrable holomorphic functions on $\Omega$, denoted by $A^2(\Omega)$, forms a closed subspace of the Hilbert space $L^2(\Omega)$. The Bergman projection associated to $\Omega$, is the orthogonal projection

$$B : L^2(\Omega) \to A^2(\Omega),$$

which has an integral representation

$$B(f)(z) = \int_{\Omega} B(z, \zeta)f(\zeta) \, dV(\zeta),$$

for all $f \in L^2(\Omega)$ and $z \in \Omega$. Here the function $B(z, \zeta)$ defined on $\Omega \times \Omega$ is the Bergman kernel.

Different types of regularity of the Bergman projection are of particular interest. When $\Omega$ is bounded, smooth, and strongly pseudoconvex (or weakly pseudoconvex with additional regularity properties on the boundary, e.g. finite type, property (P), and etc.), the regularity of $B$ in $W^k(\Omega)$ and hence in $C^\infty(\bar{\Omega})$ have been intensively studied through the literature.\(^1\) See, for example, [Str10] and references therein for details.

\(^1\)Here the Sobolev space $W^k(\Omega) = L^2_k(\Omega)$, and for the definition of $L^p_k(\Omega)$, see Chapter 8.
As well as the regularity in $W^k(\Omega)$, the regularity of $B$ in $L^p_k(\Omega)$ and the Hölder estimates also have been considerably studied for many years. We mention some important results here. In [PS77], Phong and Stein dealt with bounded smooth strongly pseudoconvex domains by applying the estimates of the Bergman kernel in [Fef74]. In [NRSW89], [MS94] and [CD06], the corresponding authors studied smoothly bounded pseudoconvex domains of finite type under additional assumptions. In [KR14], Khanh and Raich considered smoothly bounded pseudoconvex domains satisfying $f$-property, hence obtained the regularity for the finite type case and a class of domains of infinite type.

There are also results for irregularity of $B$ in $L^p_k(\Omega)$ when the underlying domains are smooth and bounded, see [Bar84, Bar92, Chr96, BS12], and regularity in $L^p(\Omega)$ when the underlying domains are only assumed to be $C^2$ smooth and bounded, see [LS12]. From these, we see besides the smoothness and boundedness of the underlying domain, we need additional regular assumption on the boundary.

When dealing with non-smooth domains, in [KP07] and [KP08], Krantz and Peloso show that the Bergman projection for the two dimensional non-smooth worm domain is bounded only when $p$ is in a range depending on the winding of the domain. Even in a planar domain, we cannot expect that the $L^p$ regularity holds for all $p \in (1, \infty)$, and the $A^+_p$ class in some sense interprets the regularity condition on the boundary, see [LS04], [Zey13], and Chapter 4 for details.\(^2\)

\(^2\)For the definition of $A^+_p$, see Chapter 4.
1.2 Problems and Results

In this dissertation, we study a class of bounded Hartogs domains which are variants of the Hartogs triangle\(^3\)

\[
\mathcal{H} = \{ (z_1, z_2) \in \mathbb{C}^2 : |z_1| < |z_2| < 1 \}.
\]

To be precise, for \( j = 1, \ldots, l \), let \( \Omega_j \) be a smooth bounded domain in \( \mathbb{C}^{m_j} \) with a biholomorphic mapping \( \phi_j : \Omega_j \to \mathbb{B}^{m_j} \) between \( \Omega_j \) and the unit ball \( \mathbb{B}^{m_j} \) in \( \mathbb{C}^{m_j} \). We use the notation \( \tilde{z}_j \) to denote the \( j \)th \( m_j \)-tuple in \( z' \in \mathbb{C}^{m_1 + \cdots + m_l} \), that is \( z' = (\tilde{z}_1, \ldots, \tilde{z}_l) \).

Let \( m = m_1 + \cdots + m_l \geq 1 \), \( d = n - m \geq 1 \), and \( z = (z', z'') \) where \( z'' \in \mathbb{C}^d \), we define the \( n \)-dimensional Hartogs triangle by

\[\mathbb{H}_n^{\phi_j} = \{ z \in \mathbb{C}^n : \max_{1 \leq j \leq l} |\phi_j(\tilde{z}_j)| < |z''_1| < |z''_2| < \cdots < |z''_d| < 1 \}. \quad (1.1)\]

When \( m = 1 \), \( n = 2 \), and \( \phi_1 \) is the identity map, we obtain the classical Hartogs triangle.

**Example 1** For nontrivial examples, we can take \( \phi_j \) to be nonsingular linear mappings.

When \( n = 4 \), \( l = 2 \), \( m_1 = 1 \), \( m_2 = 2 \), \( \phi_1(z_1) = 2z_1 - 1 \), and \( \phi_2(z_2, z_3) = (z_2 + \frac{1}{2}z_3, z_3) \), we obtain a bounded domain which is the intersection of two unbounded domains,

\[
\left\{ z \in \mathbb{C}^4 : \left| 2z_1 - 1 \right|^2 < |z_4|^2 < 1, \left| z_2 + \frac{1}{2}z_3 \right|^2 + |z_3|^2 < |z_4|^2 < 1 \right\}.
\]

We can also take \( \phi_j \) to be nonlinear; then we may obtain other types of domains.

When \( n = 3 \), \( l = 1 \), \( m_1 = 2 \), and \( \phi_1(z_1, z_2) = \left( \frac{z_1}{z_2 - 10}, 3z_2 + 1 \right) \), the domain becomes

\[
\left\{ z \in \mathbb{C}^3 : \left| \frac{z_1}{z_2 - 10} \right|^2 + |3z_2 + 1|^2 < |z_3|^2 < 1 \right\}.
\]

By this consideration, the domains \( \mathbb{H}_n^{\phi_j} \) can be a large class of bounded Hartogs domains.

\[^{3}\text{It should be mentioned that, there are several people who recently care about the regularity of the Bergman projection on the Hartogs triangle, see [CS13] and [CZ14] for related results.}\]
It is well known that the topological closure of $\mathbb{H}$ does not possess a Stein neighborhood basis, and the solution to the $\bar{\partial}$-equation on $\mathbb{H}$ is not globally regular. We cannot expect the $L^p$ regularity of Bergman projection on these variants of the Hartogs triangle to behave very well. A first question is the following.

**Question 1** *Determine the exact range for $p$, so that the Bergman projection on $\mathbb{H}_\phi^n$, is $L^p$ bounded.*

To answer this question, we have the following theorem.

**Theorem 1** *The Bergman projection $B_{\mathbb{H}_\phi^n}$ on $\mathbb{H}_\phi^n$ is bounded on $L^p(\mathbb{H}_\phi^n)$ if and only if $p$ is in the range $(\frac{2n}{n+1}, \frac{2n}{n-1})$.*

It is quite interesting that the boundedness range for $p$ does not depend on $m$ and $\{\phi_j\}$, but only on the dimension $n$. For the classical Hartogs triangle, taking $n = 2$, we see the Bergman projection on the Hartogs triangle is $L^p$ bounded if and only if $p \in (\frac{4}{3}, 4)$. Then we may ask the following natural question.

**Question 2** *When we look at some weighted space of the $(n$-dimensional) Hartogs triangle, can we obtain the $L^p$ regularity of the weighted Bergman projection for a larger range of $p$?*

The answer is affirmative. Note that, for the classical Hartogs triangle, the boundary at $(0, 0)$ is not even Lipschitz, and this singularity may blow things up. A natural way to control boundary behavior of the singularity is the use of weights which measure the distance from the points near the boundary to the singularity at the boundary. Since on the Hartogs triangle we have $|z_2| < |z| < \sqrt{2}|z_2|$ where $z = (z_1, z_2) \in \mathbb{H}$, it is reasonable to consider a weight of the form $|z_2|^{s'}$, for some $s' \in \mathbb{R}$.\footnote{See Chapter 2 for detailed definitions of weighted space and the weighted Bergman projection.}
Before stating the results, we first consider the punctured disk $D^* = \mathbb{D} \setminus \{0\}$, with weight $\mu(z) = |z|^{s'}$, where $z \in \mathbb{D}^*$ and $s' \in \mathbb{R}$.

**Theorem 2** For $s' \in \mathbb{R}$ with the unique expression $s' = s + 2k$, where $k \in \mathbb{Z}$ and $s \in (0, 2]$, let $\mathcal{B}_{s'}$ be the weighted Bergman projection on the space $(\mathbb{D}^*, \mu)$, where $\mu(z) = |z|^{s'}$.

(a) For $s' \in (0, \infty)$, $\mathcal{B}_{s'}$ is $L^p(\mu)$ bounded if and only if $p \in \left(\frac{s+2k+4}{s+k+2}, \frac{s+2k+4}{s+k+1}\right)$.

(b) For $s' \in [-3, 0]$, $\mathcal{B}_{s'}$ is $L^p(\mu)$ bounded for $p \in (1, \infty)$.

(c) For $s' \in (-4, -3)$, with $k = -2$ and $s \in (0, 1)$, $\mathcal{B}_{s'}$ is $L^p(\mu)$ bounded if and only if $p \in (2 - s, \frac{2-s}{1-s})$.

(d) When $s' = -4$, $\mathcal{B}_{-4}$ is $L^p(\mu)$ bounded for $p \in (1, \infty)$.

(e) For $s' \in (-\infty, -4)$, $\mathcal{B}_{s'}$ is $L^p(\mu)$ bounded if and only if $p \in \left(\frac{s+2k+4}{s+k+2}, \frac{s+2k+4}{s+k+1}\right)$.

By the notion of inflation,\(^5\) one obtains the following result which improves the classical case in Theorem 1.

**Theorem 3** For $s' \in [0, \infty)$ with the unique expression $s' = s + 2k$, where $k \in \mathbb{Z}$ and $s \in (0, 2]$, let $\lambda(z) = |z|^s$, where $z \in \mathbb{H}$. The weighted Bergman projection $\mathcal{B}_\lambda$ on the weighted space $(\mathbb{H}, \lambda)$ is $L^p(\mathbb{H}, \lambda)$ bounded if and only if $p \in \left(\frac{s+2k+4}{s+k+2}, \frac{s+2k+4}{s+k+1}\right)$.

If we allow the weight $\lambda$ on $\mathbb{H}$ to be unbounded, then we can obtain another result.

**Theorem 4** Given any $p_0 \in [1, 2)$ with its conjugate exponent $p_0'$, let $\lambda(z) = |z|^{-\left(p_0+4\right)}$, where $z \in \mathbb{H}$. Then the weighted Bergman projection $\mathcal{B}_\lambda$ on the weighted space $(\mathbb{H}, \lambda)$ is $L^p(\mathbb{H}, \lambda)$ bounded if and only if $p \in (p_0, p_0')$.

\(^5\)See Chapter 2 for details.
We can apply the same technique several times to obtain the result of the \( n \)-dimensional Hartogs triangle, which give a full answer to the second question.

**Theorem 5** Using the notation as in (1.1), let \( \lambda(z) = |z'|^{s_1} \cdots |z'|^{s_d} \), where \( z \in \mathbb{H}^n_{\phi_j} \) and \( s_1, \ldots, s_d \in \mathbb{R} \). Let \( B_{2m} \) be as in Theorem 2. Then the weighted Bergman projection on \( (\mathbb{H}^n_{\phi_j}, \lambda) \) is \( L^p(\lambda) \) bounded if and only if each of the following projections

\[
B_{2m+s_1}, \ B_{2m+s_1+s_2+2}, \ \cdots, \ B_{2m+s_1+\cdots+s_d+2(d-1)}
\]

is \( L^p \) bounded on the corresponding weighted space.

In other words, assume that \( p > 1 \) and for \( j = 1, 2, \ldots, d \) we let \( I_j \) be one of the intervals for \( p \) in Theorem 2, so that the \( j \)th projection above is \( L^p \) bounded if and only if \( p \in I_j \). Then the weighted Bergman projection on \( (\mathbb{H}^n_{\phi_j}, \lambda) \) is \( L^p(\lambda) \) bounded if and only if \( p \in \cap I_j \).

After considering some particular weights on the underlying domains, one may ask another natural question.

**Question 3** Can we obtain the \( L^p \) regularity of the weighted Bergman projection on the Hartogs triangle for a wider class of weights rather than some power of the norm of the variable?

The answer is partly affirmative. Follow Zeytuncu’s idea in [Zey13], and using the singular integral approach due to Lanzani and Stein in [LS04], we can consider the weighted space \( (\mathbb{D}^*, \mu) \), where \( \mu(z) = |z'|^{s'} |g(z)|^2 \), \( s' \in \mathbb{R} \), and \( g \) is a non-vanishing holomorphic function on the unit disk. Note that, by applying a Möbius transform, the isolated pole or zero indeed can be any point in the unit disk.
The key observation is that the weighted Bergman kernel $B_s'(z, \zeta)$ associated to $(\mathbb{D}^*, |z|^{s'})$, can be expressed as a "homotopy" between two weighted Bergman kernels

$$B_s'(z, \zeta) = \frac{s}{2} B_{2k+2}(z, \zeta) + \left( 1 - \frac{s}{2} \right) B_{2k}(z, \zeta)$$

for $(z, \zeta) \in \mathbb{D}^* \times \mathbb{D}^*$, where $s' = s + 2k$, $k \in \mathbb{Z}$ and $s \in (0, 2]$. Then, after applying the Cayley transform $\varphi : \mathbb{R}^2_+ \to \mathbb{D}$, where $\varphi(z) = \frac{i - z}{1 + z}$, one arrives at different types of the following two-weight inequality on the upper half plane

$$\int_{\mathbb{R}^2_+} |B_{\mathbb{R}^2_+}(f)(z)|^p \mu_1(z) dV(z) \leq C \int_{\mathbb{R}^2_+} |f(z)|^p \mu_2(z) dV(z),$$

(1.2)

where $\mu_1$ and $\mu_2$ are two weights on $\mathbb{R}^2_+$ and

$$B_{\mathbb{R}^2_+}(f)(z) = \frac{1}{\pi} \int_{\mathbb{R}^2_+} \frac{f(w) dV(w)}{(z - w)^2}$$

is the Bergman projection on the upper half plane.6

This observation leads to an extremely interesting and elegant theory in harmonic analysis. Note that the operator $B_{\mathbb{R}^2_+}$ has a similar expression as the so-called Hilbert integral

$$\mathcal{H}(f)(x) = \int_0^\infty \frac{f(y) dy}{x + y},$$

where $x > 0$, see [PS86a, PS86b] for further details. Both $B_{\mathbb{R}^2_+}$ and $\mathcal{H}$, although not singular at the diagonal line, have a very close relation with the general Calderón-Zygmund singular integrals, see [LS04]. In potential theory and classical harmonic analysis, it is of particular interest to obtain a weighted $L^p$ estimate of a singular integral for some weight on the underlying domain. In the 1970s, Muckenhoupt introduced the $A_p$ class to show

---

6We should point out that, initially the underlying domain is $\mathbb{R}^2_+ \setminus \{i\}$. However, once we extend the corresponding weights on $\mathbb{R}^2_+ \setminus \{i\}$ to $\mathbb{R}^2_+$, then the validity of (1.2) over $\mathbb{R}^2_+ \setminus \{i\}$ and $\mathbb{R}^2_+$ are equivalent. See arguments in Chapter 5.
that a necessary and sufficient condition for a general singular integral being weighted $L^p$ bounded is the weight satisfying the $A_p$ condition.\footnote{See Chapter 4 for detailed definitions of variants of $A_p$ condition.}

In view of the one-weight case in [LS04], we have the following conjecture.

**Conjecture 1** For $p > 1$, if the two weights $\mu_1$ and $\mu_2$ satisfy $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^+_2)$, then (1.2) holds for some $C > 0$.

By considering the results in [Neu83], the "power-bump" condition is also of interest.

**Conjecture 2** For $p > 1$, if the two weights $\mu_1$ and $\mu_2$ satisfy $(\mu_1^r, \mu_2^r) \in A^+_p(\mathbb{R}^+_2)$ for some $r > 1$, then (1.2) holds for some $C > 0$.

Although the validity of Conjecture 1 and Conjecture 2 will make the whole theory neater and more elegant, we have the following partial result which is sufficient for our application.

**Theorem 6** For $p > 1$, suppose that $\mu_1$ and $\mu_2$ are two weights such that $c\mu_1 \geq \mu_2$ for some $c > 0$. Then (1.2) holds for some $C > 0$ if and only if $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^+_2)$.

By using different weights in (1.2) and applying Theorem 6, we extend Theorem 2 to a wider class of weights.

**Theorem 7** Assume that $p > 1$. Let $\mu(z) = |z|^{s'}|g(z)|^2$, where $g$ is a non-vanishing holomorphic function on $\mathbb{D}$ and $s' \in \mathbb{R}$. Suppose the weighted Bergman projection $\mathcal{B}_{|g|^2}$ on $(\mathbb{D}, |g|^2)$ is $L^p(|g|^2)$ bounded, and suppose the weighted Bergman projection $\mathcal{B}_{s'}$ on $(\mathbb{D}^*, |z|^{s'})$ is $L^p(|z|^{s'})$ bounded. Then the weighted Bergman projection $\mathcal{B}_{\mu}$ on $(\mathbb{D}^*, \mu)$ is $L^p(\mu)$ bounded.
Moreover, suppose $B_{|g|^2}$ is $L^p(|g|^2)$ bounded if and only if $p \in (p_0, p_0')$ for some $p_0 \geq 1$ and suppose $B_{s'}$ is $L^p(|z|^{s'})$ bounded if and only if $p \in (p_1, p_1')$ for some $p_1 \geq 1$ as in Theorem 2. If $(p_1, p_1') \subset (p_0, p_0')$ properly, then $B_\mu$ is $L^p(\mu)$ bounded if and only if $p \in (p_1, p_1')$.

Example 2 As in [Zey13], if we take $g(z) = (z-1)^t$ for some $t > 0$, then we see $(p_0, p_0') = (\frac{2t+2}{t+2}, \frac{2t+2}{t})$. By Theorem 2, when $s' \in (0, \infty)$, we have $(p_1, p_1') = (\frac{s+2k+2}{s+k+1}, \frac{s+2k+2}{k+1})$. So $B_\mu$ is $L^p(\mu)$ bounded if $p \in (\frac{2t+2}{t+2}, \frac{2t+2}{t}) \cap (\frac{s+2k+2}{s+k+1}, \frac{s+2k+2}{k+1})$.

To answer the third question, for $z \in \mathbb{H}$ we take $\lambda(z) = |z_2|^{s'-2} |g(z_2)|^2$, where $g$ is any non-vanishing holomorphic function on $\mathbb{D}$, then we have the following result.

**Theorem 8** Assume that $p > 1$. Let $\lambda$ be as above, and let $p_0, p_1$ be as in Theorem 7. Then the weighted Bergman projection $B_\lambda$ on $(\mathbb{H}, \lambda)$ is $L^p(\lambda)$ bounded if $p \in (p_0, p_0') \cap (p_1, p_1')$. In addition, if $(p_1, p_1') \subset (p_0, p_0')$ properly, then $B_\lambda$ is $L^p(\lambda)$ bounded if and only if $p \in (p_1, p_1')$.

Again by inflation, we can apply the same technique several times to obtain a similar result for the $n$-dimensional Hartogs triangle. But we will skip this part here, since there are no new ideas.

In (1.2), we deal with two weights. Then one may ask whether we can do the same thing for the Bergman projection on the Hartogs triangle.

**Question 4** Can we also obtain the $L^p$ regularity of the (weighted) Bergman projection mapping from one (weighted) space to the other?

The answer is, of course, yes. We can consider the $L^p$ regularity of the weighted Bergman projection $B_{|z_2|^{s'}}$ on $(\mathbb{H}, |z_2|^{s'})$ mapping from $L^p(\mathbb{H}, |z_2|^{s'})$ to $L^p(\mathbb{H}, |z_2|^{t})$ for some $t \in \mathbb{R}$. For simplicity, we focus on the case $s' = 2k + 2 \geq 0$, for $k \in \mathbb{Z}$. 
Theorem 9 Suppose that $B_{\mathbb{H},2k+2}$ is the weighted Bergman projection on the weighted space $(\mathbb{H}, |z_2|^{2k+2})$. Assume $p > 1$ and $k \geq -1$. Then, for $t \leq 2k + 2$, $B_{\mathbb{H},2k+2}$ is $L^p$ bounded from $L^p(\mathbb{H}, |z_2|^{2k+2})$ to $L^p(\mathbb{H}, |z_2|^t)$ if and only if $p \in \left(\frac{2k+6}{k+4}, \frac{t+4}{k+2}\right)$. For $t > 2k + 2$, $B_{\mathbb{H},2k+2}$ is bounded from $L^p(\mathbb{H}, |z_2|^{2k+2})$ to $L^p(\mathbb{H}, |z_2|^t)$ if $p \in \left(\frac{2k+6}{k+4}, \frac{2k+6}{k+2}\right) \cup \left(\frac{t+4}{k+4}, \frac{t+4}{k+2}\right)$.

When applying the two-weight inequality (1.2), we can also consider a wider class of weights $|z_2|^{s'} |g(z_2)|^2$ rather than $|z_2|^{s''}$, where $z = (z_1, z_2) \in \mathbb{H}$ and $g$ is a non-vanishing holomorphic function on $\mathbb{D}$. Indeed, if we restrict ourselves to the weighted Bergman projection $B_{\mathbb{H},s'}$ on $(\mathbb{H}, |z_2|^{s''})$, we can consider the $L^p$ regularity of the $B_{\mathbb{H},s'}$ mapping from $L^p(\mathbb{H}, |z_2|^{s''})$ to $L^p(\mathbb{H}, \mu)$ for a more general weight $\mu$ satisfying the corresponding $A^+_p$ conditions. On the other hand, one may also consider a weight of the form $\mu(z) = |z_1|^{s''} |z_2|^{s'}$. In this case, we have to consider once more the weighted space $(\mathbb{D}, |z|^{s''})$. The statements of these variants are almost the same, and the arguments involve no new ideas, so we will skip them.

As we have already seen, the two-weight inequality (1.2) has many interesting applications. In order to prove Conjecture 1 and Conjecture 2, we need a better understanding of the $A^+_p$ class. Based on the results in [Muc72, Neu83] and [Ste93, Chapter 5], we may ask the following question.

Question 5 Since the classical $A_p$ condition is closely related to the maximal function theory, can we formulate and prove some analogues for the $A^+_p$ class?

The answer is partly affirmative, and it seems to provide a promising yet technical approach to attack Conjecture 1 and Conjecture 2. Let $\tilde{M}^+$ denote the special maximal function operator. We have the following results.

---

8See Chapter 6 for detailed definitions of the special maximal function operator.
Theorem 10  Let \( f \) be a measurable function on \( \mathbb{R}_+^2 \). Then, for any \( 0 < q < 1 \), the function \( \left( \widetilde{M}^+(f) \right)^q \) is in \( A_1^+(\mathbb{R}_+^2) \).

Theorem 11  Assume that \( p \geq 1 \). Suppose \( \mu_1 \) and \( \mu_2 \) are two weights on \( \mathbb{R}_+^2 \). Then we have a weak-type \((p, p)\) inequality: namely, there is a constant \( c > 0 \) so that

\[
\mu_1 \left( \left\{ z \in \mathbb{R}_+^2 : \widetilde{M}^+(f)(z) > \alpha \right\} \right) \leq \frac{c}{\alpha^p} \int_{\mathbb{R}_+^2} |f(z)|^p \mu_2(z) \, dV(z)
\]  

for all \( \alpha > 0 \), if and only if \( (\mu_1, \mu_2) \in A_p^+(\mathbb{R}_+^2) \).

Consider the following operator

\[
\widetilde{B}_{\mathbb{R}_+^2}(f)(z) = \frac{1}{\pi} \int_{\mathbb{R}_+^2} \frac{f(w) \, dV(w)}{|z - w|^2},
\]

which is the "absolute value" of the Bergman projection on the upper half plane. It is easy to see, for \( f \geq 0 \) and \( z, z' \in \mathbb{R}_+^2 \), that

\[
\widetilde{B}_{\mathbb{R}_+^2}(f)(z') \geq \widetilde{B}_{\mathbb{R}_+^2}(f)(z),
\]

whenever \( \Re(z') = \Re(z) \) and \( \Im(z') \leq \Im(z) \). Note that the special maximal function operator \( \widetilde{M}^+ \) also enjoys the same property above as \( \widetilde{B}_{\mathbb{R}_+^2} \). In view of this, we hope Theorem 10 and Theorem 11 could provide some clues to prove Conjecture 1 and Conjecture 2.

In [McN12], McNeal introduced a family of twist-weight factors \((\tau, \mu)\) to generalize Bell’s idea about Condition R, see [Bel81, McN12] for further details. Following this idea, we can consider the twisted-weighted Bergman projection and investigate its \( L^p \) regularity.\(^9\)

**Question 6** Can we obtain the \( L^p \) regularity of the twisted-weighted Bergman projection as we did for the weighted Bergman projection?\(^{10}\)

\(^9\)See Chapter 6 for details.

\(^{10}\)See Chapter 7 for a detailed definition of the twisted-weighted Bergman projection. See also [McN12].
The answer is partly affirmative. Under some restriction on the twist-weight factors, namely, assuming the holomorphicity of the ratio between the twist-weight factors, the $L^p$ regularity of the twisted-weighted Bergman projection can be derived from the $L^p$ regularity of a corresponding weighted Bergman projection. In particular, if we focus on planar domains, by applying Theorem 6, we have the following result.

**Theorem 12** Let $\Omega$ be a proper simply connected domain in $\mathbb{C}$, and let $\phi : \mathbb{R}^2_+ \to \Omega$ be a biholomorphism. For a weight $\mu \in C^1(\Omega)$ and for any non-vanishing $g \in \mathcal{O}(\Omega)$, define $\tau = \mu^{\frac{1}{2}} / |g|$. Then the twisted-weighted Bergman projection $B_{\tau, \mu}$ is $L^p(\Omega, \mu)$ bounded if and only if $\mu(\phi(z))^{1-\frac{p}{2}} |\phi'(z)|^{2-p} \in A^+_p(\mathbb{R}^2_+)$. 

We point out that, for a different function $g$, we have a different twist factor $\tau$, hence different coset $\mathcal{O}_\tau$. However, it is interesting to see that the $L^p$ regularities of these different non-holomorphic projections are the same, and they depend only on the weight factor $\mu$.

Again, we can apply the idea of inflation to formulate and prove similar results of twisted-weighted Bergman projections on the $(n$-dimensional) Hartogs triangle, and we will skip these for the same reason as before.

As the last application, we consider the $L^p$ Sobolev regularity of the Bergman projection on the Hartogs triangle $\mathbb{H}$. We have already mentioned that the topological closure of $\mathbb{H}$ does not possess a Stein neighborhood basis, the solution to the $\overline{\partial}$-equation on $\mathbb{H}$ is not globally regular, and the boundary at $(0, 0)$ is not even Lipschitz. So we cannot expect to obtain the regularity in the ordinary $L^p$ Sobolev spaces, nor for all $p \in (1, \infty)$. In view of the result in [CS13] and the previous results of the weighted Bergman projections, we may ask the following question.

---

11See Chapter 7 for definition of $\mathcal{O}_\tau$. 

---
**Question 7** Can we obtain a weighted $L^p$ Sobolev regularity of the Bergman projection on the Hartogs triangle, where the weight measures the distance from points near the boundary to the singularity at the boundary?

The answer is affirmative. Recall that on the Hartogs triangle we have $|z_2| < |z| < \sqrt{2} |z_2|$, where $z = (z_1, z_2) \in \mathbb{H}$. Therefore, we can consider the weighted Sobolev space\(^{12}\) $L^p_k(\mathbb{H}, |z_2|^{pk})$, and prove the following theorem.

**Theorem 13** The Bergman projection $B_\mathbb{H}$ on the Hartogs triangle $\mathbb{H}$ maps continuously from $L^p_k(\mathbb{H})$ to $L^p_k(\mathbb{H}, |z_2|^{pk})$ for $p \in \left(\frac{4}{3}, 4\right)$.

If we let $p = 2$ and replace $k$ by $2k$, then Theorem 13 will imply the result in [CS13]. Note that, in our result, there is no loss of smoothness\(^{13}\) of $B_\mathbb{H}(f)$.

Moreover, the method here also applies to the $n$-dimensional Hartogs triangle. By adopting the notation in (1.1), we have the following generalization of Theorem 13.

**Theorem 14** The Bergman projection on the $n$-dimensional Hartogs triangle $\mathbb{H}^n_{\phi_j}$ maps continuously from $L^p_k(\mathbb{H}^n_{\phi_j})$ to $L^p_k(\mathbb{H}^n_{\phi_j}, |z_1''|^{pk})$ for $p \in \left(\frac{2n}{n+1}, \frac{2n}{n-1}\right)$.

We should point out that the idea of the proof remains the same, however, the weight $|z_1''|^{pk}$ is no longer comparable to $|z|^{pk}$, some power of the distance from points near the boundary to the singularity at the boundary.

### 1.3 Outline and Organization

The original proof of Theorem 1 follows from the idea in [CS13], where the Hartogs triangle is transferred to a product domain by a biholomorphism.\(^{14}\) However, by in-

---

12 See Chapter 8 for definition of weighted Sobolev spaces.

13 Compare with [CS13, Theorem 2.3]

14 See also Chapter 8.
Introducing the notion of inflation in Chapter 2, the arguments become neat and simple. Moreover, it can be applied to the weighted cases to prove Theorem 3, Theorem 4, and Theorem 5. So, in Chapter 3, we first prove Theorem 2 by Schur’s test, then we present the new proof of the weighted cases by using inflation arguments. As a consequence, we obtain Theorem 1 from Theorem 5.

The second part of this dissertation is to investigate the two-weight inequality (1.2) and extend the previous results to a wider class of weights. In Chapter 4, we introduce the $A^+_p$ class and follow the idea from [LS04] to prove Theorem 6. In Chapter 5, we apply the results in Chapter 4 to give an alternative proof of Theorem 2 and extend it to prove Theorem 7. By applying the inflation arguments, it is easy to see that Theorem 8 follows from Theorem 7, and Theorem 9 follows from Theorem 6.\footnote{Theorem 9 can also be proved by using a variant of Schur’s test.} To get a better understanding of the $A^+_p$ class, we introduce the special maximal function operator in Chapter 6 and prove Theorem 10 and Theorem 11 by following the ideas from the classical results in [Muc72] and [Ste93, Chapter 5].

In the last part of this dissertation, we present two applications of the previous theory. In Chapter 7, we study the $L^p$ regularity of twisted-weighted Bergman projections. In particular, by applying Theorem 6, we obtain an interesting result—Theorem 12. In Chapter 8, we study the $L^p$ Sobolev regularity of the ordinary Bergman projection on the $(n$-dimensional) Hartogs triangle. To prove Theorem 13, we start with the idea from [CS13] to transfer $\mathbb{H}$ to $\mathbb{D} \times \mathbb{D}^*$. We then use a result in [Str86] and integration by parts to convert the differential operators. Finally, we apply the weighted $L^p$ estimates (Theorem 2) to complete the proof. It is not difficult to see the same argument also applies to Theorem 14.
1.4 Future Directions

We conclude this chapter by mentioning several possible directions for future work.

1.4.1 The two-weight inequality

We have already seen many applications of the two-weight inequality (1.2), and we also have a partial result for the conjectures we mentioned in §1.2. It would be very interesting if we can prove Conjecture 1 and Conjecture 2 for general weights and give a full understanding of the $A_p^+$ class. Based on the special features of the special maximal function operator, we need to develop additional analysis on this operator, especially on the behavior of the operator along the boundary (i.e. the real line). Moreover, it is reasonable to extend this theory to higher dimension. We believe that, under some regularity condition on the boundary of a higher dimensional domain, the Bergman projection can still be expressed in a fashion similar to the integral in (1.2).

1.4.2 Non-smooth domains

We have already obtained some results on a class of Hartogs domains. However, there should be other variants of Hartogs triangle which are also of interest. It would be also interesting to study the regularity of Bergman projection on other types of non-smooth domains, especially in higher dimension. Up until now, there are relatively few results in this direction. As we mentioned previously, on the $n$-dimensional Hartogs triangle, $|z''|$ is not comparable to $|z|$ as long as $n > 2$. So other types of weighted $L^p$ Sobolev regularity of the Bergman projection are also of interest. It would be very nice if we can develop a
method to control the behavior of the singularity at the boundary by some function in $|z|$ in the higher-dimensional cases.

1.4.3 Smooth domains

There are lots of classical results about the regularity of Bergman projection on smooth domains as we mentioned in §1.1. However, the story is still far from reaching the end, since there are several big problems still being studied. For example, Kohn conjectures that for the Bergman projection on a smooth bounded pseudoconvex domain, the exact regularity is equivalent to the global regularity. When the boundary of a smoothly bounded pseudoconvex domain possesses a set of points of infinite type, we in general (except for some special cases) do not know the $L^p$ (or even $L^2$) Sobolev regularity of the Bergman projection. It would be also interesting to ask whether we can obtain the regularity of the Bergman projection by only assuming minimal smoothness of the boundary, for example, a bounded pseudoconvex domain satisfying property (P) with $C^2$ boundary. On the other hand, the worm domains provide a class of smooth bounded pseudoconvex domains that have irregular Bergman projections. It would be also interesting to summarize the geometric condition on the boundary of the worm domains to explain why the regularity fails.

1.4.4 Biholomorphic mappings

The Sobolev regularity of the Bergman projection also plays an important role in the mapping properties of biholomorphisms. Inspired by Fefferman’s famous work on the boundary behavior of biholomorphic mappings in [Fef74], Bell formulated his Condition R in terms of regularity properties of Bergman projection in [Bel81]. As we mentioned pre-
viously, in [McN12] McNeal introduced a family of twist-weight factors to generalize Bell’s idea. Now we have obtained the $L^p$ regularity of the twisted-weighted Bergman projection under a certain restriction on the twist-weight factor. It would be very interesting to explore this idea further in higher dimension, weaken the restriction on the twist-weight factors, and investigate the Sobolev regularity of the corresponding twisted-weighted Bergman projections. Therefore we can study the boundary behavior of biholomorphic mappings by using this new idea in [McN12].
2. The Notion of Inflation

2.1 Preliminaries and Basic Definitions

Let us temporarily consider the general setting for a moment, and suppose \( \Omega \) is a domain in \( \mathbb{C}^n \).

**Definition 2.1.1** A measurable function \( \mu \) on \( \Omega \) is a weight if it is locally integrable and positive almost everywhere.

As long as we have a weight \( \mu \), we can define the weighted \( L^p(\mu) \) norm for a measurable function \( f \) on \( \Omega \) by

\[
\|f\|_{L^p(\Omega, \mu)} = \left( \int_{\Omega} |f(z)|^p \mu(z) \, dV(z) \right)^{\frac{1}{p}},
\]

and the weighted \( L^p(\mu) \) space by \( \{ f \text{ measurable on } \Omega : \|f\|_{L^p(\Omega, \mu)} < \infty \} \), for \( p \geq 1 \).

Sometimes, we will use a different notation \( L^p(\Omega, \mu) \) to emphasize the underlying domain.

Supposing the set of all holomorphic function on \( \Omega \) is denoted by \( \mathcal{O}(\Omega) \), then we consider the analytic subspace of \( L^p(\mu) \) which is denoted by \( A^p_{\mu}(\Omega) = L^p(\mu) \cap \mathcal{O}(\Omega) \). We focus on \( p = 2 \) in this section, since the closedness of \( A^2_{\mu}(\Omega) \) in \( L^2(\mu) \) is of principal interest.

**Definition 2.1.2** A weight \( \mu \) is admissible on \( \Omega \), if for any compact subset \( K \) of \( \Omega \), there exists \( C_K > 0 \) such that

\[
\sup_{z \in K} |f(z)| \leq C_K \|f\|_{L^2(\Omega, \mu)}
\]
for all $f \in A^2_\mu(\Omega)$. For instance, if $\mu$ is continuous and non-vanishing, then it is admissible.

It is easy to see, if $\mu$ is admissible on $\Omega$, then $A^2_\mu(\Omega)$ is closed in $L^2(\mu)$.

**Definition 2.1.3** For an admissible weight $\mu$ on $\Omega$, we define the weighted Bergman projection $B_{\Omega_\mu}$ to be the orthogonal projection from $L^2(\mu)$ to $A^2_\mu(\Omega)$. The weighted Bergman projection is an integral operator

$$B_{\Omega_\mu}(f)(z) = \int_{\Omega} B_{\Omega_\mu}(z, \zeta) f(\zeta) \mu(\zeta) \, dV(\zeta),$$

where $B_{\Omega_\mu}(z, \zeta)$ is the weighted Bergman kernel with $(z, \zeta) \in \Omega \times \Omega$.

It is not hard to see that every basic property of the ordinary Bergman theory can be moved to the weighted setting.

**Definition 2.1.4** If $\mu$ is a non-vanishing weight on $\Omega$, we define the inflation $\tilde{\Omega}$ of $\Omega$ by

$$\tilde{\Omega} = \{(z, w) \in \mathbb{C}^{m+n} : |z|^2 < \mu(w), \ w \in \Omega\}.$$

**Note** that $\tilde{\Omega}$ is a Hartogs domain.

Suppose $\mu$ is a non-vanishing weight on $\Omega$, and suppose $\lambda > 0$ is a function on $\Omega$ such that it is admissible on $\tilde{\Omega}$. Then it is easy to see that $\mu^m \lambda$ is admissible on $\Omega$.

Throughout this dissertation, as long as we deal with the weighted Bergman theory, the weight is assumed to be admissible on the corresponding domain.

### 2.2 The Inflation Theorem

Before going further, we first give two useful lemmas and the corresponding corollaries.
Lemma 2.2.1 Let $F : X_1 \to X_2$ be an isometry between two Banach spaces $X_1$ and $X_2$. Then it induces an isometry $F^* : \mathfrak{B}(X_1) \to \mathfrak{B}(X_2)$ between the spaces of the bounded operators by $F^*(T) = F \circ T \circ F^{-1}$, for any $T \in \mathfrak{B}(X_1)$.

In particular, suppose that $X_j = H_j$ is a Hilbert space, $j = 1, 2$. Let $S$ be a closed subspace of $H_1$, and let $P : H_1 \to S$ be the orthogonal projection. Then $F$ induces an orthogonal decomposition $H_2 = F(S) \oplus F(S^\perp)$, that is, $F(S)$ is closed in $H_2$ and $F(S)^\perp = F(S^\perp)$. Hence, $F^*(P) : H_2 \to F(S)$ is the orthogonal projection.

Proof The first part of the lemma is straightforward, we only prove the second part. Since $S$ is closed in $H_1$, and since $F$ is an isometry, it is easy to see that $F(S)$ is closed in $H_2$.

To prove the equality $F(S)^\perp = F(S^\perp)$, we consider the following. For any $x \in F(S^\perp)$, we have $F^{-1}(x) \in S^\perp$, then $F^{-1}(x) \perp S$. Therefore $x \perp F(S)$, which implies $x \in F(S)^\perp$. This shows $F(S^\perp) \subset F(S)^\perp$. The other direction follows from the same argument in the reverse direction.

In the last statement, for any $x \in H_2$, we have a decomposition $x = y + z$, where $y \in F(S)$ and $z \in F(S^\perp)$. Then $F^{-1}(x) = F^{-1}(y) + F^{-1}(z)$, with $F^{-1}(y) \in S$ and $F^{-1}(z) \in S^\perp$. So $F^*(P)(x) = F(P(F^{-1}(x))) = F(F^{-1}(y)) = y$ is orthogonal. \hfill \rlap{\vrule width 4pt height 6pt depth 0pt}

Corollary 2.2.2 Let $\Phi : \Omega_1 \to \Omega_2$ be a biholomorphism between two domains in $\mathbb{C}^n$. Suppose $\Omega_j$ is equipped with the weight $\mu_j$, $j = 1, 2$, and $\mu_2 = \mu_1 \circ \Phi^{-1}$. Then we have the transformation formula for the weighted Bergman kernels

$$B_{\Omega_1, \mu_1}(z, \zeta) = \det J_C \Phi(z) B_{\Omega_2, \mu_2}(\Phi(z), \Phi(\zeta)) \det \overline{J_C \Phi(\zeta)},$$

where $(z, \zeta) \in \Omega_1 \times \Omega_1$. 


Proof Let \( F : L^2(\Omega_1, \mu_1) \to L^2(\Omega_2, \mu_2) \) be the isometry, by \( F(f) = \det J_C(\Phi^{-1})f \circ \Phi^{-1} \), for any \( f \in L^2(\Omega_1, \mu_1) \). Then, by Lemma 2.2.1, we have \( F^*(B_{\Omega_1, \mu_1}) = B_{\Omega_2, \mu_2} \). By the uniqueness of the weighted Bergman kernel, we obtain the transformation formula above.

Corollary 2.2.3 Let \( \Phi : \Omega_1 \to \Omega_2 \) be a biholomorphism between two domains in \( \mathbb{C}^n \). Suppose \( B_j \) is the weighted Bergman projection for \((\Omega_j, \mu_j)\), \( j = 1, 2 \), and \( \mu_2 = |\det J_C(\Phi^{-1})|^2 \mu_1 \circ \Phi^{-1} \). Then, for \( p \geq 1 \), \( B_1 \) is \( L^p(\mu_1) \)-bounded if and only if \( B_2 \) is \( L^p(\mu_2) \)-bounded.

Proof Let \( F : L^p(\Omega_1, \mu_1) \to L^p(\Omega_2, \mu_2) \) be the isometry given by \( F(f) = f \circ \Phi^{-1} \), for any \( f \in L^p(\Omega_1, \mu_1) \). In particular, when \( p = 2 \), we have \( F^*(B_1) = B_2 \). Since this \( F \) is an isometry for all \( p \geq 1 \), we see from the first part of Lemma 2.2.1 that \( B_1 \) is \( L^p \)-bounded if and only if \( B_2 \) is \( L^p \)-bounded.

Lemma 2.2.4 Suppose we have a weight \( \mu_1 > 0 \) on \( \Omega_1 \) and a weight \( \mu_2 > 0 \) on \( \Omega_2 \), both non-vanishing.\(^1\) Let \( \mathcal{T}_1 \) and \( \mathcal{T}_2 \) be the integral operators with kernels \( T_1(w_1, \eta_1) \) on \( \Omega_1 \times \Omega_1 \) and \( T_2(w_2, \eta_2) \) on \( \Omega_2 \times \Omega_2 \), respectively. That is,

\[
\mathcal{T}_1(f)(w_1) = \int_{\Omega_1} T_1(w_1, \eta_1)f(\eta_1)\mu_1(\eta_1)\,dV(\eta_1),
\]

\[
\mathcal{T}_2(g)(w_2) = \int_{\Omega_2} T_2(w_2, \eta_2)g(\eta_2)\mu_2(\eta_2)\,dV(\eta_2).
\]

Given any \( p \in [1, \infty) \), if \( \mathcal{T}_1 \) is bounded on \( L^p(\Omega_1, \mu_1) \) and \( \mathcal{T}_2 \) is bounded on \( L^p(\Omega_2, \mu_2) \), then their product operator \( \mathcal{T} = \mathcal{T}_1 \otimes \mathcal{T}_2 \) with kernel \( T_1 \otimes T_2 \), is bounded on \( L^p(\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2) \).

Conversely, assuming \( \mathcal{T}_1 \) and \( \mathcal{T}_2 \) both are non-trivial, if one of these two operator is unbounded, then \( \mathcal{T} \) is unbounded.

\(^1\)The weights can be assumed to be non-negative, i.e. \( \mu_1, \mu_2 \geq 0 \), if we adopt the convention \( 0 \cdot \infty = 0 \).
**Proof** By definition, we have

\[
T(f)(w_1, w_2) = \int_{\Omega_1 \times \Omega_2} T_1(w_1, \eta_1)T_2(w_2, \eta_2)f(\eta_1, \eta_2)\mu_1(\eta_1)\mu_2(\eta_2) \, dV(\eta_1, \eta_2)
\]

\[
= \int_{\Omega_1} T_1(w_1, \eta_1)f(\eta_1, \eta_2)\mu_1(\eta_1) \, dV(\eta_1) \int_{\Omega_2} T_2(w_2, \eta_2)\mu_2(\eta_2) \, dV(\eta_2)
\]

\[
= \int_{\Omega_2} T_{2,\eta_2}(f(\eta_1, \eta_2))(w_1)T_2(w_2, \eta_2)\mu_2(\eta_2) \, dV(\eta_2)
\]

where \(T_{1,\eta_1}\) and \(T_{2,\eta_2}\) are operators \(T_1\) and \(T_2\) acting on \(\eta_1\) and \(\eta_2\) respectively. If \(T_1\) and \(T_2\) are both bounded, then

\[
\|T(f)\|_{L^p(\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2)} = \int_{\Omega_1 \times \Omega_2} |T_{2,\eta_2}(T_{1,\eta_1}(f(\eta_1, \eta_2))(w_1))(w_2)|^p \mu_1(w_1)\mu_2(w_2) \, dV(w_1, w_2)
\]

\[
\leq c \int_{\Omega_2} |T_{1,\eta_1}(f(\eta_1, \eta_2))(w_1)|^p \mu_2(w_2) \, dV(w_2) \int_{\Omega_1} \mu_1(w_1) \, dV(w_1)
\]

\[
= \|f\|_{L^p(\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2)}^p
\]

Conversely, without loss of generality, if we assume \(T_1\) is unbounded, then there is a sequence \(\{f_n\} \subset L^p(\Omega_1, \mu_1)\) such that \(\|f_n\|_{L^p(\Omega_1, \mu_1)} \leq c < \infty\) for some \(c > 0\) and

\[
\|T_1(f_n)\|_{L^p(\Omega_1, \mu_1)} \to \infty\ as\ n \to \infty.
\]

Since \(T_2\) is non-trivial, there is a function \(g \in L^p(\Omega_2, \mu_2)\) such that \(g \neq 0\) and \(T_2(g) \neq 0\). If we consider the sequence \(\{g \otimes f_n\}\), we have

\[
\|g \otimes f_n\|_{L^p(\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2)} = \int_{\Omega_1 \times \Omega_2} |f_n(w_1)g(w_2)|^p \mu_1(w_1)\mu_2(w_2) \, dV(w_1, w_2)
\]

\[
= \int_{\Omega_1} |f_n(w_1)|^p \mu_1(w_1) \, dV(w_1) \int_{\Omega_2} |g(w_2)|^p \mu_2(w_2) \, dV(w_2)
\]

\[
\leq c,
\]
and

\[ \lim_{n \to \infty} \|T(g \otimes f_n)\|_{L^p(\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2)}^p = \lim_{n \to \infty} \int_{\Omega_1 \times \Omega_2} |T_1(f_n)(w_1)T_2(g)(w_2)|^p \mu_1(w_1)\mu_2(w_2) dV(w_1, w_2) \]

\[ = \lim_{n \to \infty} \|T_1(f_n)\|_{L^p(\Omega_1, \mu_1)}^p \|T_2(g)\|_{L^p(\Omega_2, \mu_2)}^p \]

\[ = \infty. \]

\[ \mathbf{Remark~2.2.5} \] Lemma 2.2.4 typically applies to the Bergman projection on product space, since it is easy to see that \( \mathcal{B}_{\Omega_1 \times \Omega_2, \mu_1 \otimes \mu_2} = \mathcal{B}_{\Omega_1, \mu_1} \otimes \mathcal{B}_{\Omega_2, \mu_2}. \)

Now we are ready to prove the inflation theorem, which generalizes the result [Zey13, Corollary 4.6].

**Proposition 2.2.6 (Inflation Theorem)** Let \( \Omega \subset \mathbb{C}^n \) be a domain, and \( \mu = |g|^2 \) for some non-vanishing holomorphic function on \( \Omega \). Suppose that \( \tilde{\Omega} \subset \mathbb{C}^{m+n} \) is the inflation of \( \Omega \) via \( \mu \), and suppose that \( \lambda > 0 \) is a function on \( \Omega \) such that it is admissible on \( \tilde{\Omega} \).

Then, for \( p \geq 1 \), \( \mathcal{B}_{\tilde{\Omega}, \lambda} \) is \( L^p(\lambda) \)-bounded if and only if \( \mathcal{B}_{\Omega, \mu^m\lambda} \) is \( L^p(\mu^m\lambda) \)-bounded.

**Proof** Since \( g \) is holomorphic and non-vanishing, using the notation in Definition 2.1.4, we have the biholomorphism \( \Phi : \tilde{\Omega} \to \mathbb{B}^m \times \Omega \) via \( \Phi(z, w) = (z/g(w), w) \), where \( \mathbb{B}^m \) is the unit ball in \( \mathbb{C}^m \).

A direct computation shows that \( |\det J_{\mathbb{C}}(\Phi^{-1})|^2 = \mu^m \). So, by Corollary 2.2.3, we see that \( \mathcal{B}_{\tilde{\Omega}, \lambda} \) is \( L^p \)-bounded if and only if \( \mathcal{B}_{\mathbb{B}^m \times \Omega, \mu^m} \) is \( L^p \)-bounded.

But we know that \( \mathcal{B}_{\mathbb{B}^m \times \Omega, \mu^m} = \mathcal{B}_{\mathbb{B}^m} \otimes \mathcal{B}_{\Omega, \mu^m} \), and \( \mathcal{B}_{\mathbb{B}^m} \) is \( L^p \)-bounded for all \( p \in (1, \infty) \). By Lemma 2.2.4, we see that \( \mathcal{B}_{\tilde{\Omega}, \lambda} \) is \( L^p \)-bounded if and only if \( \mathcal{B}_{\Omega, \mu^m\lambda} \) is \( L^p \)-bounded. \[ \blacksquare \]
3. The $L^p$ Regularity

If we take $\Omega = \mathbb{D}^*$ and $\mu(w) = |w|^2$ in Proposition 2.2.6, then $\tilde{\Omega}$ is the classical Hartogs triangle $\mathbb{H}$. So in this chapter, we first prove Theorem 2, then prove Theorem 3, Theorem 4, and Theorem 5 by using inflation arguments. As a result, we obtain Theorem 1 from Theorem 5.

3.1 The Punctured Disk

We first look at the weighted space $(\mathbb{D}^*, |z|^{s'})$, for any $s' \in \mathbb{R}$.

**Lemma 3.1.1** For $s' \in \mathbb{R}$ with the unique expression $s' = s + 2k$, where $k \in \mathbb{Z}$ and $s \in (0, 2]$, the weighted Bergman kernel $B_{s'}(z, \zeta)$ on $(\mathbb{D}^*, |z|^{s'})$ has a "homotopic" expression

$$B_{s'}(z, \zeta) = \frac{s}{2} B_{2k+2}(z, \zeta) + \left(1 - \frac{s}{2}\right) B_{2k}(z, \zeta)$$

$$= \frac{s}{2} (z\overline{\zeta})^{-(k+1)} B_0(z, \zeta) + \left(1 - \frac{s}{2}\right) (z\overline{\zeta})^{-k} B_0(z, \zeta),$$

where $B_0(z, \zeta)$ is the ordinary Bergman kernel on the unit disk and $(z, \zeta) \in \mathbb{D}^* \times \mathbb{D}^*$.

**Proof** We first determine an orthonormal basis for the space $A^2(\mathbb{D}^*, |z|^{s'})$. Suppose $m, n \in \mathbb{Z}$; a direct computation shows, for $m + n + s' + 2 > 0$,

$$\int_{\mathbb{D}^*} z^n \overline{z}^m |z|^{s'} dV(z) = \begin{cases} 0, & \text{if } n \neq m, \\ \frac{2}{2m+2+s'}, & \text{if } n = m. \end{cases}$$

\footnote{Here $\mathbb{D}^* = \mathbb{D} \setminus \{0\}$ is the punctured disk.}

\footnote{We have normalized the area of $\mathbb{D}$ by setting $Area(\mathbb{D}) = 1$.}
Therefore \( \left\{ \sqrt{\frac{2m+2+s'}{2}z^m} \right\}_{m > -(1 + \frac{s'}{2})} \) is an orthonormal basis. So the weighted Bergman kernel for the space \((\mathbb{D}^s, |z|^{s'})\) is

\[
B_{s'}(z, \zeta) = \sum_{m > -(1 + \frac{s'}{2})} \frac{2m + 2 + s'}{2} z^m \zeta^{-m} = \frac{(t + \frac{s'}{2})(z\overline{\zeta})^{t-1} - (t - 1 + \frac{s'}{2})(z\overline{\zeta})^t}{(1 - z\overline{\zeta})^2},
\]

(3.2)

where \( t \) is the smallest integer satisfying \( t > -\frac{s'}{2} \).

Suppose \( s'' = s' + 2 \) and \( t_1 \) is the smallest integer such that \( t_1 > -\frac{s''}{2} \). Then \( t_1 = t - 1 \).

In this case, from (3.2), we see that

\[
B_{s''}(z, \zeta) = \frac{(t_1 + \frac{s''}{2})(z\overline{\zeta})^{t_1-1} - (t_1 - 1 + \frac{s''}{2})(z\overline{\zeta})^{t_1}}{(1 - z\overline{\zeta})^2} = \frac{(t - 1 + \frac{s' + 2}{2})(z\overline{\zeta})^{t-2} - (t - 2 + \frac{s' + 2}{2})(z\overline{\zeta})^{t-1}}{(1 - z\overline{\zeta})^2} = (z\overline{\zeta})^{-1} B_{s'}(z, \zeta).
\]

Hence 2 is a “period” of \( s' \) for the weighted Bergman kernel \( B_{s'}(z, \zeta) \). Let \( s' = s \in (0, 2] \).

Then \( t = 0 \), and from (3.2) we have

\[
B_s(z, \zeta) = \frac{\frac{s}{2} (z\overline{\zeta})^{-1} + (1 - \frac{s}{2})}{(1 - z\overline{\zeta})^2} = \frac{s}{2} (z\overline{\zeta})^{-1} B_0(z, \zeta) + \left(1 - \frac{s}{2}\right) B_0(z, \zeta).
\]

(3.4)

Therefore, combining (3.3) and (3.4), we obtain (3.1).

Following the idea in [HKZ00], to prove Theorem 2 we need three lemmas.

Lemma 3.1.2 (Schur’s Test) Suppose \( X \) is a measure space with a positive measure \( \mu \). Let \( T(x, y) \) be a positive measurable function on \( X \times X \), and let \( T \) be the integral operator associated to the kernel function \( T(x, y) \).

Given \( p \in (1, \infty) \) with its conjugate exponent \( p' \), if there exists a strictly positive function \( h \) a.e. on \( X \) and a constant \( M > 0 \), such that

25
1. \( \int_X T(x, y)h(y)^p \, d\mu(y) \leq Mh(x)^p \), for a.e. \( x \in X \), and

2. \( \int_X T(x, y)h(x)^p \, d\mu(x) \leq Mh(y)^p \), for a.e. \( y \in X \).

Then \( T \) is bounded on \( L^p(X, d\mu) \) with \( \|T\| \leq M \).

**Proof**  Let \( f \in L^p(X, d\mu) \). By Hölder’s inequality and Condition 1 in the assumption, we have

\[
|T(f)(x)| \leq \int_X T(x, y)|f(y)| \, d\mu(y) 
\leq \left( \int_X T(x, y)h(y)^p \, d\mu(y) \right)^{\frac{1}{p'}} \left( \int_X T(x, y)h(y)^{-p} |f(y)|^p \, d\mu(y) \right)^{\frac{1}{p}} 
\leq M^{\frac{1}{p'}} h(x) \left( \int_X T(x, y)h(y)^{-p} |f(y)|^p \, d\mu(y) \right)^{\frac{1}{p}} 
\]

for a.e. \( x \in X \). So, by Fubini’s theorem and Condition 2 in the assumption, we have

\[
\int_X |T(f)(x)|^p \, d\mu(x) \leq M^{\frac{p}{p'}} \int_X h(x)^p \, d\mu(x) \int_X T(x, y)h(y)^{-p} |f(y)|^p \, d\mu(y) 
= M^{\frac{p}{p'}} \int_X T(x, y)h(x)^p \, d\mu(x) \int_X h(y)^{-p} |f(y)|^p \, d\mu(y) 
\leq M^{\frac{p}{p'}+1} \int_X |f(y)|^p \, d\mu(y) 
= M^p \|f\|^p. 
\]

This completes the proof.

**Lemma 3.1.3**  For \(-1 < \alpha < 0\) and \( \beta > -2 \), define

\[
I_{\alpha,\beta}(z) = \int_{\mathbb{D}^*} \left( \frac{1 - |\zeta|^2}{|1-z\bar{\zeta}|^2} \right)^\alpha |\zeta|^\beta \, dV(\zeta),
\]

where \( z \in \mathbb{D}^* \). Then we have \( I_{\alpha,\beta}(z) \sim (1 - |z|^2)^\alpha \), for any \( z \in \mathbb{D}^* \).

\(^3\)The restrictions \( \alpha > -1 \) and \( \beta > -2 \) make the integral \( I_{\alpha,\beta}(z) \) convergent.

\(^4\)The notation \( A \sim B \) means there is a constant \( c > 0 \) so that \( c^{-1}B \leq A \leq cB \).
For $z, \zeta \in \mathbb{D}$, we expand the kernel function
\[
\frac{1}{|1 - z\zeta|^2} = \sum_{n=0}^{\infty} (z\zeta)^n \sum_{m=0}^{\infty} (\overline{z}\zeta)^m.
\]
Substitute the expansion back to the integral, and integrate term by term. By the rotational symmetry on $\mathbb{D}$, we obtain
\[
I_{\alpha,\beta}(z) = \sum_{n=0}^{\infty} \int_{\mathbb{D}} |z\zeta|^{2n} (1 - |\zeta|^2)^\alpha |\zeta|^\beta dV(\zeta)
\]
\[
= \sum_{n=0}^{\infty} |z|^{2n} \int_{0}^{1} 2r^{2n+\beta+1} (1 - r)^\alpha dr
\]
\[
= \sum_{n=0}^{\infty} |z|^{2n} \int_{0}^{1} t^{n+\beta} (1 - t)^\alpha dt
\]
\[
= \sum_{n=0}^{\infty} |z|^{2n} B\left(\alpha + 1, n + \frac{\beta}{2} + 1\right)
\]
\[
= \sum_{n=0}^{\infty} \frac{\Gamma(\alpha + 1)\Gamma(n + \frac{\beta}{2} + 1)}{\Gamma(n + \frac{\beta}{2} + \alpha + 2)} |z|^{2n}
\]
\[
\sim \sum_{n=0}^{\infty} \frac{\Gamma(n - \alpha)}{\Gamma(n + 1)\Gamma(-\alpha)} |z|^{2n}
\]
\[
= (1 - |z|^2)^\alpha.
\]

Here we first use the polar coordinate $\zeta = re^{i\theta}$, then apply the substitution $t = r^2$. By basic properties of the Beta function\(^5\) and Stirling’s formula, we obtain the asymptotic behavior for the Gamma functions as $n \to \infty$. The last equality holds since $\alpha < 0$.

**Lemma 3.1.4** Let $a_j = \left(\frac{1}{j}\right)^j$, $j = 1, 2, 3, \ldots$. For $p \geq 1$, the sum $A_{n,p} = \sum_{j=1}^{n} j \left(a_j^{p/j} - a_{j+1}^{p/(j+1)}\right)$ diverges when $p = 1$ and converges when $p > 1$, as $n \to \infty$. More precisely, we have
\[
\lim_{n \to \infty} A_{n,1} = \infty
\]
and
\[
\lim_{n \to \infty} A_{n,p} \leq c \sum_{j=1}^{\infty} \frac{1}{j^{1+\epsilon}} < \infty
\]

\(^5\)We temporarily denote the Beta function by $B$. Except for the argument in this lemma, a function $B$ is understood as the Bergman kernel on some domain.
for all \( p > 1 \) with some \( c > 0 \) and sufficiently small \( \epsilon > 0 \).

**Proof** We first prove the following statement,

\[
\left(\frac{1}{j}\right)^2 \lesssim \frac{1}{j} - \left(\frac{1}{j+1}\right)^{\frac{j+1}{j}} \lesssim \left(\frac{1}{j}\right)^{2-\epsilon'}
\]

for any \( \epsilon' > 0 \), as \( j \to \infty \).\(^6\)

We obtain the first inequality in (3.5) by looking at the limit (with L’Hôpital’s rule applied)

\[
\lim_{j \to \infty} \frac{\frac{1}{j} - \left(\frac{1}{j+1}\right)^{\frac{j+1}{j}}}{\left(\frac{1}{j}\right)^2} = \lim_{j \to \infty} \frac{-\frac{1}{j^2} + \left(\frac{1}{j+1}\right)^{\frac{j+1}{j}} \left(-\frac{1}{j^2} \log(j + 1) + \frac{1}{j}\right)}{-2 \left(\frac{1}{j}\right)^3}
\]

\[
= \frac{1}{2} \lim_{j \to \infty} \frac{1}{j} \cdot \lim_{j \to \infty} \frac{1 + \frac{1}{j} - \left(\frac{1}{j+1}\right)^{\frac{1}{j}}}{j + 1} + \lim_{j \to \infty} \left(\frac{1}{j+1}\right)^{\frac{1}{j}} \frac{j}{j+1} \log(j + 1)
\]

\[
= \frac{1}{2} \lim_{j \to \infty} \frac{1 - \left(\frac{1}{j+1}\right)^{\frac{1}{j}}}{j + 1} + 1 + \lim_{j \to \infty} \log(j + 1)
\]

(L’Hôpital’s rule) \(= \frac{1}{2} \lim_{j \to \infty} \frac{\left(\frac{1}{j+1}\right)^{\frac{1}{j}} \left(-\frac{1}{j^2} \log(j + 1) + \frac{1}{j(j+1)}\right)}{-\frac{1}{j^3}} + 1 + \lim_{j \to \infty} \log(j + 1)
\]

\[
= \lim_{j \to \infty} \log(j + 1)
\]

\(= \infty \).

\(^6\)The notation \( A \lesssim B \) means there is a constant \( c > 0 \) so that \( A \leq cB \).
Similarly, for the second inequality in (3.5), we look at the limit (with L'Hôpital's rule applied)

\[
\lim_{j \to \infty} \frac{\frac{1}{j} - \left( \frac{1}{j+1} \right)^{\frac{j+1}{j}}}{\left( \frac{1}{j} \right)^{2-\epsilon'}} = \lim_{j \to \infty} \frac{-\frac{1}{j^2} + \left( \frac{1}{j+1} \right)^{\frac{j+1}{j}} \left( -\frac{1}{j^2} \log(j+1) + \frac{1}{j} \right)}{(\epsilon' - 2) \left( \frac{1}{j} \right)^{3-\epsilon'}}
\]

\[
= \frac{1}{2 - \epsilon'} \lim_{j \to \infty} \frac{1 + \left( \frac{1}{j+1} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)}}{\left( \frac{1}{j} \right)^{1-\epsilon'}}
\]

\[
= \frac{1}{2 - \epsilon'} \left[ \lim_{j \to \infty} \left( 1 - \left( \frac{1}{j+1} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)} \right) + \lim_{j \to \infty} \left( \frac{1}{j} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)} \right]
\]

(L'Hôpital's rule) \[
= \frac{1}{2 - \epsilon'} \left[ \lim_{j \to \infty} \left( \frac{1}{j} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)} + \lim_{j \to \infty} \left( \frac{1}{j} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)} \right] + 0
\]

\[
= \frac{1}{2 - \epsilon'} \lim_{j \to \infty} \left( \frac{1}{j} \right)^{\frac{j}{j+1} \left( \log(j+1) - j \right)} \left( \frac{\log(j+1) - j}{j^{\epsilon'}} \right)
\]

\[
= 0.
\]

This shows the second inequality in (3.5).

Now, for \( p = 1 \), we have

\[
A_{n,1} = \sum_{j=1}^{n} \left( a_{j} - a_{j+1} \right)
\]

\[
= \sum_{j=1}^{n} j \left[ \left( \frac{1}{j} \right)^{\frac{j}{j+1}} - \left( \frac{1}{j+1} \right)^{\frac{j}{j+1}} \right]
\]

\[
= \sum_{j=1}^{n} j \left[ \frac{1}{j} - \left( \frac{1}{j+1} \right)^{\frac{j}{j+1}} \right]
\]
So, from (3.5), we have
\[ \lim_{n \to \infty} A_{n,1} \geq \sum_{j=1}^{\infty} j \cdot \left( \frac{1}{j} \right)^2 = \sum_{j=1}^{\infty} \frac{1}{j} = \infty. \]

For \( p > 1 \), we consider the function \( \phi(x) = x^p \), \( x \in (0,1] \). By the mean-value theorem, for each \( j \), we have
\[ \phi \left( \frac{1}{j} \right) - \phi \left( \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \right) = \left[ \frac{1}{j} - \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \right] \phi'(x_j), \]
where \( \phi'(x) = px^{p-1} \) and \( \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \leq x_j \leq \frac{1}{j} \). Since \( p - 1 > 0 \), we have
\[ x_j^{p-1} \leq \left( \frac{1}{j} \right)^{p-1}. \]

So we obtain
\[ \phi \left( \frac{1}{j} \right) - \phi \left( \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \right) \leq \left[ \frac{1}{j} - \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \right] p \left( \frac{1}{j} \right)^{p-1}. \]

Therefore, from (3.5), we have
\[
\lim_{n \to \infty} A_{n,p} = \sum_{j=1}^{\infty} j \left( \frac{1}{j+1} \right)^{p-1} \left( \frac{1}{j} \right)^{p-1} \\
\leq \sum_{j=1}^{\infty} \left[ \phi \left( \frac{1}{j} \right) - \phi \left( \left( \frac{1}{j+1} \right)^{\frac{1}{p+1}} \right) \right] p \left( \frac{1}{j} \right)^{p-1} \\
\leq \sum_{j=1}^{\infty} \left( \frac{1}{j} \right)^{2-p-\epsilon'} \left( \frac{1}{j} \right)^{p-1} \\
= \sum_{j=1}^{\infty} \left( \frac{1}{j} \right)^{p-\epsilon'} \\
< \infty,
\]
for sufficiently small \( \epsilon' > 0 \), such that \( p - \epsilon' = 1 + \epsilon \) for some \( \epsilon > 0 \).

Now we are ready to prove Theorem 2.
**Theorem 2** For \( s' \in \mathbb{R} \) with the unique expression \( s' = s + 2k \), where \( k \in \mathbb{Z} \) and \( s \in (0, 2] \), let \( B_{s'} \) be the weighted Bergman projection on the space \((\mathbb{D}^*, \mu)\), where \( \mu(z) = |z|^{s'} \).

(a) For \( s' \in (0, \infty) \), \( B_{s'} \) is \( L^p(\mu) \) bounded if and only if \( p \in \left( \frac{s + 2k + 2}{s + k + 1}, \frac{s + 2k + 2}{k + 1} \right) \).

(b) For \( s' \in [-3, 0] \), \( B_{s'} \) is \( L^p(\mu) \) bounded for \( p \in (1, \infty) \).

(c) For \( s' \in (-4, -3) \), with \( k = -2 \) and \( s \in (0, 1) \), \( B_{s'} \) is \( L^p(\mu) \) bounded if and only if \( p \in \left( 2 - s, \frac{2 - s}{1 - s} \right) \).

(d) When \( s' = -4 \), \( B_{-4} \) is \( L^p(\mu) \) bounded for \( p \in (1, \infty) \).

(e) For \( s' \in (-\infty, -4) \), \( B_{s'} \) is \( L^p(\mu) \) bounded if and only if \( p \in \left( \frac{s + 2k + 2}{k + 1}, \frac{s + 2k + 2}{s + k + 1} \right) \).

**Proof** For the boundedness part, by (3.1), we have

\[ |B_{s'}(z, \zeta)| \leq |z\zeta|^{-(k+1)} |B_0(z, \zeta)| \]

since \((z, \zeta) \in \mathbb{D}^* \times \mathbb{D}^*\). So it suffices to apply Lemma 3.1.2 to the kernel

\[ T(z, \zeta) = |z\zeta|^{-(k+1)} \cdot \frac{1}{|1 - z\zeta|^2} \]

on \( \mathbb{D}^* \times \mathbb{D}^* \), with the positive function

\[ h(z) = (1 - |z|^2)^{\delta} |z|^\sigma \]

on \( \mathbb{D}^* \) for some \( \delta, \sigma \in \mathbb{R} \) and the measure \( d\mu(z) = |z|^{s'} dV(z) \).

Now we check the first condition in Lemma 3.1.2. By Lemma 3.1.3, we see that

\[ \mathcal{T}(h^{s'}) (z) = \int_{\mathbb{D}^*} \frac{(1 - |\zeta|^2)^{\delta'}}{|z|^{k+1}} \frac{|\zeta|^\sigma |\zeta|^{s' + s - (k+1)}}{|1 - z\zeta|^2} dV(\zeta) \]

\[ = I_{\delta', \sigma, s+k-1}(z) \cdot |z|^{-(k+1)} \]

\[ \lesssim (1 - |z|^2)^{\delta'} |z|^{-(k+1)} \]

\[ \leq h(z)^{s'} , \]
provided \(-1 < \delta p' < 0, -2 < \sigma p' + s + k - 1\), and \(\sigma p' \leq -(k + 1)\), i.e., \(\delta \in (\frac{-1}{p}, 0)\) and \(\sigma \in (-\frac{s+k+1}{p'}, -\frac{k+1}{p'})\). Similarly, the second condition in Lemma 3.1.2

\[
\mathcal{T}(h^p)(\zeta) \lesssim h(\zeta)^p
\]

holds if \(\delta \in (\frac{-1}{p}, 0)\) and \(\sigma \in (-\frac{s+k+1}{p'}, -\frac{k+1}{p'})\).

Therefore such \(\delta\) and \(\sigma\) exist if \((-\frac{1}{p}, 0) \cap (\frac{-1}{p}, 0) \neq \emptyset\) and \((-\frac{s+k+1}{p'}, -\frac{k+1}{p'}) \cap (\frac{-s+k+1}{p'}, -\frac{k+1}{p'}) \neq \emptyset\). By Lemma 3.1.2, the existence of \(h\) will imply the boundedness of \(B_{s'}\). By a direct computation, we see that \(B_{s'}\) is \(L^p(\mu)\) bounded, when

1. \(k \geq 0, p \in (\frac{s+2k+2}{s+k+1}, \frac{s+2k+2}{k+1})\);

2. \(k = -1, p \in (1, \infty)\);

3. \(k = -2 \text{ and } 1 \leq s \leq 2, p \in (1, \infty)\);

4. \(k = -2 \text{ and } 0 < s < 1, p \in (2-s, \frac{2-s}{1-s})\);

5. \(k = -3 \text{ and } s = 2, p \in (1, \infty)\);

6. \(k = -3 \text{ and } 0 < s < 2, p \in (\frac{s+2k+2}{k+1}, \frac{s+2k+2}{s+k+1})\);

7. \(k < -3, p \in (\frac{s+2k+2}{k+1}, \frac{s+2k+2}{s+k+1})\).

It is easy to see, the conditions above is equivalent to the conditions in Theorem 2.

To show the unboundedness part, since \(B_{s'}\) is self-adjoint, by the interpolation theorem, we only need to look at the endpoint \(p = \frac{s+2k+2}{s+k+1}\). Let \(a_j = (\frac{1}{j})^j, j = 1, 2, 3, \ldots\), and define a function \(g\) on \((0,1]\) such that \(g(r) = r^{\frac{1}{j}-(s+k+1)}\), \(r \in (a_{j+1}, a_j]\). We consider the sequence

\[
f_n(z) = \begin{cases} 
g(|z|) \left(\frac{z}{|z|}\right)^{k+1}, & |z| \in (a_{n+1}, 1], \\
0, & |z| \in [0, a_{n+1}].
\end{cases}
\]

32
Since each $f_n$ is supported away from the origin and bounded above, it is easy to see that 
\[ \{f_n\} \subset L^2(D^s, |z|^s'). \]
Since $p = \frac{s+2k+2}{s+k+1} > 1$, by Lemma 3.1.4, we have
\[
\|f_n\|_{L^p(\mu)}^p = \int_{|z| < 1} g(|z|) |z|^s' dV(z) \\
= \sum_{j=1}^{n} \int_{a_j+1}^{a_j} 2_\mu \left[ \frac{1}{2} \right]^{(s+k+1)} |z|^{p} dV(z) \\
= 2 \sum_{j=1}^{n} \frac{j}{p} \left( a_j^\frac{p}{2} - a_{j+1}^\frac{p}{2} \right) \\
= \frac{2}{p} A_{n,p} \\
\leq c \sum_{j=1}^{\infty} \frac{1}{j^{1+\epsilon}},
\]
for some $\epsilon > 0$ and some $c > 0$.

On the other hand, by (3.1), we see that
\[
B_{s'}(f_n)(z) = \frac{s}{2} \int_{\mathbb{D}} \frac{(z\zeta)^{-k} f_n(\zeta) |\zeta|^{s'} dV(\zeta)}{(1-z\zeta)^2} + \left( 1 - \frac{s}{2} \right) \int_{\mathbb{D}} \frac{(z\zeta)^{-k} f_n(\zeta) |\zeta|^{s+k-1} dV(\zeta)}{(1-z\zeta)^2} \\
= I + II.
\]
For the second integral,
\[
II = \left( 1 - \frac{s}{2} \right) z^{-k} \int_{|\zeta| < 1} \frac{g(|\zeta|) |\zeta|^{s+k-1} dV(\zeta)}{(1-z\zeta)^2} \\
= 0.
\]
In the last line, we expand the kernel $(1 - z\zeta)^{-2}$ and use the rotational symmetries. For the first integral, a similar computation shows that
\[
I = \frac{s}{2} z^{-(k+1)} \int_{|\zeta| < 1} \frac{g(|\zeta|) |\zeta|^{s+k-1} dV(\zeta)}{(1-z\zeta)^2} \\
= \frac{s}{2} z^{-(k+1)} \int_{|\zeta| < 1} g(|\zeta|) |\zeta|^{s+k-1} dV(\zeta) \\
= sz^{-(k+1)} \sum_{j=1}^{n} \int_{a_j+1}^{a_j} \frac{1}{r} r^{-s-k+1} + s+k dV(z) \\
= sz^{-(k+1)} \sum_{j=1}^{n} j \left( a_j^\frac{1}{2} - a_{j+1}^\frac{1}{2} \right).
\]
Therefore we have

\[ B'(f_n)(z) = sz^{-(k+1)}A_{n,1}. \]

It is easy to see that

\[ s + 2k - (k + 1)p = -2 + \nu, \]

for some \( \nu > 0 \). So we obtain

\[ \|B'(f_n)\|_{L^p(\mu)} = s \left( \frac{2}{\nu} \right)^{\frac{1}{2}} A_{n,1}. \]

Hence, from Lemma 3.1.4, we see that

\[ \lim_{n \to \infty} \|B'(f_n)\|_{L^p(\mu)} = \infty. \]

This completes the proof.

**Remark 3.1.5** The range for \( p \) does not change continuously as \( s' \) varies. In fact, there are jumps around the integers \( s' = 0, 2, 4, \ldots \), and the integers \( s' = -4, -6, -8, \ldots \). The range changes continuously only when \( s' \) lies between the consecutive integers above or \( s' \in (-4, 0] \) (there is no jump around \( s' = -2 \)).

### 3.2 The Hartogs Triangle

Now we are ready to prove Theorem 3 and Theorem 4 by using inflation arguments.

**Theorem 3** For \( s' \in [0, \infty) \) with the unique expression \( s' = s + 2k \), where \( k \in \mathbb{Z} \) and \( s \in (0, 2] \), let \( \lambda(z) = |z|^s \), where \( z \in \mathbb{H} \). The weighted Bergman projection \( B_\lambda \) on the weighted space \( (\mathbb{H}, \lambda) \) is \( L^p(\mathbb{H}, \lambda) \) bounded if and only if \( p \in \left( \frac{s+2k+4}{s+k+2}, \frac{s+2k+4}{k+2} \right) \).

**Proof** Using the notation in Proposition 2.2.6, if we take \( \Omega = \mathbb{D}^* \) and \( \mu(w) = |w|^2 \), then we see that \( B_{\mathbb{D}, \lambda} \) is \( L^p(\mathbb{D}, \lambda) \) bounded if and only if \( B_{\mathbb{D}^*, \mu\lambda} \) is \( L^p(\mathbb{D}^*, \mu\lambda) \) bounded.

By Theorem 2 (a), the latter is true if and only if \( p \in \left( \frac{s+2k+4}{s+k+2}, \frac{s+2k+4}{k+2} \right) \) for \( s' \in [0, \infty) \). 

34
Theorem 4 Given any \( p_0 \in [1, 2) \) with its conjugate exponent \( p'_0 \), let \( \lambda(z) = |z|^-(p_0+4) \), where \( z \in \mathbb{H} \). Then the weighted Bergman projection \( B_\lambda \) on the weighted space \((\mathbb{H}, \lambda)\) is \( L^p(\mathbb{H}, \lambda) \) bounded if and only if \( p \in (p_0, p'_0) \).

Proof Similarly, this is a direct consequence by combining Proposition 2.2.6 with \( \Omega = \mathbb{D}^* \) and \( \mu(w) = |w|^2 \), and Theorem 2 (b) (c) with \( s' = -(2 + p_0) \).

3.3 The \( n \)-dimensional Hartogs Triangle

To prove Theorem 5, we need a lemma.

Lemma 3.3.1 Let \( \mathbb{H}^{d*} = \{ z \in \mathbb{C}^d | 0 < |z_1| < \cdots < |z_d| < 1 \} \) be the punctured \( d \)-dimensional standard Hartogs triangle. Suppose we have a weight \( \lambda(z) = |z_1|^{s_1} \cdots |z_d|^{s_d} \) on \( \mathbb{H}^{d*} \), where \( s_1, \ldots, s_d \in \mathbb{R} \). Then the weighted Bergman projection \( B_{\mathbb{H}^{d*}, \lambda} \) is \( L^p(\lambda) \) bounded if and only if each of the following projections

\[ B_{s_1}, B_{s_1+s_2+2}, \cdots, B_{s_1+\cdots+s_d+2(d-1)} \]

is \( L^p \) bounded on the corresponding weighted space.

Proof As in the proof of Proposition 2.2.6, we have the biholomorphism \( \Phi : \mathbb{H}^{d*} \to (\mathbb{D}^*)^{\times d} \) via \( \Phi(z) = (\frac{z_1}{z_2}, \cdots, \frac{z_{d-1}}{z_d}, z_d) \). By Corollary 2.2.3, we see that \( B_{\mathbb{H}^{d*}, \lambda} \) is \( L^p(\lambda) \) bounded if and only if \( B_{(\mathbb{D}^*)^{\times d}, \tilde{\lambda}} \) is \( L^p(\tilde{\lambda}) \)-bounded, where \( \tilde{\lambda} = |\det J_\mathbb{C}\Phi^{-1}|^2 \lambda(\Phi^{-1}) \). A direct computation shows that

\[ |\det J_\mathbb{C}\Phi^{-1}(w)|^2 = |w_2 w_3^2 \cdots w_d^d| \],

where \( w \in (\mathbb{D}^*)^{\times d} \). So we see that

\[ B_{(\mathbb{D}^*)^{\times d}, \tilde{\lambda}} = B_{s_1} \otimes B_{s_1+s_2+2} \otimes \cdots \otimes B_{s_1+\cdots+s_d+2(d-1)}, \]

which implies the conclusion in view of Lemma 2.2.4. \( \square \)
Now we are ready to prove Theorem 5.

**Theorem 5** Using the notation as in (1.1), let \( \lambda(z) = |z_1''|^{s_1} \cdots |z_d''|^{s_d} \), where \( z \in \mathbb{H}_n^{\mathcal{D}} \) and \( s_1, \ldots, s_d \in \mathbb{R} \). Let \( B_{s'} \) be as in Theorem 2. Then the weighted Bergman projection on \((\mathbb{H}_n^{\mathcal{D}}, \lambda)\) is \( L^p(\lambda) \) bounded if and only if each of the following projections

\[
B_{2m+s_1}, \ B_{2m+s_1+s_2+2}, \ldots, \ B_{2m+s_1+\cdots+s_d+2(d-1)}
\]

is \( L^p \) bounded on the corresponding weighted space.

In other words, assume that \( p > 1 \) and for \( j = 1, 2, \ldots, d \) we let \( I_j \) be one of the intervals for \( p \) in Theorem 2, so that the \( j \)th projection above is \( L^p \) bounded if and only if \( p \in I_j \). Then the weighted Bergman projection on \((\mathbb{H}_n^{\mathcal{D}}, \lambda)\) is \( L^p(\lambda) \) bounded if and only if \( p \in \bigcap I_j \).

**Proof** Iteratively apply Proposition 2.2.6 \( l \) times to \( \Omega = \mathbb{H}^{d*} = \{ z'' \in \mathbb{C}^d \mid 0 < |z_1''| < \cdots < |z_d''| < 1 \} \) with the same weight \( |z_1''|^2 \). Then we will arrive at the space

\[
\mathbb{H}^n = \{ (z', z'') \in \mathbb{C}^{m_1+\cdots+m_l+d} : \max_{1 \leq j \leq l} |\tilde{z}_j''| < |z_1''| < |z_2''| < \cdots < |z_d''| < 1 \}.
\]

So the weighted Bergman projection \( B_{\mathbb{H}^n, \lambda} \) is \( L^p(\lambda) \) bounded if and only if \( B_{\mathbb{H}^{d*}, \tilde{\lambda}} \) is \( L^p(\tilde{\lambda}) \) bounded, where \( \lambda(z) = |z_1''|^{s_1} \cdots |z_d''|^{s_d} \) and \( \tilde{\lambda}(z) = |z_1''|^{2m_1} \lambda(z) \). Applying Lemma 3.3.1 to \( B_{\mathbb{H}^{d*}, \tilde{\lambda}} \), we obtain a special case of Theorem 5, namely, the \( L^p \) boundedness of the weighted Bergman projection on \((\mathbb{H}^n, \lambda)\).

On the other hand, we look at the biholomorphism \( \Phi : \mathbb{H}_n^{\mathcal{D}} \rightarrow \mathbb{H}^n \) via

\[
\Phi(z) = (\phi_1(\tilde{z}_1), \ldots, \phi_l(\tilde{z}_l), z_1'', \ldots, z_d'').
\]

A direct computation shows, for \( z \in \mathbb{H}_n^{\mathcal{D}} \), that

\[
\det J_C \Phi(z) = \prod_{j=1}^l \det J_C \phi_j(\tilde{z}_j).
\]
For each $j$, we have the biholomorphism $\phi_j : \Omega_j \to \mathbb{B}^{m_j}$, with both $\Omega_j$ and $\mathbb{B}^{m_j}$ being smooth and bounded. Since $\mathbb{B}^{m_j}$ is strongly pseudoconvex, it satisfies condition R. By Bell’s extension theorem in [Bel81], both $\phi_j$ and $\phi_j^{-1}$ extend smoothly to the boundaries. Therefore we can find two positive real numbers $c_j$ and $d_j$, so that for any $\tilde{z}_j \in \Omega_j$, 

$$0 < c_j \leq |\det J_C \phi_j(\tilde{z}_j)| \leq d_j.$$ 

Hence, if we let $c = \prod_{j=1}^{l} c_j$ and $d = \prod_{j=1}^{l} d_j$, then for $z \in \mathbb{H}^n_{\phi_j}$ we have 

$$0 < c \leq |\det J_C \Phi(z)| \leq d.$$ 

Now suppose for some $p \in (1, \infty)$ that the weighted Bergman projection $B_{\mathbb{H}^n_{\phi_j}, \lambda}$ is bounded on $L^p(\mathbb{H}^n_{\phi_j}, \lambda)$. Then, by the transformation formula in Corollary 2.2.2, for $f \in L^p(\mathbb{H}^n, \lambda)$ we have 

$$\|B_{\mathbb{H}^n, \lambda}(f)\|_{L^p(\mathbb{H}^n, \lambda)}^p = \int_{\mathbb{H}^n} |B_{\mathbb{H}^n, \lambda}(f)(z)|^p \lambda(z) dV(z)$$ 

$$= \int_{\mathbb{H}^n_{\phi_j}} \left|B_{\mathbb{H}^n_{\phi_j}, \lambda}(\det J_C \Phi \cdot f \circ \Phi)(z)\right|^p |\det J_C \Phi(z)|^{2-p} \lambda(z) dV(z)$$ 

$$\leq \max\{c^{2-p}, d^{2-p}\} \left\|B_{\mathbb{H}^n_{\phi_j}, \lambda}(\det J_C \Phi \cdot f \circ \Phi)\right\|_{L^p(\mathbb{H}^n_{\phi_j}, \lambda)}^p$$ 

$$\leq C \max\{c^{2-p}, d^{2-p}\} \left\||\det J_C \Phi \cdot f \circ \Phi\|_{L^p(\mathbb{H}^n_{\phi_j}, \lambda)}^p\right.$$ 

$$\leq C c^{-[p-2]} d^{[2-p]} \|f\|_{L^p(\mathbb{H}^n, \lambda)}^p$$ 

for some $C > 0$. So the weighted Bergman projection $B_{\mathbb{H}^n, \lambda}$ is bounded on $L^p(\mathbb{H}^n, \lambda)$.

Conversely, if we apply the same argument to $\Phi^{-1} : \mathbb{H}^n \to \mathbb{H}^n_{\phi_j}$, we see the weighted $L^p$ boundedness of $B_{\mathbb{H}^n, \lambda}$ will imply the weighted $L^p$ boundedness of $B_{\mathbb{H}^n_{\phi_j}, \lambda}$. Therefore, we see that $B_{\mathbb{H}^n_{\phi_j}, \lambda}$ is $L^p(\lambda)$ bounded if and only if $B_{\mathbb{H}^n, \lambda}$ is $L^p(\lambda)$ bounded. This completes the proof.

As a consequence, we obtain Theorem 1 from Theorem 5.
**Theorem 1**  The Bergman projection $B_{H^n_{\phi_j}}$ on $H^n_{\phi_j}$ is bounded on $L^p(H^n_{\phi_j})$ if and only if $p$ is in the range $(\frac{2n}{n+1}, \frac{2n}{n-1})$.

**Proof**  Letting $s_1 = s_2 = \cdots = s_d = 0$ in Theorem 5, we see that $\lambda(z) = 1$. Therefore, the Bergman projection $B_{H^n_{\phi_j}}$ on $H^n_{\phi_j}$ is bounded on $L^p(H^n_{\phi_j})$ if and only if each of the following projections

$$B_{2m}, B_{2m+2}, \ldots, B_{2m+2(d-1)}$$

is $L^p$ bounded on the corresponding weighted space. Note that, for $j = 1, 2, \ldots, d$, by Theorem 2, $B_{2(m+j-1)}$ is $L^p$ bounded if and only if $p \in \left( \frac{2(m+j)}{m+j+1}, \frac{2(m+j)}{m+j-1} \right)$. Hence, $B_{H^n_{\phi_j}}$ is $L^p$ bounded if and only if $p \in \bigcap_{j=1}^d \left( \frac{2(m+j)}{m+j+1}, \frac{2(m+j)}{m+j-1} \right) = \left( \frac{2n}{n+1}, \frac{2n}{n-1} \right)$.  

\[38\]
4. The Two-weight Inequality

In this chapter, we mainly focus on the two-weight inequality (1.2) introduced in §1.2, and prove Theorem 6. In the next chapter, we will see as an application, that Theorem 6 gives an alternative proof of Theorem 2 and extends it to a wider class of weights.

4.1 Preliminaries and Basic Definitions

Throughout this chapter, \( z \) and \( w \) will denote complex variables in \( \mathbb{R}^2_+ \) (or \( \mathbb{C} = \mathbb{R}^2 \)), any weight \( \mu \) will be considered to be locally integrable on \( \mathbb{R}^2_+ \) (or \( \mathbb{R}^2 \)), \( \mathcal{B} \) will denote the Bergman projection on \( \mathbb{R}^2_+ \), and we have

\[
\mathcal{B}(f)(z) = \int_{\mathbb{R}^2_+} \frac{1}{(z-w)^2} f(w) \, dV(w),
\]

for all measurable \( f \) on \( \mathbb{R}^2_+ \) whenever it is well-defined.\(^1\) We also consider the "absolute value" operator \( \mathcal{\tilde{B}} \) of \( \mathcal{B} \), which is defined as

\[
\mathcal{\tilde{B}}(f)(z) = \int_{\mathbb{R}^2_+} \frac{1}{|z-w|^2} f(w) \, dV(w),
\]

where we replace the kernel \(-\frac{1}{(z-w)^2}\) by its absolute value.

For a weight \( \mu \), a measurable function \( f \), and any measurable set \( W \) with its Lebesgue measure \( |W| \), we may use the notation

\[
\mu(W) = \int_W \mu(z) \, dV(z)
\]

\(^1\)One may consider \( f \in C^\infty_c(\mathbb{R}^2_+) \), and the conclusion of Theorem 6 will follow from the passage from \( C^\infty_c(\mathbb{R}^2_+) \) to \( L^p(\mathbb{R}^2_+, \mu_2) \). We omit the coefficient \( \frac{1}{\pi} \) in front of the integral in order to coincide with the normalization \( \text{Area}(\mathbb{D}) = 1 \) in the previous chapter.
and
\[ \int_W f(z) \, dV(z) = \frac{1}{|W|} \int_W f(z) \, dV(z). \]

In this chapter, the symbol \( c \) will denote some positive constant independent of the variables and the functions in the context. So two \( c \)'s in the same equation could be different, but it does not matter at all.

In our notation, the inequality (1.2) becomes
\[ \int_{\mathbb{R}^2_+} |B(f)(z)|^p \mu_1(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} |f(z)|^p \mu_2(z) \, dV(z). \]

In order to prove Theorem 6, following Lanzani and Stein’s idea in [LS04], we first give the definitions of several variants of the \( A_p \) condition, which was introduced by Muckenhoupt.\(^2\)

**Definition 4.1.1** For \( p > 1 \), let \( p' \) denote the conjugate exponent of \( p \). We say the two weights \( \mu_1 \) and \( \mu_2 \) are in the \( A_p(\mathbb{R}^2_+) \) class denoted by \( (\mu_1, \mu_2) \in A_p(\mathbb{R}^2_+) \) if there is a positive constant \( c \) so that
\[ \int_{D \cap \mathbb{R}^2_+} \mu_1(z) \, dV(z) \left( \int_{D \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{p'}{p}} \, dV(z) \right)^{\frac{p}{p'}} \leq c, \]
for all disks \( D \) centered at \( z \in \mathbb{R}^2_+ \). A disk is said to be a special disk if it is centered at \( x \in \mathbb{R} \). We say \( (\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+) \) if the above inequality holds for all special disks. The class \( A_p(\mathbb{R}^2) \) is defined in the same way as \( A_p(\mathbb{R}^2_+) \) except replacing \( \mathbb{R}^2_+ \) by \( \mathbb{R}^2 \). For some weight \( \mu \), if \( (\mu, \mu) \in A^+_p(\mathbb{R}^2_+) \) (resp. \( A_p(\mathbb{R}^2_+) \) and \( A_p(\mathbb{R}^2) \)), we may simply adopt the notation \( \mu \in A^+_p(\mathbb{R}^2_+) \) (resp. \( A_p(\mathbb{R}^2_+) \) and \( A_p(\mathbb{R}^2) \)).

**Remark 4.1.1** The class \( A^+_p(\mathbb{R}^2_+) \) is strictly wider than the class \( A_p(\mathbb{R}^2_+) \). For the one-weight case see the comments following the definition of \( A^+_p \) in [LS04]. For two-weight case see Proposition 5.1.1 in Chapter 5.

\(^2\)See also [Muc72] and [Ste93, Chapter 5].
As in [LS04], we now introduce a standard “tiling” of \( \mathbb{R}^2_+ \) and the associated averaging operator (the “conditional expectation”).

**Definition 4.1.2** The standard “tiling” of \( \mathbb{R}^2_+ \) are the squares \( \{ S_{j,k} \} \) of form

\[
S_{j,k} = \{ z = x + iy \in \mathbb{C} : 2^k \leq y \leq 2^{k+1} \text{ and } j \cdot 2^k \leq x \leq (j+1) \cdot 2^{k+1} \}
\]

for all \( j, k \in \mathbb{Z} \). Note that each \( S_{j,k} \) has side-length \( 2^k \), the interiors of \( S_{j,k} \)'s are disjoint, and \( \mathbb{R}^2_+ = \bigcup_{j,k \in \mathbb{Z}} S_{j,k} \).

Define the associated averaging operator \( E \) by

\[
E(f)(z) = \int_{S_{j,k}} f(z) \, dV(z), \text{ if } z \in S_{j,k},
\]

for any nonnegative measurable function \( f \) on \( \mathbb{R}^2_+ \).

### 4.2 The Properties of the Operator \( E \)

In this section, we give two propositions about the operator \( E \). The proofs can also be found in [LS04], but we will give the details here, in order to be self-contained.

**Proposition 4.2.1** We have the following basic properties of \( E \). For any nonnegative measurable functions \( f \) and \( g \), letting \( p' \) be the conjugate exponent of \( p \), we have

(a) \( \int_{\mathbb{R}^2_+} E(f)(z)g(z) \, dV(z) = \int_{\mathbb{R}^2_+} E(f)(z)E(g)(z) \, dV(z) \),

(b) \( \int_{\mathbb{R}^2_+} (E(f)(z))^p g(z) \, dV(z) \leq \int_{\mathbb{R}^2_+} E(f^p)(z)g(z) \, dV(z) \),

(c) \( E(fg)(z) \leq \left( E(f^p)(z) \right)^{\frac{1}{p}} \left( E(g^{p'})(z) \right)^{\frac{1}{p'}} \) for all \( z \in \mathbb{R}^2_+ \).

**Proof** For (a), the left hand side of the equality is

\[
\sum_{j,k} \int_{S_{j,k}} E(f)(z)g(z) \, dV(z) = \sum_{j,k} E(f)(z)\chi_{S_{j,k}}(z) \int_{S_{j,k}} g(z) \, dV(z)
\]

\[
= \sum_{j,k} E(f)(z)\chi_{S_{j,k}}(z)E(g)(z) |S_{j,k}|.
\]
On the other hand, the right hand side of the equality is
\[
\sum_{j,k} \int_{S_{j,k}} E(f)(z) E(g)(z) \, dV(z) = \sum_{j,k} E(f)(z) E(g)(z) \chi_{S_{j,k}}(z) |S_{j,k}|,
\]
which equals the left hand side.

For (b), we apply Jensen’s inequality to the integral \( \int_{S_{j,k}} f(z) \, dV(z) \), via the convex function \( x^p \). We see that
\[
(E(f)(z))^p g(z) \leq E(f^p)(z) g(z),
\]
for all \( z \in S_{j,k} \). Integrate over \( S_{j,k} \) and sum over all \( j, k \in \mathbb{Z} \), then we get the desired inequality.

For (c), it is a direct consequence of Hölder’s inequality. □

**Proposition 4.2.2** For any \( f \geq 0 \), we have
\[
\tilde{B}(f) \leq cE\tilde{E}E(f). \tag{4.1}
\]

**Proof** We first show, for any \( z, w \in \mathbb{R}_+^2 \), that
\[
E_z E_w \left( \frac{1}{|z - w|^2} \right) \geq \frac{c}{|z - w|^2}, \tag{4.2}
\]
where \( E_z \) and \( E_w \) are operators \( E \) acting on \( z \) and \( w \) respectively. Suppose that \( z \in S_{j,k} \) and \( w \in S_{j',k'} \), with \( k \geq k' \). We separate our arguments into two cases.

Case (I), \( |\Re(z - w)| \leq 2^k \).

Since \( z \in S_{j,k} \) and \( w \in S_{j',k'} \), we see \( |\Im(z - w)| \geq 2^k + 2^{k'} \geq 2^k \). Then
\[
\frac{1}{|z - w|^2} \leq \frac{1}{|\Im(z - w)|^2} \leq \frac{1}{2^{2k}}.
\]
On the other hand, for any \( \zeta \in S_{j,k} \) and \( \eta \in S_{j',k'} \), we have
\[
|\Re(\zeta - \eta)| \leq |\Re(\zeta - z)| + |\Re(z - w)| + |\Re(w - \eta)| \leq 2^k + 2^k + 2^{k'} \leq 3 \cdot 2^k,
\]
and
\[ |\Im(\zeta - \eta)| \leq 2^{k+1} + 2^{k'} + 1 \leq 2^{k+2}. \]

So we obtain
\[ \frac{1}{|\zeta - \eta|^2} \geq \frac{1}{(3 \cdot 2^k)^2 + (2^{k+2})^2} = \frac{1}{22k} \cdot \frac{1}{25}. \]

Therefore we have
\[
E_z E_w \left( \frac{1}{|z - \overline{w}|} \right) = \int_{S_{j,k}} \int_{S'_{j',k'}} \frac{1}{|\zeta - \eta|^2} dV(\eta) dV(\zeta)
\geq \frac{1}{25} \cdot \frac{1}{2^{2k}}
\geq \frac{1}{25} \cdot \frac{1}{|z - \overline{w}|^2}.
\]

Case (II), \(|\Re(z - \overline{w})| > 2^k\).

Similarly, we have
\[ \frac{1}{|z - \overline{w}|^2} \leq \frac{1}{|\Re(z - \overline{w})|^2}. \]

For any \(\zeta \in S_{j,k}\) and \(\eta \in S'_{j',k'}\), again we see
\[ |\Re(\zeta - \eta)| \leq 2^k + |\Re(z - \overline{w})| + 2^{k'} \leq 3 |\Re(z - \overline{w})|, \]

and
\[ |\Im(\zeta - \eta)| \leq 2^{k+1} + 2^{k'+1} \leq 4 |\Re(z - \overline{w})|. \]

So we obtain
\[ \frac{1}{|\zeta - \eta|^2} \geq \frac{1}{(3 |\Re(z - \overline{w})|)^2 + (4 |\Re(z - \overline{w})|)^2} = \frac{1}{25} \cdot \frac{1}{|\Re(z - \overline{w})|^2}. \]

Therefore we have
\[
E_z E_w \left( \frac{1}{|z - \overline{w}|} \right) = \int_{S_{j,k}} \int_{S'_{j',k'}} \frac{1}{|\zeta - \eta|^2} dV(\eta) dV(\zeta)
\geq \frac{1}{25} \cdot \frac{1}{|\Re(z - \overline{w})|^2}
\geq \frac{1}{25} \cdot \frac{1}{|z - \overline{w}|^2}.
\]
For \( k' \geq k \), all arguments remain the same except switching \( k' \) with \( k \). Thus we have proved (4.2). Now (4.1) follows from the argument below,

\[
E\bar{B}E(f)(z) = E_z \left( \int_{\mathbb{R}^2_+} \frac{1}{|z-w|^2} E(f)(w) \, dV(w) \right) \\
= E_z \left( \int_{\mathbb{R}^2_+} E_w \left( \frac{1}{|z-w|^2} \right) f(w) \, dV(w) \right) \\
= \int_{\mathbb{R}^2_+} E_z E_w \left( \frac{1}{|z-w|^2} \right) f(w) \, dV(w) \\
\geq \int_{\mathbb{R}^2_+} \frac{c}{|z-w|^2} f(w) \, dV(w) \\
= c\bar{B}(f)(z),
\]

where we have applied Proposition 4.2.1 (a) in the second line.

\[ \tag*{\blacksquare} \]

4.3 Analysis on Variants of \( A_p \) Class

In this section, we do some analysis on the variants of the \( A_p \) class. One important observation is the following proposition.

**Proposition 4.3.1** If \((\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)\), then \((E(\mu_1), E(\mu_2)) \in A_p(\mathbb{R}^2_+)\).

The proof is essentially the same as that of the one weight case [LS04, Proposition 4.6]. Again, to be self-contained, we will give all the details here.

**Definition 4.3.1** Let \( W_1, \ldots, W_N \) be \( N \) measurable subsets in \( \mathbb{R}^2_+ \), we say they are comparable to each other if there is a special disk \( D_R(x_0) \) centered at \( x_0 \in \mathbb{R} \), so that \( W_l \subset D_R(x_0) \cap \mathbb{R}^2_+ \), while \( |D_R(x_0) \cap \mathbb{R}^2_+| \leq a |W_l| \), for some \( a \geq 1 \), \( l = 1, 2, \ldots, N \).

**Lemma 4.3.2** If \((\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+) \) and if \( W_1 \) and \( W_2 \) are comparable, then there is a \( C = C(a) \geq 1 \), such that \( \mu_1(W_1) \leq C \mu_2(W_2) \).
Proof Since \( W_1 \) and \( W_2 \) are comparable, we can find a special disk \( D_R(x_0) \) so that \( W_i \subset D_R(x_0) \cap \mathbb{R}_+^2 \) and \( |D_R(x_0) \cap \mathbb{R}_+^2| \leq a |W_i|, \ l = 1, 2. \) Then it is easy to see

\[
\int_{W_i} \mu_1(z) \, dV(z) \leq a \int_{D_R(x_0) \cap \mathbb{R}_+^2} \mu_1(z) \, dV(z). \tag{4.3}
\]

Apply Jensen’s inequality to the integral \( \int_{W_2} \mu_2(z) \, dV(z) \), via the convex function \( x^{\frac{2}{p}} \), we have

\[
\left( \int_{W_2} \mu_2(z) \, dV(z) \right)^{\frac{2}{p}} \leq \int_{W_2} \mu_2(z)^{\frac{2}{p}} \, dV(z) \leq a \int_{D_R(x_0) \cap \mathbb{R}_+^2} \mu_2(z)^{\frac{2}{p}} \, dV(z). \tag{4.4}
\]

Combine (4.3) and (4.4), since \( |W_1| \leq |D_R(x_0) \cap \mathbb{R}_+^2| \leq a |W_2| \) and since \( (\mu_1, \mu_2) \in A_p^+(\mathbb{R}_+^2) \), we see

\[
\mu_1(W_1) \leq ca^{\frac{2}{p}+\frac{2}{p}} \mu_2(W_2). \]

\[\blacksquare\]

Proof [Proof of Proposition 4.3.1.]

For any disk \( D_R(z_0) \) centered at \( z_0 \in \mathbb{R}_+^2 \), let \( x_0 = \Re(z_0) \) and \( y_0 = \Im(z_0) \), denote \( \{W_i\} = \{S_{j,k} : D_R(z_0) \cap \mathbb{R}_+^2 \cap S_{j,k} \neq \emptyset\} \). We separate our arguments into two cases.

Case (I), \( y_0 \geq 2R \).

Suppose \( 2^{k_0} \leq y_0 - R \leq 2^{k_0+1} \), for some \( k_0 \in \mathbb{Z} \). Since \( y_0 \geq 2R \), we see \( R \leq 2^{k_0+1}, y_0 \leq 2^{k_0+2}, \) and \( y_0 + R \leq 2^{k_0+3} \). Therefore, \( D_R(z_0) \) must be covered by the union of 2 squares of side-length \( 2^{k_0+2} \), 4 squares of side-length \( 2^{k_0+1} \), and 8 squares of side-length \( 2^{k_0} \). So the cardinality of the collection \( \{W_i\} \) is at most \( 2 + 4 + 8 = 14 \).

Now, if \( x+iy \in D_R(z_0) \cap S_{j,k} \), for some \( j, k \in \mathbb{Z} \). Then we have \( y_0 - R \leq y \leq y_0 + R \) and \( 2^k \leq y \leq 2^{k+1} \). So it is easy to see that \( \frac{y_0}{4} \leq 2^k \leq \frac{3}{2} y_0 \). For such \( S_{j,k} \), any \( x' + iy' \in S_{j,k} \), we have \( y' \leq 2^{k+1} \leq 3y_0 \), and \( |x' - x| \leq R + 2^k \leq 2y_0 \). Then \( x' + iy' \in D_{4y_0}(x_0) \cap \mathbb{R}_+^2 \), and hence \( S_{j,k} \subset D_{4y_0}(x_0) \cap \mathbb{R}_+^2 \). But \( |D_{4y_0}(x_0) \cap \mathbb{R}_+^2| = 8\pi y_0^2 \) and \( |S_{j,k}| = (2^k)^2 \geq \frac{y_0^2}{16} \), so we
see that \( |D_{4y_0}(x_0) \cap \mathbb{R}^2_+| \leq a |S_{j,k}| \) for \( a = 128\pi \). Therefore we obtain a finite collection \( \{W_i\} \) whose elements are comparable to each other.

Let \( M = \frac{\mu_1(W_1)}{|W_1|} = \max \frac{\mu_l(W_i)}{|W_i|} \) and \( m = \frac{\mu_2(W_2)}{|W_2|} = \min \frac{\mu_j(W_j)}{|W_j|} \). When \( z \in D_R(z_0) \), we must have \( z \in W_l \) for some \( l \), then \( E(\mu_1)(z) = \frac{\mu_1(W_l)}{|W_l|} \leq M \) and \( E(\mu_2)(z) = \frac{\mu_2(W_l)}{|W_l|} \geq m \).

Since \( W_1 \) and \( W_2 \) are comparable, by Lemma 4.3.2, we see that

\[
\mu_1(W_1) \leq C(a)\mu_2(W_2).
\]

Note that \( |W_2| \leq a |W_1| \), we obtain \( M \leq C(a)m \), for some \( C(a) > 1 \) independent of \( D_R(z_0) \). Therefore

\[
\int_{D_R(z_0)} E(\mu_1)(z)\,dV(z) \left( \int_{D_R(z_0)} E(\mu_2)(z)^{-\frac{p}{2}}\,dV(z) \right)^{\frac{p}{2}} \leq Mm^{-1} \leq c.
\]

Case (II), \( y_0 < 2R \).

Let \( S^* = \bigcup W_i \) be the union of the collection \( \{W_i\} \), then \( D_R(z_0) \cap \mathbb{R}^2_+ \subset S^* \subset D_{8R}(x_0) \cap \mathbb{R}^2_+ \). To see the second inclusion, we follow a similar argument as case (I). If \( x + iy \in D_R(z_0) \cap \mathbb{R}^2_+ \cap S_{j,k} \), for some \( j, k \in \mathbb{Z} \), then \( y \leq y_0 + R \) and \( 2^k \leq y \). Since \( y_0 < 2R \), so we see \( 2^k < 3R \). For such \( S_{j,k} \), any \( x' + iy' \in S_{j,k} \), we have \( y' \leq 2^{k+1} \leq 6R \), and \( |x' - x| \leq R + 2^k < 4R \). So \( x' + iy' \in D_{8R}(x_0) \mathbb{R}^2_+ \), and hence \( S_{j,k} \subset D_{8R}(x_0) \mathbb{R}^2_+ \) as desired.

It is easy to see \( \int_{S_{j,k}} E(\mu_1)(z)\,dV(z) = \int_{S_{j,k}} \mu_1(z)\,dV(z) \) for every \( S_{j,k} \), so we have

\[
\int_{D_R(z_0) \cap \mathbb{R}^2_+} E(\mu_1)(z)\,dV(z) \leq \int_{S^*} E(\mu_1)(z)\,dV(z) = \int_{S^*} \mu_1(z)\,dV(z) \leq \int_{D_{8R}(x_0) \cap \mathbb{R}^2_+} \mu_1(z)\,dV(z).
\]

Note that \( |D_{8R}(x_0) \cap \mathbb{R}^2_+| = 32R^2\pi \) and \( |D_R(z_0) \cap \mathbb{R}^2_+| \geq \frac{R^2}{2}\pi \), so we obtain

\[
\int_{D_R(z_0) \cap \mathbb{R}^2_+} E(\mu_1)(z)\,dV(z) \leq 64 \int_{D_{8R}(x_0) \cap \mathbb{R}^2_+} \mu_1(z)\,dV(z). \tag{4.5}
\]

46
Next, for every $S_{j,k}$, when $z \in S_{j,k}$, we have $E(\mu_2)(z)^{-\frac{p'}{p}} \leq \int_{S_{j,k}} \mu_2(z)^{-\frac{p'}{p}} dV(z)$ by Jensen’s inequality applied to the convex function $x^{-\frac{p'}{p}}$. So we see that $\int_{S_{j,k}} E(\mu_2)(z)^{-\frac{p'}{p}} dV(z) \leq \int_{S_{j,k}} \mu_2(z)^{-\frac{p'}{p}} dV(z)$, and hence

$$
\int_{D_R(x_0) \cap \mathbb{R}^2_+} E(\mu_2)(z)^{-\frac{p'}{p}} dV(z) \leq \int_{S^*} E(\mu_2)(z)^{-\frac{p'}{p}} dV(z) \\
\leq \int_{S^*} \mu_2(z)^{-\frac{p'}{p}} dV(z) \\
\leq \int_{D_R(x_0) \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{p'}{p}} dV(z).
$$

Again, by taking the average, we obtain

$$
\int_{D_R(x_0) \cap \mathbb{R}^2_+} E(\mu_2)(z)^{-\frac{p'}{p}} dV(z) \leq 64 \int_{D_R(x_0) \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{p'}{p}} dV(z). \tag{4.6}
$$

Since $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+)$, by (4.5) and (4.6), we obtain $(E(\mu_1), E(\mu_2)) \in A_p(\mathbb{R}^2_+)$.

Now we turn to another observation on the two-weight $A_p$ condition.

**Lemma 4.3.3** If $(\mu_1, \mu_2) \in A_p(\mathbb{R}^2)$, then $\mu_1 \leq c \mu_2$ for some $c > 0$.

**Proof** It is easy to see that the $A_p$ condition is equivalent to the following

$$
\mu_1(Q) \left( \int_Q f(z) dV(z) \right)^p \leq c \int_Q f(z)^p \mu_2(z) dV(z), \tag{4.7}
$$

for all $f \geq 0$ and all squares $Q$ in $\mathbb{R}^2$.

Letting $f = \chi_Q$ in (4.7), we see that $\mu_1(Q) \leq c \mu_2(Q)$ for all squares $Q$ in $\mathbb{R}^2$. But the $\sigma$-algebra can be generated from the set of squares, we obtain $\mu_1 \leq c \mu_2$ almost everywhere.

---

\(^3\)See an analogue for the one weight case in [Ste93, Chapter 5]. See also the proof of the necessary part of Theorem 6.
4.4 Proof of Theorem 6.

Before proving Theorem 6, we first prove the following proposition. Then Theorem 6 can be derived from it very easily.

**Proposition 4.4.1** For $p > 1$, if the two weights $\mu_1$ and $\mu_2$ satisfy $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+) \cap B_p^+(\mathbb{R}^2_+)$ and either $\mu_1 \in A_p^+(\mathbb{R}^2_+)$ or $\mu_2 \in A_p^+(\mathbb{R}^2_+)$, then (1.2) holds for some $C > 0$.

**Proof** We first assume $\mu_2 \in A_p^+(\mathbb{R}^2_+)$. It suffices to prove the boundedness of $\tilde{B}$ for $f \geq 0$. By Proposition 4.3.1, we have $(E(\mu_1), E(\mu_2)) \in A_p(\mathbb{R}^2_+)$ and $E(\mu_2) \in A_p(\mathbb{R}^2_+)$. We extend $E(\mu_1)$ and $E(\mu_2)$ to $\mathbb{R}^2$ by reflection about the $x$-axis, that is, $E(\mu_j)(z) = E(\mu_j)(\overline{z})$ for $z \in \mathbb{R}^2_+$, $j = 1, 2$. Then it is easy to see that $(E(\mu_1), E(\mu_2)) \in A_p(\mathbb{R}^2)$ and $E(\mu_2) \in A_p(\mathbb{R}^2)$. Hence, by Lemma 4.3.3, $E(\mu_1) \leq c E(\mu_2)$ almost everywhere, and in particular, it is true on $\mathbb{R}^2_+$. We also extend $f$ to $\mathbb{R}^2$ by setting $f(z) = 0$ for $z \in \mathbb{R}^2_+$.

Let $K(z) = \kappa(\theta)/r^2$ for $z \in \mathbb{R}^2_+ \setminus \{0\}$, where $z = re^{i\theta}$, $\kappa$ is smooth with $\kappa(\theta) = 1$ if $\theta \in [0, \pi]$, and $\int_0^{2\pi} \kappa(\theta) \, d\theta = 0$. Then $T(f) = K \ast f$ defines a singular integral operator with the cancellation property $\int |z| = 1 K(z) \, d\sigma(z) = 0$ and the radial decreasing property

$$\left| \left( \frac{\partial}{\partial x} \right)^{\alpha_1} \left( \frac{\partial}{\partial y} \right)^{\alpha_2} K(z) \right| \leq c |z|^{-2 - |\alpha|}$$

for all $z \neq 0$ and $\alpha_1 + \alpha_2 \leq 1$, where $z = x + iy$. Since $E(\mu_2) \in A_p(\mathbb{R}^2)$ and it is easy to see $E(\mu_2)$ is locally integrable on $\mathbb{R}^2$, we have

$$\int_{\mathbb{R}^2} T(f)(z)^p E(\mu_2)(z) \, dV(z) \leq c \int_{\mathbb{R}^2} f(z)^p E(\mu_2)(z) \, dV(z)$$

for all $f \in L^p(\mathbb{R}^2, E(\mu_2))$. Letting $J f(z) = f(\overline{z})$, since $E(\mu_2)(\overline{z}) = E(\mu_2)(z)$, we have

$$\int_{\mathbb{R}^2} T(J f)(z)^p E(\mu_2)(z) \, dV(z) \leq c \int_{\mathbb{R}^2} J f(z)^p E(\mu_2)(z) \, dV(z)$$

$$= c \int_{\mathbb{R}^2} f(z)^p E(\mu_2)(z) \, dV(z)$$

$$= c \int_{\mathbb{R}^2_+} f(z)^p E(\mu_2)(z) \, dV(z)$$

---

4This follows from the classical result of weighted $L^p$ boundedness of singular integrals. For a general consideration of this topic, see [Ste93, Chapter 5, Chapter 6 §4.5, and Chapter 7] for details.
for our extended $f$. Noting that $T(Jf)(z) = K * Jf(z) = \tilde{B}(f)(z)$ for $z \in \mathbb{R}^2_+$, we see that

$$\int_{\mathbb{R}^2_+} \tilde{B}(f)(z)^p E(\mu_2)(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} f(z)^p E(\mu_2)(z) \, dV(z).$$

Together with the relation $E(\mu_1) \leq cE(\mu_2)$, we obtain

$$\int_{\mathbb{R}^2_+} \tilde{B}(f)(z)^p E(\mu_1)(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} f(z)^p E(\mu_2)(z) \, dV(z).$$

(4.8)

Now, for $f \geq 0$, as in [LS04, Proposition 4.5], we have

$$\int_{\mathbb{R}^2_+} \left( \tilde{B}(f)(z) \right)^p \mu_1(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} \left( E \tilde{B} E (f)(z) \right)^p \mu_1(z) \, dV(z)$$

$$\leq c \int_{\mathbb{R}^2_+} E \left( \tilde{B} E (f)(z) \right)^p \mu_1(z) \, dV(z)$$

$$= c \int_{\mathbb{R}^2_+} \left( \tilde{B} E (f)(z) \right)^p E(\mu_1)(z) \, dV(z)$$

$$\leq c \int_{\mathbb{R}^2_+} (E(f)(z))^p E(\mu_2)(z) \, dV(z),$$

(4.9)

where the first line follows from (4.1), the second line follows from Proposition 4.2.1 (b), the third line follows from Proposition 4.2.1 (a), and the last line follows from (4.8).

On the other hand, by Proposition 4.2.1 (c), we see

$$E(f)(z) = E(f \mu_2^\frac{1}{p} \cdot \mu_2^{-\frac{1}{p}})(z) \leq \left( E(f\mu_2)(z) \right)^{\frac{1}{p}} \left( E(\mu_2^{-\frac{1}{p}})(z) \right)^{\frac{1}{p}}.$$

(4.10)

For any $z = x + iy \in S_{j,k}$, let $x_0$ be the real part of the center of $S_{j,k}$, then $|z - x_0| \leq 2^k + 2^{k+1} \leq 2^{k+2}$. Let $D = D_{2^{k+2}}(x_0)$ be the special disk of radius $2^{k+2}$ centered at
for some $c > 0$ independent of $S_{j,k}$. Therefore combining (4.9), (4.10) and (4.11), we see that

$$
\int_{\mathbb{R}^2_+} \left( \mathcal{B}(f)(z) \right)^p \mu_1(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} E(f^p \mu_2)(z) \left( E(\mu_2^{-\frac{p'}{p}})(z) \right)^{\frac{p}{p'}} E(\mu_2)(z) \, dV(z)
$$

$$
\leq c \sum_{j,k} \int_{S_{j,k}} E(f^p \mu_2)(z) \, dV(z)
$$

$$
= c \int_{\mathbb{R}^2_+} f(z)^p \mu_2(z) \, dV(z)
$$

for $f \in L^p(\mathbb{R}^2_+, \mu_2)$, which completes the proof of the case $\mu_2 \in A_p^+(\mathbb{R}^2_+)$. 

Now assume $\mu_1 \in A_p^+(\mathbb{R}^2_+)$. Then we have $E(\mu_1) \in A_p(\mathbb{R}^2_+)$. Almost the same argument shows that (4.9) becomes

$$
\int_{\mathbb{R}^2_+} \left( \mathcal{B}(f)(z) \right)^p \mu_1(z) \, dV(z) \leq c \int_{\mathbb{R}^2_+} (E(f)(z))^p E(\mu_1)(z) \, dV(z),
$$

and (4.11) becomes

$$
E(\mu_1)(z) \left( E(\mu_2^{-\frac{p'}{p}})(z) \right)^{\frac{p}{p'}} \leq c,
$$

since $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+)$. This completes the proof.

Now we are ready to prove Theorem 6.

**Theorem 6** For $p > 1$, suppose that $\mu_1$ and $\mu_2$ are two weights such that $c\mu_1 \geq \mu_2$ for some $c > 0$. Then (1.2) holds for some $C > 0$ if and only if $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+)$. 

50
Proof The sufficiency is immediate. Since \((\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)\) and \(c\mu_1 \geq \mu_2\), it is easy to see that \(\mu_2 \in A^+_p(\mathbb{R}^2_+)\), then the boundedness of \(B\) follows from Proposition 4.4.1.

Now we show the necessary part. For any special disk \(D = D_R(x_0)\) with \(x_0 \in \mathbb{R}\) and \(R > 0\), let \(D' = D_R(x_0 + 10Ri)\) be the disk\(^5\) with the same radius but centered at \((x_0, 10R) \in \mathbb{R}^2_+\). For this pair \(D\) and \(D'\), we see that if \(z \in D'\) and \(w \in D\), or if \(z \in D\) and \(w \in D'\), we have \(\Re\left(-\frac{1}{(z-w)^2}\right) \geq cR^{-2}\) for some \(c > 0\). If \(B\) is bounded, we see that

\[
\int_{D \cap \mathbb{R}^2_+} |B(f)(z)|^p \mu_1(z) dV(z) \leq c \int_{\mathbb{R}^2_+} |f(z)|^p \mu_2(z) dV(z). \tag{4.12}
\]

Taking \(f = \chi_{D'}\) in (4.12), we obtain

\[
\mu_1(D \cap \mathbb{R}^2_+) \leq c \mu_2(D') \leq c \mu_1(D'). \tag{4.13}
\]

On the other hand, for any \(f \geq 0\) on \(\mathbb{R}^2_+\), we apply (4.12) to the function \(f \chi_{D' \cap \mathbb{R}^2_+}\), provided \(f \chi_{D' \cap \mathbb{R}^2_+} \in L^p(\mathbb{R}^2_+, \mu_2)\). We see that

\[
\int_{D'} |B(f)(z)|^p \mu_1(z) dV(z) \leq \int_{\mathbb{R}^2_+} |B(f)(z)|^p \mu_1(z) dV(z) \leq c \int_{D' \cap \mathbb{R}^2_+} f(z)^p \mu_2(z) dV(z)
\]

and, for \(z \in D'\),

\[
|B(f)(z)|^p \geq \left( cR^{-2} \int_{D' \cap \mathbb{R}^2_+} f(w)^p dV(w) \right)^p \geq c \left( \int_{D' \cap \mathbb{R}^2_+} f(z)^p dV(z) \right)^p.
\]

So we obtain

\[
\mu_1(D') \left( \int_{D' \cap \mathbb{R}^2_+} f(z)^p dV(z) \right)^p \leq c \int_{D' \cap \mathbb{R}^2_+} f(z)^p \mu_2(z) dV(z), \tag{4.14}
\]

provided \(f \chi_{D' \cap \mathbb{R}^2_+} \in L^p(\mathbb{R}^2_+, \mu_2)\). Therefore, combining (4.13) and (4.14), we have

\[
\mu_1(D \cap \mathbb{R}^2_+) \left( \int_{D \cap \mathbb{R}^2_+} f(z)^p dV(z) \right)^p \leq c \int_{D \cap \mathbb{R}^2_+} f(z)^p \mu_2(z) dV(z), \tag{4.15}
\]

for some \(c > 0\), provided \(f \chi_{D \cap \mathbb{R}^2_+} \in L^p(\mathbb{R}^2_+, \mu_2)\).

\(^{5}\)Here \(i\) denotes \(\sqrt{-1}\) as usual.
To show (4.15) is indeed the $A_p^+(\mathbb{R}_+^2)$ condition, we argue as in the proof of the necessary part of [Muc72, Theorem 1]. Suppose that $\int_{D \cap \mathbb{R}_+^2} \mu_2(z)^{-\frac{1}{p'}} dV(z) = \infty$. Then, by duality of the space $L^p(D \cap \mathbb{R}_+^2)$, there is a $g \in L^p(D \cap \mathbb{R}_+^2)$, so that $\int_{D \cap \mathbb{R}_+^2} g(z) \mu_2(z)^{-\frac{1}{p}} dV(z) = \infty$. Take $f = g \mu_2^{-\frac{1}{p}} \chi_{D \cap \mathbb{R}_+^2}$ in (4.15). Then $\int_{D \cap \mathbb{R}_+^2} f(z) dV(z) = \infty$ and $\int_{D \cap \mathbb{R}_+^2} f(z)^p \mu_2(z) dV(z) < \infty$. So (4.15) gives $\mu_1(D \cap \mathbb{R}_+^2) = 0$, which contradicts the assumption $\mu_1 > 0$ almost everywhere. So we see that $\int_{D \cap \mathbb{R}_+^2} \mu_2(z)^{-\frac{1}{p'}} dV(z) < \infty$.

Now take $f = (\mu_2)^{-\frac{1}{p'}} \chi_{D \cap \mathbb{R}_+^2}$ in (4.15) and note that

$$\int_{D \cap \mathbb{R}_+^2} f(z)^p \mu_2(z) dV(z) = \int_{D \cap \mathbb{R}_+^2} \mu_2(z)^{-\frac{1}{p'}} dV(z) < \infty,$$

since $\frac{1}{p'} = p' - 1$. We see (4.15) implies the $A_p^+(\mathbb{R}_+^2)$ condition.

In fact, (4.15) is equivalent to the $A_p^+(\mathbb{R}_+^2)$ condition. The other direction, the $A_p^+(\mathbb{R}_+^2)$ condition implies (4.15), follows easily from the Hölder’s inequality applied to the integral

$$\int_{D \cap \mathbb{R}_+^2} f(z) \mu_2(z)^{\frac{1}{p}} \mu_2(z)^{-\frac{1}{p'}} dV(z).$$
5. A Wider Class of Weights

In this chapter, we apply Theorem 6 to extend the previous results to a wider class of weights.

5.1 Alternative Proof of Theorem 2 and Its Extension

Before giving an alternative proof of Theorem 2, we first have the following observation.

**Proposition 5.1.1** For $z \in \mathbb{R}^2_+, k \in \mathbb{Z}, s \in (0, 2]$ and $p > 1$, suppose

$$\mu_1(z) = \left| \frac{i - z}{i + z} \right|^{-(k + 1)p + s + 2k}$$

and

$$\mu_2(z) = \left| \frac{i - z}{i + z} \right|^{(1-s-k)p + s + 2k},$$

then $(\mu_1, \mu_2) \not\in A_p(\mathbb{R}^2_+)$ for $s \neq 2$. But we have $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+)$ if and only if $s + 2k + 2 > (k + 1)p$ and $p(s + k + 1) > s + 2k + 2$.

**Proof** To show $(\mu_1, \mu_2) \not\in A_p(\mathbb{R}^2_+)$, we consider any disk $D_\epsilon(i)$ centered at $i$ with radius $\epsilon < \frac{1}{2}$. For $z \in D_\epsilon(i)$, since $|i - z| < \epsilon < \frac{1}{2}$, we see that $\frac{3}{2} \leq |i + z| \leq \frac{5}{2}$. So, by Definition 4.1.1, we only need to look at

$$\int_{D_\epsilon(i)} |i - z|^{-(k + 1)p + s + 2k} dV(z) \left( \int_{D_\epsilon(i)} |i - z|^{-(1-s-k)p + s + 2k} dV(z) \right)^{\frac{p}{p'}}.$$
Assuming both integrands are integrable, we obtain $\epsilon^{(s-2)p}$. But $s \in (0, 2)$ and $p > 1$, so we see the quantity above tends to $\infty$ as $\epsilon \to 0$.

To show $(\mu_1, \mu_2) \in A_+^+ (\mathbb{R}_+^2)$, we consider two integrals

$$I_1 = \frac{1}{|D \cap \mathbb{R}_+^2|} \int_{D \cap \mathbb{R}_+^2} \frac{|i - z|^{-(k+1)p+s+2k}}{|i + z|} dV(z),$$

and

$$I_2 = \frac{1}{|D \cap \mathbb{R}_+^2|} \int_{D \cap \mathbb{R}_+^2} \frac{|i - z|^{-(1-s-k)p+s+2k}}{|i + z|} dV(z),$$

where $D = D_R(x_0)$ is any special disk with radius $R$ centered at $x_0 \in \mathbb{R}$. Let $D_0 = D_{\frac{1}{2}} (i)$ be the disk with radius $\frac{1}{2}$ centered at $i$. We separate our arguments into two cases.

Case (I), $R < \frac{1}{2}$.

It is easy to see that $D \cap D_0 = \emptyset$ hence $|i - z| > \frac{1}{2}$. Note that, as $|z| \to \infty$, $\frac{|i - z|}{|i + z|} \to 1$, so there is an $M$ such that, when $|z| > M$, $1 \geq \frac{|i - z|}{|i + z|} \geq \frac{1}{2}$. But when $|z| \leq M$, $|i + z| \leq M + 1$, so $1 \geq \frac{|i - z|}{|i + z|} \geq \frac{1}{2(M+1)}$. Therefore, the integrands in $I_1$ and $I_2$ are bounded above by some constants that are independent of the special disk $D$. Then $I_1 I_2 \leq c$, for some $c > 0$.

Case (II), $R \geq \frac{1}{2}$.

We split both $I_1$ and $I_2$ into two integrals respectively, one integrates over $D \cap \mathbb{R}_+^2 \setminus D_0$ and the other integrates over $D \cap \mathbb{R}_+^2 \cap D_0$. For the same reasoning as in case (I), the parts integrated over $D \cap \mathbb{R}_+^2 \setminus D_0$ is bounded. The parts integrated over $D \cap \mathbb{R}_+^2 \cap D_0$ are bounded respectively by

$$\frac{8}{\pi} \int_{D_0} \frac{|i - z|^{-(k+1)p+s+2k}}{|i + z|} dV(z),$$

and

$$\frac{8}{\pi} \int_{D_0} \frac{|i - z|^{-(1-s-k)p+s+2k}}{|i + z|} dV(z).$$
Since $|i - z| \leq \frac{1}{2}$ for $z \in D_0$, we see that $\frac{3}{2} \leq |i + z| \leq \frac{5}{2}$, so the two integrals above are bounded respectively by

$$c \int_{D_0} |i - z|^{-(k+1)p+s+2k} \, dV(z)$$

and

$$c \int_{D_0} |i - z|^{-\frac{p'}{p}((1-s-k)p+s+2k)} \, dV(z).$$

The first integral above is bounded by a constant if and only if $-(k+1)p+s+2k+2 > 0$, and the second is bounded if and only if $-\frac{p'}{p}[(1-s-k)p+s+2k] + 2 > 0$. Solving the two inequalities, we see that $s + 2k + 2 > (k+1)p$ and $p(s + k + 1) > s + 2k + 2$.

**Remark 5.1.2** From the proof we see that if two weights $c\mu_1 \geq \mu_2$ only have zeros or poles away from the $x$-axis and bounded above and below at $\infty$, then $(\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+)$ if and only if both $\mu_1$ and $\mu_2 - \frac{p'}{p}$ are locally integrable.

**Remark 5.1.3** Combining the fact that $c\mu_1 \geq \mu_2$ with Theorem 6 we see that, for the Bergman projection on $\mathbb{R}^2_+$, the two-weight $A_p$ condition is not a necessary condition for (1.2) (compare to the general Calderón-Zygmund type singular integral). The reason is that the Bergman kernel is not singular at all on $\mathbb{R}^2_+$, and it should be a two dimensional analogue of the so-called Hilbert integral.\(^1\)

Now we are ready to give an alternative proof of Theorem 2.

**Theorem 2** For $s' \in \mathbb{R}$ with the unique expression $s' = s + 2k$, where $k \in \mathbb{Z}$ and $s \in (0, 2]$, let $B_{s'}$ be the weighted Bergman projection on the space $(\mathbb{D}^*, \mu)$, where $\mu(z) = |z|^{s'}$.

(a) For $s' \in (0, \infty)$, $B_{s'}$ is $L^p(\mu)$ bounded if and only if $p \in \left(\frac{s+2k+2}{s+k+1}, \frac{s+2k+2}{k+1}\right)$.

(b) For $s' \in [-3, 0]$, $B_{s'}$ is $L^p(\mu)$ bounded for $p \in (1, \infty)$.

\(^1\)See also [PS86a, PS86b].
(c) For \( s' \in (-4, -3) \), with \( k = -2 \) and \( s \in (0, 1) \), \( \mathcal{B}_{s'} \) is \( L^p(\mu) \) bounded if and only if
\[ p \in \left( 2 - s, \frac{2 + s}{1 - s} \right). \]

(d) When \( s' = -4 \), \( \mathcal{B}_{-4} \) is \( L^p(\mu) \) bounded for \( p \in (1, \infty) \).

(e) For \( s' \in (-\infty, -4) \), \( \mathcal{B}_{s'} \) is \( L^p(\mu) \) bounded if and only if
\[ p \in \left( \frac{s + 2k + 2}{k + 1}, \frac{s + 2k + 2}{s + k + 1} \right). \]

**Proof**

For \( s' = s + 2k \), from (3.1) we know that
\[
\mathcal{B}_{s'}(z, \zeta) = \frac{s}{2} (z\overline{\zeta})^{-(k+1)} B_0(z, \zeta) + \left( 1 - \frac{s}{2} \right) (z\overline{\zeta})^{-k} B_0(z, \zeta)
\]
in \( D^* \). So we may write \( \mathcal{B}_{s'} = \frac{s}{2} \mathcal{T}_1 + (1 - \frac{s}{2}) \mathcal{T}_2 \), where \( \mathcal{T}_1 \) is the operator associated to the kernel \((z\overline{\zeta})^{-(k+1)} B_0(z, \zeta)\) with weight \(|\zeta|^{s'}\) and \( \mathcal{T}_2 \) is the operator associated to the kernel \((z\overline{\zeta})^{-k} B_0(z, \zeta)\) with weight \(|\zeta|^s\).

For the operator \( \mathcal{T}_1 \), showing its boundedness is the same as showing
\[
\int_{D^*} \left| \int_{D^*} \frac{(z\overline{\zeta})^{-(k+1)} f(\zeta)}{(1 - z\overline{\zeta})^2} |\zeta|^{s'} dV(\zeta) \right|^p |z|^s dV(z) \leq C \int_{D^*} |f(z)|^p |z|^{s'} dV(z).
\]

By the Cayley transform \( \varphi : \mathbb{R}^2_+ \to \mathbb{D} \), where \( \varphi(z) = \frac{i - z}{i + z} \), and using the notations in Chapter 4, we see the above inequality is equivalent to
\[
\int_{\mathbb{R}^2_+ - \{i\}} \left| \int_{\mathbb{R}^2_+ - \{i\}} - \frac{\tilde{f}(w) dV(w)}{(z - w)^2} \right|^p \mu_1(z) dV(z) \leq C \int_{\mathbb{R}^2_+ - \{i\}} \left| \tilde{f}(z) \right|^p \mu_2(z) dV(z),
\]
where \( \tilde{f}(z) = f(\varphi(z)) \varphi(z)^{k+1} |\varphi(z)|^{s-2} \cdot \left| \frac{i - z}{i + z} \right|^{-(k+1)p+s+2k} \cdot \left| \frac{i - z}{i + z} \right|^{-p} \) and \( \mu_2(z) = 4 \left| \frac{i - z}{i + z} \right|^{1-s-k+p+s+2k} \cdot \left| \frac{i - z}{i + z} \right|^{2-p} \cdot \left| \frac{i - z}{i + z} \right|^{2-p} \). This is exactly (1.2), except that \( \mu_1 \) and \( \mu_2 \) are only locally integrable on \( \mathbb{R}^2_+ \setminus \{i\} \)—not on \( \mathbb{R}^2_+ \). However, since \( \left| \frac{i - z}{i + z} \right| \leq 1 \) and \( s \leq 2 \), we have \( \mu_1(z)/\mu_2(z) = |(i - z)/(i + z)|^{(s-2)p} \geq 1 \), so the local integrability of \( \mu_2 \) will be guaranteed by the local integrability of \( \mu_1 \) at \( i \) as we will see below. Moreover, by the relation \( \mu_1 \geq \mu_2 \), Theorem 6 applies,\(^2\) that is, \( \mathcal{T}_1 \) is bounded if and only if \( (\mu_1, \mu_2) \in A_p^+(\mathbb{R}^2_+) \).

\(^2\)From the proof of the necessity, we see the boundedness of \( \mathcal{T}_1 \) will imply the local integrability of \( \mu_1 \) and \( \mu_2 \) at \( i \).
For the condition $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)$, we first note that $\sigma(z) = \left| \frac{1}{i+z} \right|^{2-p} \in A^+_p(\mathbb{R}^2_+)$ for all $p > 1$. To see this, from the classical result $B_0$ is $L^p$ bounded for all $p > 1$, where $B_0$ is the ordinary Bergman projection on $D^*$ which is the same as the ordinary Bergman projection on the unit disk. Then (1.2) holds with both $\mu_1$ and $\mu_2$ replaced by $\sigma$, and hence $\sigma \in A^+_p(\mathbb{R}^2_+)$ for all $p > 1$ by Theorem 6.3

As in Proposition 5.1.1, we consider two integrals

$$I_1 = \frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} 4 \left| \frac{i-x}{i+z} \right|^{-(k+1)p+s+2k} \cdot \left| \frac{1}{i+z} \right|^{2-p} dV(z)$$

and

$$I_2 = \frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} \left( 4 \left| \frac{i-x}{i+z} \right|^{(1-s-k)p+s+2k} \cdot \left| \frac{1}{i+z} \right|^{2-p} \right)^{-\frac{p'}{p}} dV(z),$$

where $D = D_R(x_0)$ is again any special disk with radius $R$ centered at $x_0 \in \mathbb{R}$.

For $R < 1/2$, the same argument as in the proof of Proposition 5.1.1 case (I), shows that the integrands in $I_1$ and $I_2$ are bounded above by $c \sigma$ and $c \sigma^{-\frac{p'}{p}}$ respectively. So this case follows from the fact that $\sigma \in A^+_p(\mathbb{R}^2_+)$ for all $p > 1$.

For $R \geq 1/2$, the same argument as in the proof of Proposition 5.1.1 case (II) and Remark 5.1.2 show that we only need to consider whether

$$|i-z|^{-(k+1)p+s+2k} \quad \text{and} \quad |i-z|^{-\frac{p'}{p}(1-s-k)p+s+2k}$$

are locally integrable away from the $x$-axis. This shows the local integrabilities of $\mu_1$ and $\mu_2$ and, by Proposition 5.1.1, we see this is true if and only if $s+2k+2 > (k+1)p$ and $p(s+k+1) > s+2k+2$.

Denoting by $U_1 = \{ p \in (1, \infty) \mid s+2k+2 > (k+1)p \text{ and } p(s+k+1) > s+2k+2 \}$ the range for $p$, it is not difficult to see that $U_1$ is an open interval. So we obtain $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)$ and hence $T_1$ is bounded if and only if $p \in U_1$.

Indeed, the fact that $\sigma \in A^+_p(\mathbb{R}^2_+)$ for all $p > 1$ can be derived by a direct computation.
Similarly, $\mathcal{T}_2$ is bounded if and only if (1.2) holds for $\mu_1(z) = 4\sigma(z)\left|\frac{i-z}{i+z}\right|^{-kp+\epsilon+2k}$ and $\mu_2(z) = 4\sigma(z)\left|\frac{i-z}{i+z}\right|^{-(s+k)p+\epsilon+2k}$. Again, $\mu_1$ and $\mu_2$ may not be locally integrable. Fortunately, we have $\mu_1(z)/\mu_2(z) = |(i-z)/(i+z)|^{sp} \leq 1$, since $|(i-z)(i+z)| \leq 1$ and $s > 0$. So we do not need both of $\mu_1$ and $\mu_2$ to be locally integrable, indeed, they will not be in some cases. We instead apply Theorem 6 to a single weight, either to $\mu_1$ or to $\mu_2$, then by $\mu_1 \leq \mu_2$ we get the desired inequality. That is, $\mathcal{T}_2$ is bounded if $\mu_1 \in A^+_p(\mathbb{R}^2_+) \cap L^1_{loc}(\mathbb{R}^2_+)$ or $\mu_2 \in A^+_p(\mathbb{R}^2_+) \cap L^1_{loc}(\mathbb{R}^2_+)$.

Following a similar argument, $\mu_j \in A^+_p(\mathbb{R}^2_+)$ will guarantee the local integrability of $\mu_j$, for $j = 1, 2$. Then we see, by listing all possibilities of $k \in \mathbb{Z}$, $\mu_1 \in A^+_p(\mathbb{R}^2_+)$ or $\mu_2 \in A^+_p(\mathbb{R}^2_+)$ if and only if $p \in U_2 = \{p \in (1, \infty) \mid s+2k+2 > pk \text{ and } (s+k+2)p > s+2k+2\}$ for $s \neq 2$. But for $s = 2$ we do not need to worry about $\mathcal{T}_2$, since $\mathcal{B}_\sigma = \frac{s}{2}\mathcal{T}_1 + (1 - \frac{s}{2})\mathcal{T}_2$. It is not hard to see that $U_2$ is also an open interval, and we have $\mathcal{T}_2$ is bounded if $p \in U_2$.

Now, if both $\mathcal{T}_1$ and $\mathcal{T}_2$ are bounded, then $\mathcal{B}_\sigma$ is bounded. Since a simple argument shows that $U_1 \subset U_2$ properly, we see that $\mathcal{B}_\sigma$ is bounded if $p \in U_1$. Conversely, if we look at the endpoint $p$ of $U_1$, then $p \notin U_1$ but $p \in U_2$. In this case, we see that $\mathcal{T}_1$ is unbounded, $\mathcal{T}_2$ is bounded, and hence $\mathcal{B}_\sigma$ is unbounded. So by interpolation we see that $\mathcal{B}_\sigma$ is unbounded for all $p \notin U_1$.

Therefore, for $p > 1$, $\mathcal{B}_\sigma$ is bounded if and only if $p \in U_1$. When $s' \in (0, \infty)$, $U_1 = \left(\frac{s+2k+2}{s+k+1}, \frac{s+2k+2}{k+1}\right)$. When $s' \in [-3, 0]$, $U_1 = (1, \infty)$. When $s' \in (-4, -3)$, $U_1 = (2-s, \frac{2-s}{1-s})$.

When $s' = -4$, $U_1 = (1, \infty)$. When $s' \in (-\infty, -4)$, $U_1 = (\frac{s+2k+2}{k+1}, \frac{s+2k+2}{s+k+1})$.

### Remark 5.1.4

Besides Theorem 6, the analysis for $\mathcal{T}_2$ here also supports our Conjecture 1, since the “effective” bound for $p$ is obtained by checking that $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)$. Note that, in this case, we may extend our Conjecture 1 to a more general situation, that is, without the assumption of local integrabilities of $\mu_1$ and $\mu_2$. 

58
Now we extend the arguments above to prove Theorem 7.

**Theorem 7** Assume that \( p > 1 \). Let \( \mu(z) = |z|^s' |g(z)|^2 \), where \( g \) is a non-vanishing holomorphic function on \( \mathbb{D} \) and \( s' \in \mathbb{R} \). Suppose the weighted Bergman projection \( B_{|g|^2} \) on \((\mathbb{D}, |g|^2)\) is \( L^p(|g|^2) \) bounded, and suppose the weighted Bergman projection \( B_{s'} \) on \((\mathbb{D}^*, |z|^{s'})\) is \( L^p(|z|^{s'}) \) bounded. Then the weighted Bergman projection \( B_{\mu} \) on \((\mathbb{D}^*, \mu)\) is \( L^p(\mu) \) bounded.

Moreover, suppose \( B_{|g|^2} \) is \( L^p(|g|^2) \) bounded if and only if \( p \in (p_0, p_0') \) for some \( p_0 \geq 1 \) and suppose \( B_{s'} \) is \( L^p(|z|^{s'}) \) bounded if and only if \( p \in (p_1, p_1') \) for some \( p_1 \geq 1 \) as in Theorem 2. If \((p_1, p_1') \subset (p_0, p_0')\) properly, then \( B_{\mu} \) is \( L^p(\mu) \) bounded if and only if \( p \in (p_1, p_1') \).

**Proof** For the Bergman kernel on the weighted space \((\mathbb{D}, |g|^2)\), we have

\[
B_{|g|^2}(z, \zeta) = \frac{1}{g(z)g(\zeta)} \frac{1}{(1 - z\zeta)^2}.
\]

This follows from applying Lemma 2.2.1 with the isometry,

\[
F : L^2(\mathbb{D}, |g|^2) \rightarrow L^2(\mathbb{D})
\]

where\(^4\) \( F(f) = fg \) for \( f \in L^2(\mathbb{D}, |g|^2) \). Similar arguments as in the alternative proof of Theorem 2 show that \( B_{|g|^2} \) is \( L^p \) bounded if and only if (1.2) holds with both \( \mu_1 \) and \( \mu_2 \) replaced by \( \sigma(z) = \left| g(\varphi(z)) \cdot \frac{1}{(1 + z)^2} \right|^{2-p} \). From the statement of Theorem 7, \( B_{|g|^2} \) is \( L^p(|g|^2) \) bounded if and only if \( p \in (p_0, p_0') \) for some \( p_0 \geq 1 \). So, by Theorem 6, we see that \( \sigma \in A^+_p(\mathbb{R}^2_+) \) if and only if \( p \in (p_0, p_0') \).

Note that \( \mu(z) = |z|^s' |g(z)|^2 \) on \( \mathbb{D}^* \). The same argument above applies to the weighted Bergman projection \( B_{\mu} \), whose associated weighted Bergman kernel is

\[
B_{\mu}(z, \zeta) = \frac{1}{g(z)g(\zeta)} B_{s'}(z, \zeta).
\]

\(^4\)See also [Zey13, Theorem 3.4].
Then by the relation $B_{s'} = \frac{s}{2} T_1 + (1 - \frac{s}{2}) T_2$ in the alternative proof of Theorem 2 above, $B_\mu$ is $L^p(\mu)$ bounded if (1.2) holds both for the first pair

$$
\mu_1(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-(k+1)p + s + 2k}, \quad \mu_2(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-(1 - s-k)p + s + 2k},
$$

and for the second pair

$$
\mu_1(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-kp + s + 2k}, \quad \mu_2(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-(s+k)p + s + 2k}.
$$

Follow the same argument as in the alternative proof of Theorem 2 above, and noting that $g$ is bounded above and below on the disk $D_\frac{1}{2}(i)$ with radius $\frac{1}{2}$ centered at $i$, we see (1.2) holds for the first pair if and only if $p \in (p_0, p'_0) \cap (p_1, p'_1)$. Similarly, (1.2) holds for the second pair if $p \in (p_0, p'_0) \cap U$, for some larger open interval $U$ which contains $p_1$ and $p'_1$. Therefore $B_\mu$ is $L^p(\mu)$ bounded if $p \in (p_0, p'_0) \cap (p_1, p'_1)$.

If, in addition, $(p_1, p'_1) \subset (p_0, p'_0)$ properly then, for $p = p_1$ and $p = p'_1$, (1.2) fails for the first pair, but holds for the second. So $B_{s', |g|^2}$ is unbounded for these $p$s. Hence $B_\mu$ is bounded if and only if $p \in (p_1, p'_1)$.

By inflation, we can extend the previous result to a wider class of weights on the Hartogs triangle. Namely, we consider a weight of the form $\lambda(z) = |z_2|^{s'-2} |g(z_2)|^2$ for $z \in \mathbb{H}$, where $g$ is some non-vanishing holomorphic function on $\mathbb{D}$.

**Theorem 8** Assume that $p > 1$. Let $\lambda$ be as above, and let $p_0$, $p_1$ be as in Theorem 7. Then the weighted Bergman projection $B_\lambda$ on $(\mathbb{H}, \lambda)$ is $L^p(\lambda)$ bounded if $p \in (p_0, p'_0) \cap (p_1, p'_1)$. In addition, if $(p_1, p'_1) \subset (p_0, p'_0)$ properly, then $B_\lambda$ is $L^p(\lambda)$ bounded if and only if $p \in (p_1, p'_1)$.

**Proof** This is a direct consequence of Proposition 2.2.6 and Theorem 7.\[5If (p_1, p'_1) = (1, \infty), then the conclusion is trivial.\]}
5.2 A Two-weight Estimate on the Hartogs Triangle

As a last application in this chapter, we use the two-weight inequality to prove the $L^p$ regularity of the weighted Bergman projection $B_{\mathbb{H}, 2k+2}$ on $(\mathbb{H}, |z_2|^{2k+2})$ mapping from $L^p(\mathbb{H}, |z_2|^{2k+2})$ to $L^p(\mathbb{H}, |z_2|^t)$ for some $t \in \mathbb{R}$. For simplicity, we focus on $k \geq -1$ and $k \in \mathbb{Z}$.

Theorem 9 Suppose that $B_{\mathbb{H}, 2k+2}$ is the weighted Bergman projection on the weighted space $(\mathbb{H}, |z_2|^{2k+2})$. Assume $p > 1$ and $k \geq -1$. Then, for $t \leq 2k+2$, $B_{\mathbb{H}, 2k+2}$ is $L^p$ bounded from $L^p(\mathbb{H}, |z_2|^{2k+2})$ to $L^p(\mathbb{H}, |z_2|^t)$ if and only if $p \in (\frac{2k+6}{k+1}, \frac{t+4}{k+2})$. For $t > 2k+2$, $B_{\mathbb{H}, 2k+2}$ is bounded from $L^p(\mathbb{H}, |z_2|^{2k+2})$ to $L^p(\mathbb{H}, |z_2|^t)$ if $p \in (\frac{2k+6}{k+1}, \frac{2k+6}{k+2}) \cup (\frac{t+4}{k+1}, \frac{t+4}{k+2})$.

Proof The boundedness of the mapping is equivalent to

$$\int_{\mathbb{H}} |B_{\mathbb{H}, 2k+2}(f)(z)|^p |z_2|^t \, dV(z) \leq C \int_{\mathbb{H}} |f(z)|^p |z_2|^{2k+2} \, dV(z).$$

By Corollary 2.2.2, and considering the biholomorphism $\Phi : \mathbb{H} \to \mathbb{D} \times \mathbb{D}^*$ via $\Phi(z) = (\frac{z_1}{z_2}, z_2)$, the above inequality is equivalent to

$$\int_{\mathbb{D} \times \mathbb{D}^*} \left| \int_{\mathbb{D} \times \mathbb{D}^*} B_0 \otimes B_{2k+2}(z, \zeta) f(\zeta) \zeta^{2k+2} \, dV(\zeta) \right|^p |z_2|^{t+2-p} \, dV(z) \leq C \int_{\mathbb{D} \times \mathbb{D}^*} |f(z)|^p |z_2|^{2k+4-p} \, dV(z),$$

where $B_{2k+2}$ is the weighted Bergman kernel on $(\mathbb{D}^*, |z|^{2k+2})$ and $B_0$ is the ordinary Bergman kernel on $\mathbb{D}$. By Lemma 2.2.4, and the fact that the ordinary Bergman projection on the unit disk is $L^p$ bounded for all $p > 1$, we see that the above inequality is equivalent to

$$\int_{\mathbb{D}^*} \left| \int_{\mathbb{D}^*} B_{2k+2}(z, \zeta) f(\zeta) |\zeta|^{2k+2} \, dV(\zeta) \right|^p |z|^{t+2-p} \, dV(z) \leq C \int_{\mathbb{D}^*} |f(z)|^p |z|^{2k+4-p} \, dV(z).$$
Applying the same argument as in the alternative proof of Theorem 2, since \( s = 2 \), we see that \( \mathcal{B}_{H,2k+2} \) is bounded if (1.2) holds for

\[
\mu_1(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-(k+2)p+t+2} \quad \text{and} \quad \mu_2(z) = 4\sigma(z) \left| \frac{i - z}{i + z} \right|^{-(k+2)p+2k+4},
\]

where \( \sigma(z) = \left| \frac{1}{(i+z)^2} \right|^{2-p} \in A_p^+(\mathbb{R}^2_+) \) for all \( p > 1 \).

When \( t \leq 2k + 2 \), Theorem 6 tells us that \( \mathcal{B}_{H,2k+2} \) is bounded if and only if \( p \in \left( \frac{2k+6}{k+3}, \frac{t+4}{k+2} \right) \). When \( t > 2k + 2 \), Theorem 6 again tells us that \( \mathcal{B}_{H,2k+2} \) is bounded if \( p \in \left( \frac{2k+6}{k+3}, \frac{2k+6}{k+2} \right) \cup \left( \frac{t+4}{k+3}, \frac{t+4}{k+2} \right) \). This completes the proof.

**Remark 5.2.1** If we take \( k = -1 \) and \( t = p - 2 \), then Theorem 9 will imply [CZ14, Theorem 1.1].
6. More Analysis on the \( A_p^+ (\mathbb{R}_+^2) \) Class

To prove Conjecture 1 and Conjecture 2 introduced in Chapter 1, we need a better understanding of the \( A_p^+ (\mathbb{R}_+^2) \) class. In this chapter, we introduce the special maximal function operator and prove Theorem 10 and Theorem 11.

6.1 Preliminaries and Basic Definitions

In Chapter 4, we introduced the \( A_p^+ (\mathbb{R}_+^2) \) class for \( p > 1 \). Now we extend this class to the case \( p = 1 \).

Definition 6.1.1 Two weights \( \mu_1 \) and \( \mu_2 \) on \( \mathbb{R}_+^2 \) are in the class \( A_1^+ (\mathbb{R}_+^2) \), denoted by the ordered pair \( (\mu_1, \mu_2) \in A_1^+ (\mathbb{R}_+^2) \), if there is a \( c > 0 \) so that, for all special disks \( D \), we have

\[
\frac{1}{|D \cap \mathbb{R}_+^2|} \int_{D \cap \mathbb{R}_+^2} \mu_1(\zeta) dV(\zeta) \leq c\mu_2(z)
\]

for any \( z \in D \cap \mathbb{R}_+^2 \). For some weight \( \mu \), if it satisfies \( (\mu, \mu) \in A_1^+ (\mathbb{R}_+^2) \), we simply adopt the notation \( \mu \in A_1^+ (\mathbb{R}_+^2) \).

According to the classical results, the \( A_p \) class is closely related to the maximal function operator.\(^1\) So it is reasonable to introduce a suitable maximal function operator associated to the \( A_p^+ (\mathbb{R}_+^2) \) class.

\(^1\)See [Ste93, Chapter 5] for a general consideration of this topic.
Definition 6.1.2  For any measurable function $f$ on $\mathbb{R}^2_+$, we define the special maximal function operator $\tilde{M}^+$ by

$$\tilde{M}^+(f)(z) = \sup_{z \in D} \frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} |f(\zeta)| \, dV(\zeta)$$

for $z \in \mathbb{R}^2_+$, where the supremum is taken over all special disks $D$ containing $z$. It is clear that $\tilde{M}^+(f)$ is lower semi-continuous.

Remark 6.1.1  It is easy to see $(\mu_1, \mu_2) \in A^+_1(\mathbb{R}^2_+)$ if and only if $\tilde{M}^+(\mu_1) \leq c \mu_2$. In particular, a weight $\mu$ belonging to the class $A^+_1(\mathbb{R}^2_+)$ is equivalent to $\tilde{M}^+(\mu) \leq c \mu$.

Remark 6.1.2  It is easy to see, for $z, z' \in \mathbb{R}^2_+$, that

$$\tilde{M}^+(f)(z') \geq \tilde{M}^+(f)(z)$$

whenever $\Re(z') = \Re(z)$ and $\Im(z') \leq \Im(z)$. Note that the "absolute value" of the Bergman projection on the upper half plane

$$\tilde{B}(f)(z) = \int_{\mathbb{R}^2_+} \frac{1}{|z - w|^2} f(w) \, dV(w),$$

also has the same property above as $\tilde{M}^+$ for $f \geq 0$.

Associated to the special maximal function operator $\tilde{M}^+$ and the corresponding special disks, we also introduce a collection of special squares.

Definition 6.1.3  Let $S$ be the collection of all the special squares of form

$$\tilde{S}_{j,k} = \{ x + iy \in \mathbb{R}^2_+ : j \cdot 2^k \leq x \leq (j + 1) \cdot 2^k \text{ and } 0 \leq y \leq 2^k \},$$

where $j, k \in \mathbb{Z}$. Given a special square $\tilde{S}_{j,k}$, we define

$$\tilde{S}^*_{j,k} = \{ x + iy \in \mathbb{R}^2_+ : (j - 2) \cdot 2^k \leq x \leq (j + 3) \cdot 2^k \text{ and } 0 \leq y \leq 5 \cdot 2^k \}.$$
6.2 Properties of the Special Maximal Function Operator

Before investigating properties of the special maximal function operator, we first give a simple observation for a special product of two $A_1^+$ weights.

**Proposition 6.2.1** Suppose that $\mu_1$ and $\mu_2$ are two weights and $\mu_j \in A_1^+(\mathbb{R}^2_+)$, $j = 1, 2$. Then, for $1 \leq p < \infty$, we have $\mu_1 \mu_2^{1-p} \in A_p^+(\mathbb{R}^2_+)$.  

**Proof** By definition, for $j = 1, 2$, we have
\[
\frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} \mu_j(z) \, dV(z) \leq c \inf_{z \in D \cap \mathbb{R}^2_+} \mu_j(z),
\]
for all special disks $D$. Then we see that
\[
\frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} \mu_1(z) \mu_2(z)^{1-p} \, dV(z) \leq c \inf_{z \in D \cap \mathbb{R}^2_+} \mu_1(z) \left( \inf_{z \in D \cap \mathbb{R}^2_+} \mu_2(z) \right)^{1-p}
\]
and
\[
\left( \frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} (\mu_1(z) \mu_2(z)^{1-p})^{-\frac{p}{p'}} \, dV(z) \right)^{\frac{p'}{p}} \leq c \left( \inf_{z \in D \cap \mathbb{R}^2_+} \mu_1(z) \right)^{-1} \left( \inf_{z \in D \cap \mathbb{R}^2_+} \mu_2(z) \right)^{p-1}.
\]
Combining these two inequalities above, we obtain $\mu_1 \mu_2^{1-p} \in A_p^+(\mathbb{R}^2_+)$.  

**Remark 6.2.2** From Proposition 6.2.1, we see as long as we have two $A_1^+(\mathbb{R}^2_+)$ weights, we can construct an $A_p^+(\mathbb{R}^2_+)$ weight by taking a special product of the two $A_1^+(\mathbb{R}^2_+)$ weights.

To construct an $A_1^+(\mathbb{R}^2_+)$ weight and consider some mapping properties of $M^+$, we need two lemmas. The first lemma we introduce is an analogue of [Muc72, Lemma 7].

**Lemma 6.2.3** Let $f \geq 0$ be an integrable function on $\mathbb{R}^2_+$, and suppose $\alpha > 0$. Then there is a sequence of measurable sets $\{W_i\}$, and a sequence of special squares $\{S_i\}$ such that

(a) The intersection of different $W_i$'s has measure 0.
(b) \( \tilde{S}_l \subset W_l \subset \tilde{S}_l^* \).

(c) \( \frac{\alpha}{16} \left| \tilde{S}_l \right| \leq \int_{W_l} f(\zeta) \, dV(\zeta) \).

(d) If \( \tilde{M}^+(f)(z) > \alpha \), then \( z \in \bigcup W_l \).

**Proof** Following the idea in [Muc72], we argue as in the classical Calderón-Zygmund lemma. Since \( \int_{\mathbb{R}^2_+} f(\zeta) \, dV(\zeta) < \infty \), there is a \( k_0 \in \mathbb{Z}^+ \) so that, for all \( k \geq k_0 \) and all \( j \in \mathbb{Z} \), we have

\[
\frac{1}{|S_{j,k}|} \int_{S_{j,k}} f(\zeta) \, dV(\zeta) \leq \frac{\alpha}{16}. \tag{6.1}
\]

For the \( k = k_0 - 1 \) level, to each \( j \in \mathbb{Z} \), we have either (6.1) still true or

\[
\frac{\alpha}{16} < \frac{1}{|S_{j,k}|} \int_{S_{j,k}} f(\zeta) \, dV(\zeta) \leq \frac{\alpha}{4}. \tag{6.2}
\]

The right hand side of (6.2) follows from (6.1) in the \( k + 1 \) level. If (6.2) holds for this \( j \), we collect this special square \( \tilde{S}_{j,k} \) into the sequence \( \{\tilde{S}_l\} \), otherwise we continue this process to the \( k - 1 \) level in this \( \tilde{S}_{j,k} \). Therefore, we obtain a sequence of almost disjoint special squares \( \{\tilde{S}_l\} \) satisfying (6.2).

Define \( W_1 = \tilde{S}_1^* \setminus \left( \cup_{m \neq 1} \tilde{S}_m \right) \), and successively let

\[ W_l = \tilde{S}_l^* \setminus \left( \cup_{m \neq l} \tilde{S}_m \bigcup \cup_{l' < l} W_{l'} \right), \]

for \( l > 1 \). Properties (a) and (b) are easy to check from this definition. Property (c) follows from \( \tilde{S}_l \subset W_l \) and \( \tilde{S}_l \) satisfies (6.2). If \( \tilde{M}^+(f)(z) > \alpha \), then there is a special disk \( D_z = D_r(x_0) \) centered at \( x_0 \in \mathbb{R} \) with radius \( r > 0 \) so that \( z \in D_z \) and

\[
\frac{1}{|D_z \cap \mathbb{R}^2_+|} \int_{D_z \cap \mathbb{R}^2_+} f(\zeta) \, dV(\zeta) > \alpha.
\]

If \( 2^{k_1 - 1} \leq r < 2^{k_1} \) for some \( k_1 \in \mathbb{Z} \), then \( D_z \) intersects at most three special squares \( \tilde{S}_{j,k_1} \)'s and it is contained in the union of these squares. Moreover, we have

\[
|D_z \cap \mathbb{R}^2_+| \leq \frac{\pi}{2} |\tilde{S}_{j,k_1}| < 4 |D_z \cap \mathbb{R}^2_+|.
\]
Therefore at least one such special square, say $\tilde{S}_{j_1,k_1}$, satisfies

$$\int_{D_z \cap \mathbb{R}^2_+ \cap \tilde{S}_{j_1,k_1}} f(\zeta) \, dV(\zeta) > \frac{1}{3} \alpha |D_z \cap \mathbb{R}^2_+|.$$ 

So we obtain

$$\int_{\tilde{S}_{j_1,k_1}} f(\zeta) \, dV(\zeta) > \frac{\pi}{24} \alpha |\tilde{S}_{j_1,k_1}| > \frac{\alpha}{16} |\tilde{S}_{j_1,k_1}|.$$ 

From our construction of the sequence $\{\tilde{S}_l\}$, $\tilde{S}_{j_1,k_1}$ cannot be any of those satisfying (6.1), so $\tilde{S}_{j_1,k_1}$ is contained in one of the special squares $\{\tilde{S}_l\}$. Since $\tilde{S}_{j_1,k_1}$ intersects $D_z$, we must have $z \in D_z \subset \tilde{S}_{j_1,k_1} \subset \tilde{S}_l$ for some $l_1$. By the definition of $\{W_l\}$, if $z$ is not in $W_1, \ldots, W_{l_1}$, then $z$ must be in $\tilde{S}_{m_1}$ for some $m_1$, hence $z \in W_{m_1}$, which implies (d). $
$ 

Lemma 6.2.4 Let $f$ be a measurable function on $\mathbb{R}^2_+$. Then either $\tilde{M}^+(f)(z) = \infty$ for all $z \in \mathbb{R}^2_+$, or $\tilde{M}^+(f)(z) < \infty$ for all $z \in \mathbb{R}^2_+$.

Proof Assuming that $\tilde{M}^+(f)(z) = \infty$ for some $z \in \mathbb{R}^2_+$, we show that $\tilde{M}^+(f)(z') = \infty$ for any $z' \in \mathbb{R}^2_+$. By definition, there is a sequence of special disks $\{D_n\}$ with $z \in D_n$ and

$$\frac{1}{|D_n \cap \mathbb{R}^2_+|} \int_{D_n \cap \mathbb{R}^2_+} |f(\zeta)| \, dV(\zeta) > n, \quad (6.3)$$

for all $n \in \mathbb{Z}^+$. Let $r_n$ be the radius of $D_n$, and let $x_n$ be the center, then $D_n = D_{r_n}(x_n)$. Since $z \in D_n$, we see $r_n > \Im(z) > 0$.

If $\{r_n\}$ is not bounded above then, by selecting a subsequence, we may assume that $\lim r_n = \infty$. Then, given any $z' \in \mathbb{R}^2_+$, we have $r_n \geq |z' - z|$ for $n$ sufficiently large. In this case, it is easy to see $z' \in D_{2r_n}(x_n)$, the special disk centered at $x_n$ with radius $2r_n$.

From (6.3), we see that

$$\frac{1}{|D_{2r_n}(x_n) \cap \mathbb{R}^2_+|} \int_{D_{2r_n}(x_n) \cap \mathbb{R}^2_+} |f(\zeta)| \, dV(\zeta) > \frac{1}{4} n,$$

for $n$ sufficiently large. This implies $\tilde{M}^+(f)(z') = \infty$. 

67
If \( \{r_n\} \) is bounded above then, by selecting a subsequence, we may assume that \( \lim r_n = r \), for some \( r \) with \( \Im(z) \leq r < \infty \). Note that, since \( z \in D_n \), we have \( \Re(z) \in D_n \), so \( D_n \subset D_{3r}(\Re(z)) \) for \( n \) sufficiently large, where \( D_{3r}(\Re(z)) \) is a special disk centered at \( \Re(z) \) with radius \( 3r \). Therefore, from (6.3), we see that

\[
\int_{D_{3r}(\Re(z)) \cap \mathbb{R}_+^2} |f(\zeta)| \, dV(\zeta) > \frac{1}{2} n \pi r_n^2 \geq cn,
\]

where \( c = \frac{1}{2} \pi \Im(z) > 0 \), for \( n \) sufficiently large. So we obtain

\[
\int_{D_{3r}(\Re(z)) \cap \mathbb{R}_+^2} |f(\zeta)| \, dV(\zeta) = \infty.
\]

Now, for any \( z' \in \mathbb{R}_+^2 \), it is easy to see that \( z' \in D_{3r+|z'-z|}(\Re(z)) \), the special disk centered at \( \Re(z) \) with radius \( 3r + |z' - z| \). From the equality above, we have

\[
\frac{1}{|D_{3r+|z'-z|}(\Re(z)) \cap \mathbb{R}_+^2|} \int_{D_{3r+|z'-z|}(\Re(z)) \cap \mathbb{R}_+^2} |f(\zeta)| \, dV(\zeta) = \infty,
\]

which implies \( \tilde{M}^+(f)(z') = \infty \). This completes the proof.

Now we are ready to apply \( \tilde{M}^+ \) to construct \( A_1^+(\mathbb{R}_+^2) \) weights.

**Theorem 10** Let \( f \) be a measurable function on \( \mathbb{R}_+^2 \). Then, for any \( 0 < q < 1 \), the function \( \left( \tilde{M}^+(f) \right)^q \) is in \( A_1^+(\mathbb{R}_+^2) \).

**Proof** It suffices to show the conclusion for \( f \geq 0 \). By Lemma 6.2.4, we can assume \( \tilde{M}^+(f)(z) < \infty \) for all \( z \in \mathbb{R}_+^2 \); otherwise, the conclusion is trivial. If \( \tilde{M}^+(f)(z) = 0 \) for some \( z \in \mathbb{R}_+^2 \), then it is easy to see that \( f = 0 \) on \( \mathbb{R}_+^2 \). In this case, the conclusion is trivial again. So we may assume that \( 0 < \tilde{M}^+(f) < \infty \) on \( \mathbb{R}_+^2 \).

We use an analogue of the argument in [Ste93, Chapter 5.2]. Let \( \mu(z) = \left( \tilde{M}^+(f)(z) \right)^q \); we show that \( \tilde{M}^+(\mu)(z) \leq c \mu(z) \). That implies \( \mu \in A_1^+(\mathbb{R}_+^2) \).
Fixing $z \in \mathbb{R}^2_+$, we normalize $f$ by dividing by $\tilde{M}^+(f)(z)$, so we may assume that $\tilde{M}^+(f)(z) = 1$ and $\mu(z) = 1$. Hence it suffices to show that there is a $c > 0$ such that

$$\frac{1}{|D \cap \mathbb{R}^2_+|} \int_{D \cap \mathbb{R}^2_+} \mu(\zeta) \, dV(\zeta) \leq c,$$

(6.4)

for any special $D$ containing $z$.

Given a special disk $D = D_R(x_0)$ that contains $z$, let $f_1 = \chi_{D_2R(x_0) \cap \mathbb{R}^2_+} f$ and $f_2 = f - f_1$. We first deal with $f_1$. Let $V_\alpha = \{ \zeta \in D \cap \mathbb{R}^2_+ : \tilde{M}^+(f_1)(\zeta) > \alpha \}$, we have

$$\int_{D \cap \mathbb{R}^2_+} \left( \frac{\tilde{M}^+(f_1)(\zeta)}{q} \right)^q \, dV(\zeta) = \int_0^\infty q \alpha^{q-1} |V_\alpha| \, d\alpha$$

(6.5)

$$= \int_0^1 + \int_1^\infty q \alpha^{q-1} |V_\alpha| \, d\alpha.$$

Since $|V_\alpha| \leq |D|$, we see the first integral of (6.5) is bounded by $cR^2$. For the second integral, since $\tilde{M}^+(f)(z) = 1$ and $z \in D_2R(x_0) \cap \mathbb{R}^2_+$, we see $f_1$ is integrable on $\mathbb{R}^2_+$. By Lemma 6.2.3, we have

$$|V_\alpha| \leq \sum_l \left| \bar{S}_l^+ \right| = \sum_l 25 \left| \bar{S}_l \right|$$

$$\leq c \sum_l \frac{1}{\alpha} \int_{W_l} f_1(\eta) \, dV(\eta)$$

$$\leq c \int_{\mathbb{R}^2_+} f_1(\eta) \, dV(\eta)$$

$$= c \int_{D_2R(x_0) \cap \mathbb{R}^2_+} f(\eta) \, dV(\eta)$$

$$\leq \frac{cR^2}{\alpha} \tilde{M}^+(f)(z)$$

$$= \frac{cR^2}{\alpha}.$$

So the second integral of (6.5) is bounded by $cR^2$. Hence, so is (6.5).

Next we deal with $f_2$. For any $\zeta \in D \cap \mathbb{R}^2_+$, we consider an arbitrary special disk $D'_r$ that contains $\zeta$ and whose radius is $r$. It is easy to see that $D'_r \subseteq D_{2r+R}(x_0)$. When
2r < R, we have \( D'_r \subset D_{2r+R}(x_0) \subset D_{2R}(x_0) \). Since \( f_2 \) vanishes on \( D_{2R}(x_0) \cap \mathbb{R}^2_+ \), we see that

\[
\frac{1}{|D'_r \cap \mathbb{R}^2_+|} \int_{D'_r \cap \mathbb{R}^2_+} f_2(\eta) \, dV(\eta) = 0 < c,
\]

for any \( c > 0 \). When \( 2r \geq R \), then \((2r + R)^2 \leq 16r^2\), so we have

\[
\int_{D'_r \cap \mathbb{R}^2_+} f_2(\eta) \, dV(\eta) \leq \int_{D_{2r+R}(x_0) \cap \mathbb{R}^2_+} f(\eta) \, dV(\eta)
\leq |D_{2r+R}(x_0) \cap \mathbb{R}^2_+| \, \widetilde{M}^+(f)(z)
= c(2r + R)^2
\leq cr^2,
\]

since \( z \in D \subset D_{2r+R}(x_0) \). In either case, we obtain

\[
\frac{1}{|D'_r \cap \mathbb{R}^2_+|} \int_{D'_r \cap \mathbb{R}^2_+} f_2(\eta) \, dV(\eta) < c.
\]

Since \( D'_r \) is arbitrary, we see \( \widetilde{M}^+(f_2)(\zeta) \leq c \), for any \( \zeta \in D \cap \mathbb{R}^2_+ \). Therefore we obtain

\[
\int_{D \cap \mathbb{R}^2_+} \left( \widetilde{M}^+(f_2)(\zeta) \right)^q \, dV(\zeta) \leq cR^2. \tag{6.6}
\]

Combining (6.6) with the fact that (6.5) is bounded by \( cR^2 \), we see that

\[
\int_{D \cap \mathbb{R}^2_+} \left( \widetilde{M}^+(f)(\zeta) \right)^q \, dV(\zeta) \leq cR^2,
\]

which implies (6.4). This completes the proof.

Following the idea in [Muc72], we now investigate the weak-type \((p,p)\) mapping property of the special maximal function operator \( \widetilde{M}^+ \).

**Theorem 11** Assume that \( p \geq 1 \). Suppose \( \mu_1 \) and \( \mu_2 \) are two weights on \( \mathbb{R}^2_+ \). Then we have a weak-type \((p,p)\) inequality: namely, there is a constant \( c > 0 \) so that

\[
\mu_1 \left( \{ z \in \mathbb{R}^2_+ : \widetilde{M}^+(f)(z) > \alpha \} \right) \leq \frac{c}{\alpha^p} \int_{\mathbb{R}^2_+} |f(z)|^p \mu_2(z) \, dV(z) \tag{1.3}
\]

for all \( \alpha > 0 \), if and only if \((\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)\).
**Proof** We use an analogue of the argument in [Muc72, Theorem 8]. For the sufficient part, we only need to prove (1.3) for integrable $f \geq 0$. To see this, note that any measurable function $f \geq 0$ on $\mathbb{R}^2_+$ can be approximated by the increasing sequence $\{f\chi_{D_R}\}_{R>0}$, where $D_R = D_R(x_0)$ is a sequence of special disks centered at $x_0 \in \mathbb{R}$ with radius $R$. Note that the set $\{z \in \mathbb{R}^2_+ : \widetilde{M}^+(f)(z) > \alpha\}$ is the increasing union of the same sets formed with the $f\chi_{D_R}$’s. If we prove (1.3) for $f\chi_{D_R}$, then the monotonic convergent theorem will imply (1.3) for $f$. Note that any $f\chi_{D_R}$ can be approximated by an increasing sequence of simple functions. Since the support of $f\chi_{D_R}$ is bounded, these simple functions are integrable. By the same limiting argument, (1.3) for integrable functions will imply (1.3) for $f\chi_{D_R}$.

Let $V_\alpha = \{z \in \mathbb{R}^2_+ : \widetilde{M}^+(f)(z) > \alpha\}$. By Lemma 6.2.3, for $p > 1$, we have

\[
\mu_1(V_\alpha) \leq \sum_l \mu_1(W_l) \\
\leq \sum_l \mu_1(W_l) \left( \frac{16}{\alpha |S^*_l|} \int_{W_l} f(z) dV(z) \right)^p \\
\leq \sum_l \frac{c \mu_1(W_l)}{\alpha^p |S^*_l|} \int_{W_l} f(z)^p \mu_2(z) dV(z) \left( \frac{1}{|S^*_l|} \int_{W_l} \mu_2(z)^{-\frac{p'}{p}} dV(z) \right)^{p/p'} \\
\leq \sum_l \frac{c}{\alpha^p} \int_{W_l} f(z)^p \mu_2(z) dV(z) \left( \frac{\mu_1(S^*_l)}{|S^*_l|} \int_{S^*_l} \mu_2(z)^{-\frac{p'}{p}} dV(z) \right)^{p/p'} \\
\leq \sum_l \frac{c}{\alpha^p} \int_{W_l} f(z)^p \mu_2(z) dV(z) \\
\leq \frac{c}{\alpha^p} \int_{\mathbb{R}^2_+} f(z)^p \mu_2(z) dV(z).
\]
For $p = 1$, similarly, we have
\[
\mu_1(V_a) \leq \sum_i \frac{16\mu_1(W_i)}{\alpha|S_i|} \int_{W_i} f(z) dV(z)
\]
\[
\leq \sum_i \frac{c \mu_1(W_i)}{\alpha} \int_{W_i} f(z) \mu_2(z) dV(z) \left( \inf_{z \in W_i} \mu_2(z) \right)^{-1}
\]
\[
\leq \sum_i \frac{c}{\alpha} \int_{W_i} f(z) \mu_2(z) dV(z)
\]
\[
\leq \frac{c}{\alpha} \int_{\mathbb{R}^2_+} f(z) \mu_2(z) dV(z).
\]

For the necessary part, we first consider $p > 1$. Given any special disk $D$, we assume that $\int_{D \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{1}{p}} dV(z) = \infty$. Then, by duality of the space $L^p(D \cap \mathbb{R}^2_+)$, there is a $g \in L^p(D \cap \mathbb{R}^2_+)$ so that $\int_{D \cap \mathbb{R}^2_+} g(z) \mu_2(z)^{-\frac{1}{p}} dV(z) = \infty$. Let $f = g \mu_2^{-\frac{1}{p}} \chi_{D \cap \mathbb{R}^2_+}$ on $\mathbb{R}^2_+$. Then $\overline{M}(f)(z) = \infty$ for all $z \in D \cap \mathbb{R}^2_+$. So (1.3) gives $\mu_1(D \cap \mathbb{R}^2_+) = 0$, which contradicts the assumption $\mu_1 > 0$ almost everywhere. We also exclude the trivial case $\mu_2 = \infty$ on $D \cap \mathbb{R}^2_+$ to see that indeed we have $0 < \int_{D \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{1}{p}} dV(z) < \infty$.

Take $f = \mu_2^{-\frac{1}{p'}} \chi_{D \cap \mathbb{R}^2_+}$ and $\alpha = \frac{1}{|D\cap\mathbb{R}^2_+|} \int_{D\cap\mathbb{R}^2_+} \mu_2(z)^{-\frac{1}{p'}} dV(z)$ in (1.3). We see that
\[
\mu_1(D \cap \mathbb{R}^2_+) \leq \frac{c}{\alpha^p} \int_{D \cap \mathbb{R}^2_+} \mu_2(z)^{-\frac{1}{p'}} \mu_2(z) dV(z)
\]
\[
= \frac{c|D \cap \mathbb{R}^2_+|}{\alpha^{p-1}},
\]
which is equivalent to $(\mu_1, \mu_2) \in A^+_p(\mathbb{R}^2_+)$. 

When $p = 1$, given any special disk $D$, we exclude the trivial case $\inf \mu_2 = \infty$, where the infimum is taken over all $z \in D \cap \mathbb{R}^2_+$. Then, for any $\epsilon > 0$, there must be a measurable set $U \subset D \cap \mathbb{R}^2_+$ with $|U| > 0$, so that $\mu_2(z) < \epsilon + \inf \mu_2$ on $U$.

Taking $f = \chi_U$ and $\alpha = \frac{|U|}{|D\cap\mathbb{R}^2_+|}$ in (1.3), we see that
\[
\mu_1(D \cap \mathbb{R}^2_+) \leq \frac{c|D \cap \mathbb{R}^2_+|}{|U|} \int_U \mu_2(z) dV(z)
\]
\[
\leq c \frac{|D \cap \mathbb{R}^2_+|}{|U|} \left( \epsilon + \inf_{z \in D \cap \mathbb{R}^2_+} \mu_2(z) \right).
\]

72
Letting \( \epsilon \to 0^+ \), we see that the inequality above is equivalent to \((\mu_1, \mu_2) \in A_1^+(\mathbb{R}^2_+)\).

This completes the proof. 

\[\text{Remark 6.2.5} \quad \text{For any measurable } f \geq 0, \text{ we do not have the basic inequality } f \leq \tilde{M}^+(f). \text{ So we cannot follow the classical approach to show the reverse Hölder inequality for a weight in } A_p^+(\mathbb{R}^2_+). \text{ Hence we cannot obtain the strong-type } (p, p) \text{ inequality, nor the factorization of a } A_p^+ \text{ weight.}^2\]

---

^2Compare to the classical results for \( A_p \) weights, see [Ste93, Chapter 5] for details.
7. Twisted-Weighted Projections

7.1 Preliminaries and Basic Definitions

To apply the previous analysis to the twisted-weighted Bergman theory, let us temporarily consider the general setting for a twisted-weighted space. Assume that $\Omega$ is a domain in $\mathbb{C}^n$.

**Definition 7.1.1** Suppose $\tau \in C^1(\Omega)$ and $\tau > 0$. We define the set of $\tau$-twisted holomorphic functions on $\Omega$ by

$$O_\tau(\Omega) = \{ f \in C^1(\Omega) : \overline{\partial}_\tau(f) = 0 \},$$

where the $\tau$-twisted $\overline{\partial}$ operator is defined by $\overline{\partial}_\tau(f) = \overline{\partial}(\tau f)$. Note that $O_\tau(\Omega)$ is just a coset of the set of holomorphic functions on $\Omega$, that is, $O_\tau(\Omega) = \frac{1}{\tau} O(\Omega)$.

**Definition 7.1.2** Let $\mu$ be a weight on $\Omega$. Define $A^2_{\tau,\mu}(\Omega) = O_\tau(\Omega) \cap L^2(\Omega, \mu)$. We say that $\mu$ is admissible with respect to $\tau$, if for any compact subset $K \subset \Omega$, there is a constant $C_K > 0$, so that

$$\sup_K |f(z)| \leq C_K \|f\|_{L^2(\Omega, \mu)}$$

for all $f \in A^2_{\tau,\mu}(\Omega)$. For instance, if $\mu$ is continuous and non-vanishing, then it is admissible.\(^1\)

\(^1\)For a more general class of admissible weights, see [McN12, Proposition 2.4] for details.
Remark 7.1.1 With an admissible weight \( \mu \), \( A^2_{\tau,\mu}(\Omega) \) is a closed subspace of \( L^2(\Omega, \mu) \). To see this, let \( \{f_n\} \subset A^2_{\tau,\mu}(\Omega) \) be a sequence that converges to \( f \) in \( L^2(\Omega, \mu) \). By admissibility, for each \( K \subset \Omega \), \( f_n \) converges to \( f \) uniformly on \( K \). Since \( \tau \in C^1(\Omega) \), we have \( \sup_K |\tau| \leq C'_K \). Hence \( \tau f_n \) converges to \( \tau f \) uniformly on \( K \). Noting that each \( \tau f_n \) is holomorphic, we finally obtain \( f \in O(\Omega) \).

Throughout this chapter, we always assume that the weight \( \mu \) on the underlying domain \( \Omega \) is admissible with respect to the twist factor \( \tau \). With this convention, we can now talk about the orthogonal projection from \( L^2(\Omega, \mu) \) to \( A^2_{\tau,\mu}(\Omega) \).

Definition 7.1.3 Define the twisted-weighted Bergman projection associated to the twist-weight pair \( (\tau, \mu) \) to be the orthogonal projection \( B_{\tau,\mu} : L^2(\Omega, \mu) \to A^2_{\tau,\mu}(\Omega) \), represented by the integral

\[
B_{\tau,\mu}(f)(z) = \int_{\Omega} B_{\tau,\mu}(z, \zeta) f(\zeta) \mu(\zeta) \, dV(\zeta),
\]

where \( B_{\tau,\mu}(z, \zeta) \) on \( \Omega \times \Omega \) is the twisted-weighted Bergman kernel.

Remark 7.1.2 The twisted-weighted Bergman projection satisfies all the properties of abstract Bergman theory in a Hilbert space. For example, \( B_{\tau,\mu} \) is self-adjoint and it reproduces \( A^2_{\tau,\mu}(\Omega) \) functions. Note that the twisted-weighted Bergman kernel \( B_{\tau,\mu}(z, \zeta) \) is \( \partial_{\tau} \)-closed in the variable \( z \) and anti-\( \partial_{\tau} \)-closed in the variable \( \zeta \). Moreover, the twisted-weighted Bergman kernel is uniquely determined by these properties.\(^2\)

By applying Lemma 2.2.1, we have the following transformation formula, which generalizes Corollary 2.2.2.

Corollary 7.1.3 Let \( \Phi : \Omega_1 \to \Omega_2 \) be a biholomorphism between two domains in \( \mathbb{C}^n \).

Suppose that \( \Omega_j \) is equipped with the weight \( \mu_j \) and the twist factor \( \tau_j \), \( j = 1, 2 \). Assume

\(^2\)See [McN12, Proposition 2.8] for details.
that $\mu_2 = \mu_1 \circ \Phi^{-1}$ and $\tau_2 = \tau_1 \circ \Phi^{-1}$. Then we have the transformation formula for the twisted-weighted Bergman kernels

$$B_{\tau_1, \mu_1}(z, \zeta) = \det J_\mathcal{C}_\Phi(z) B_{\tau_2, \mu_2}(\Phi(z), \Phi(\zeta)) \det J_\mathcal{C}_\Phi(\zeta),$$

where $(z, \zeta) \in \Omega_1 \times \Omega_1$ and $B_{\tau_j, \mu_j}$ is the twisted-weighted Bergman kernel on $\Omega_j \times \Omega_j$, $j = 1, 2$.

**Proof**  Repeat the argument in Corollary 2.2.2. 

### 7.2 The $L^p$ Regularity

Now let us take a closer look at the twist-weight pair $(\tau, \mu)$. Define $\tilde{\mu} = \mu/\tau^2$, and consider the space $A^2_\tilde{\mu}(\Omega) = L^2(\Omega, \tilde{\mu}) \cap \mathcal{O}(\Omega)$. It is easy to see that the closedness of the subspace $A^2_\tilde{\mu}(\Omega)$ in $L^2(\Omega, \tilde{\mu})$ follows from the closedness of $A^2_{\tau, \mu}(\Omega)$ in $L^2(\Omega, \mu)$. Then, we can consider the weighted Bergman projection $B_{\tilde{\mu}}$, which is the orthogonal projection from $L^2(\Omega, \tilde{\mu})$ to $A^2_\tilde{\mu}(\Omega)$. Indeed, we have the following observation.

**Proposition 7.2.1** Let $\sigma = \tau^{2-p} \tilde{\mu}$. The twisted-weighted Bergman projection $B_{\tau, \mu}$ is bounded on $L^p(\Omega, \mu)$ if and only if the weighted Bergman projection $B_{\tilde{\mu}}$ is bounded on $L^p(\Omega, \sigma)$.

In particular, if $\tilde{\mu} = |g|^2$ for some non-vanishing holomorphic function $g$ on $\Omega$, then $B_{\tau, \mu}$ is bounded on $L^p(\Omega, \mu)$ if and only if $B$ is bounded on $L^p(\Omega, \tilde{\sigma})$, where $B$ is the ordinary Bergman projection on $\Omega$ and $\tilde{\sigma} = \mu^{1 - \frac{2}{p}}$.

**Proof**  Consider the isometry $F : L^2(\Omega, \mu) \to L^2(\Omega, \tilde{\mu})$ via $F(f) = \tau f$. By Lemma 2.2.1, we have the twisted-weighted Bergman kernel

$$B_{\tau, \mu}(z, \zeta) = \frac{1}{\tau(z) \tau(\zeta)} B_{\tilde{\mu}}(z, \zeta),$$
where \((z, \zeta) \in \Omega \times \Omega\) and \(B_{\tilde{\mu}}\) is the weighted Bergman kernel on \((\Omega, \tilde{\mu})\). By this relation, we see that

\[
\int_{\Omega} \left| \int_{\Omega} B_{\tau, \mu}(z, \zeta) f(\zeta) \mu(\zeta) \, dV(\zeta) \right|^p \mu(z) \, dV(z) \leq C \int_{\Omega} |f(z)|^p \mu(z) \, dV(z)
\]

is equivalent to

\[
\int_{\Omega} \left| \int_{\Omega} B_{\tilde{\mu}}(z, \zeta) \tilde{f}(\zeta) \tilde{\mu}(\zeta) \, dV(\zeta) \right|^p \sigma(z) \, dV(z) \leq C \int_{\Omega} |\tilde{f}(z)|^p \sigma(z) \, dV(z), \quad (7.1)
\]

where \(\tilde{f} = \tau f\). This proves the first part of the proposition.

Now we assume that \(\tilde{\mu} = |g|^2\) for some non-vanishing holomorphic function \(g\) on \(\Omega\). Applying Lemma 2.2.1 once again to the isometry \(\tilde{F} : L^2(\Omega, |g|^2) \to L^2(\Omega)\) via \(\tilde{F}(f) = fg\), we see that

\[
B_{\tilde{\mu}}(z, \zeta) = \frac{1}{g(z)g(\zeta)} B(z, \zeta),
\]

where \((z, \zeta) \in \Omega \times \Omega\) and \(B\) is the ordinary Bergman kernel on \(\Omega\). Hence, (7.1) is equivalent to

\[
\int_{\Omega} \left| \int_{\Omega} B(z, \zeta) h(\zeta) \, dV(\zeta) \right|^p \tilde{\sigma}(z) \, dV(z) \leq C \int_{\Omega} |h(z)|^p \tilde{\sigma}(z) \, dV(z), \quad (7.2)
\]

where \(h = \tilde{f}g\). This completes the proof.

Remark 7.2.2 When \(\mu/\tau^2 = |g|^2\), \(\mu\) is always admissible with respect to \(\tau\). An important observation is that the \(L^p(\Omega, \tilde{\sigma})\) boundedness of \(B\) is independent of the choice of \(\tau\) and \(g\). Note that, in general, for different \(\tau\) the coset \(O_\tau\) is different.

As an application, we now focus on simply connected proper planar domains in \(\mathbb{C}\), and apply Theorem 6 to investigate the \(L^p\) regularity of the twisted-weighted Bergman projection.
Theorem 12 Let $\Omega$ be a proper simply connected domain in $\mathbb{C}$, and let $\phi : \mathbb{R}^2_+ \to \Omega$ be a biholomorphism. For a weight $\mu \in C^1(\Omega)$ and for any non-vanishing $g \in \mathcal{O}(\Omega)$, define $\tau = \mu^{1/2}/|g|$. Then the twisted-weighted Bergman projection $B_{\tau,\mu}$ is bounded if and only if $\mu(\phi(z))^{1-\frac{p}{2}}|\phi'(z)|^{2-p} \in A^+_p(\mathbb{R}^2_+)$. 

Proof By Proposition 7.2.1, we see that the twisted-weighted Bergman projection $B_{\tau,\mu}$ is bounded on $L^p(\Omega, \mu)$ if and only if the ordinary Bergman projection $B$ on $\Omega$ is bounded on $L^p(\Omega, \mu^{1-\frac{p}{2}})$, i.e., (7.2) holds.

Consider the biholomorphism $\phi : \mathbb{R}^2_+ \to \Omega$. By the transformation formula for ordinary Bergman kernels (a special case of Corollary 2.2.2 or Corollary 7.1.3), we see that (7.2) is equivalent to

$$\int_{\mathbb{R}^2_+} \left| \int_{\mathbb{R}^2_+} \frac{f(w)}{(z-w)^2} dV(w) \right|^p \sigma(z) dV(z) \leq C \int_{\mathbb{R}^2_+} |f(z)|^p \sigma(z) dV(z),$$

(7.3)

where $\sigma(z) = |\tau(\phi(z))g(\phi(z))\phi'(z)|^{2-p} = \mu(\phi(z))^{1-\frac{p}{2}}|\phi'(z)|^{2-p}$. Note that (7.3) is nothing but (1.2) with both $\mu_1$ and $\mu_2$ replaced by $\sigma$. Therefore, by Theorem 6, we see that (7.3) holds if and only if $\sigma \in A^+_p(\mathbb{R}^2_+)$. This completes the proof.
8. The $L^p$ Sobolev Regularity

In this chapter, as the last application, we study the $L^p$ Sobolev mapping property of the Bergman projection on the Hartogs triangle, and generalize it to higher dimension.

8.1 Preliminaries and Basic Definitions

Throughout this chapter, $B$ will denote the Bergman projection on the Hartogs triangle and $B$ will be its associated Bergman kernel, that is,

$$B(f)(z) = \int_{\mathbb{H}} B(z, \zeta)f(\zeta)\,dV(\zeta)$$

for $z \in \mathbb{H}$. We then make a precise definition of the weighted Sobolev space on $\mathbb{H}$.

**Definition 8.1.1** On the Hartogs triangle $\mathbb{H}$, for each $k \in \mathbb{Z}^+ \cup \{0\}$, $s \in \mathbb{R}$, and $p \in (1, \infty)$, we define the weighted Sobolev space by

$$L^p_k(\mathbb{H}, |z_2|^s) = \{ f \in L^1_{\text{loc}}(\mathbb{H}) : \|f\|_{p,k,s} < \infty \},$$

where the norm is defined as

$$\|f\|_{p,k,s} = \left( \int_{\mathbb{H}} \sum_{|\alpha| \leq k} \left| D^\alpha_{z,z}(f)(z) \right|^p |z_2|^s \,dV(z) \right)^{\frac{1}{p}}.$$  

Here $\alpha = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ is the multi-index running over all $|\alpha| \leq k$, and

$$D^\alpha_{z,z} = \frac{\partial^{|\alpha|}}{\partial z_1^{\alpha_1} \partial z_2^{\alpha_2} \partial \overline{z}_1^{\alpha_3} \partial \overline{z}_2^{\alpha_4}}.$$
denotes the differential operator in the weak sense. We also denote the ordinary (un-weighted) Sobolev space by $L^p_k(\mathbb{H})$, with its usual norm
\[
\|f\|_{p,k} = \left( \int_{\mathbb{H}} \sum_{|\alpha| \leq k} |D^\alpha_{z,z}(f)(z)|^p \, dV(z) \right)^{\frac{1}{p}}.
\]

**Remark 8.1.1** By Definition 8.1.1 above, Theorem 13 can be rephrased in the following way. For each $k \in \mathbb{Z}^+ \cup \{0\}$ and $p \in \left(\frac{4}{3}, 4\right)$, there exists a constant $C_{p,k} > 0$, so that
\[
\|B(f)\|_{p,k,pk} \leq C_{p,k} \|f\|_{p,k},
\]
for any $f \in L^p_k(\mathbb{H})$.

We also adopt the following notation.

**Definition 8.1.2** Let $\beta = (\beta_1, \beta_2)$ be a multi-index. We use the notation below to denote the differential operators
\[
D^\beta_z = \frac{\partial^{|eta|}}{\partial z_1^{\beta_1} \partial z_2^{\beta_2}}
\]
and
\[
D^\beta_{z_j, z_j} = \frac{\partial^{|eta|}}{\partial z_j^{\beta_1} \partial z_j^{\beta_2}}
\]
for $j = 1, 2$.

By Theorem 1, we see that $B(f) \in A^p(\mathbb{H}) = L^p(\mathbb{H}) \cap \mathcal{O}(\mathbb{H})$ whenever $p \in \left(\frac{4}{3}, 4\right)$ and $f \in L^p(\mathbb{H})$. So we can rewrite the weighted $L^p$ Sobolev norm of $B(f)$ as
\[
\|B(f)\|_{p,k,pk}^p = \sum_{|eta| \leq k} \int_{\mathbb{H}} |D^\beta_z(B(f))(z)|^p |z_2|^{pk} \, dV(z), \tag{8.1}
\]
where $\beta$ and $D^\beta_z$ are as in Definition 8.1.2.


8.2 Transfer to the Product Model

In order to transfer $\mathbb{H}$ to the product model, we first recall the transformation formula for the Bergman kernels.

**Proposition 8.2.1** Let $\Omega_j$ be domains in $\mathbb{C}^n$ and $B_j$ be their Bergman kernels on $\Omega_j \times \Omega_j$, $j = 1, 2$. Suppose that $\Psi : \Omega_1 \to \Omega_2$ is a biholomorphism. Then, for $(w, \eta) \in \Omega_1 \times \Omega_1$, we have

$$\det J_C \Psi(w) B_2(\Psi(w), \Psi(\eta)) \det J_C \Psi(\eta) = B_1(w, \eta).$$

**Proof** This is a special case of Corollary 2.2.2 and Corollary 7.1.3.\(^1\)

Now let us consider the biholomorphism

$$\Phi : \mathbb{H} \to \mathbb{D} \times \mathbb{D}^*$$

with its inverse

$$\Psi : \mathbb{D} \times \mathbb{D}^* \to \mathbb{H},$$

where

$$\Phi(z_1, z_2) = \left(\frac{z_1}{z_2}, z_2\right) \quad \text{and} \quad \Psi(w_1, w_2) = (w_1 w_2, w_2).$$

A simple computation shows that $\det J_C \Psi(w) = w_2$, for $w = (w_1, w_2) \in \mathbb{D} \times \mathbb{D}^*$. Therefore, by Proposition 8.2.1, we have

$$B(\Psi(w), \Psi(\eta)) = \frac{1}{w_2 \eta_2} \cdot \frac{1}{1 - w_1 \eta_1} \cdot \frac{1}{1 - w_2 \eta_2}^{\frac{1}{2}},$$

(8.2)

where $B$ is the Bergman kernel on $\mathbb{H} \times \mathbb{H}$ and $(w, \eta) \in \mathbb{D} \times \mathbb{D}^* \times \mathbb{D} \times \mathbb{D}^*$.

We next need to transfer the differential operators $D_2^\beta$ to the ones in the new variable $w$, so we need a lemma.

\(^1\)See also [Kra01, Proposition 1.4.12].
Lemma 8.2.2 Under the above biholomorphism $\Phi(z) = w$, for each $\beta$ let $m = |\beta|$, we have
\[
D_z^\beta = \sum_{a + b \leq m} \frac{p_{a, b, \beta}(w_1)}{w_2^{m-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^b},
\]
where $p_{a, b, \beta}(w_1)$ is a polynomial of degree at most $m$ in variable $w_1$. In addition, if $|\beta| \leq k$ for some $k \in \mathbb{Z}^+ \cup \{0\}$, then $|p_{a, b, \beta}(w_1)| \leq C_k$ on $\mathbb{D}$ uniformly in $\beta$, $a$, and $b$, for some constant $C_k > 0$ depending only on $k$.

Proof We prove (8.3) by induction on $m = |\beta|$. The case $m = 0$ is trivial. When $m = 1$, a direct computation shows that
\[
\frac{\partial}{\partial z_1} = \frac{1}{w_2} \cdot \frac{\partial}{\partial w_1}
\]
and
\[
\frac{\partial}{\partial z_2} = -\frac{w_1}{w_2} \cdot \frac{\partial}{\partial w_1} + \frac{\partial}{\partial w_2}.
\]
It is obvious that both of $\frac{\partial}{\partial z_1}$ and $\frac{\partial}{\partial z_2}$ are of the form (8.3).

Suppose, for all $\beta$ with $|\beta| = m$, the $D_z^\beta$'s are of the form (8.3). We now check the case $|\beta'| = m + 1$. Note that $D_z^\beta = \frac{\partial}{\partial z_1} \circ D_z^\beta$ or $D_z^\beta = \frac{\partial}{\partial z_2} \circ D_z^\beta$, for some $\beta$. By the inductive assumption, we have
\[
\frac{\partial}{\partial z_1} D_z^\beta = \frac{1}{w_2} \cdot \frac{\partial}{\partial w_1} \sum_{a + b \leq m} \frac{p_{a, b, \beta}(w_1)}{w_2^{m-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^b}
\]
\[
= \sum_{a + b \leq m} \frac{p'_{a, b, \beta}(w_1)}{w_2^{m+1-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^{b+1}} + \sum_{a + b \leq m} \frac{p_{a, b, \beta}(w_1)}{w_2^{m+1-b}} \cdot \frac{\partial^{a+b+1}}{\partial w_1^a \partial w_2^{b+1}}
\]
\[
= \sum_{a + b \leq m+1} \frac{p_{a, b, \beta'}(w_1)}{w_2^{m+1-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^{b+1}}.
\]
and

\[ \frac{\partial}{\partial z_2} D_\beta^z = \left( -\frac{w_1}{w_2} \cdot \frac{\partial}{\partial w_1} + \frac{\partial}{\partial w_2} \right) \sum_{a+b\leq m} \frac{p_{a,b,\beta}(w_1)}{w_2^{m-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^b} \]

\[ = \sum_{a+b\leq m} -w_1 p_{a,b,\beta}'(w_1) \cdot \frac{\partial^{a+b}}{w_2^{m+1-b}} + \frac{w_1^{m+1-b}}{w_2^{m-b}} \cdot \frac{\partial^{a+b+1}}{\partial w_1^a \partial w_2^{b+1}} \]

\[ = \sum_{a+b\leq m+1} \frac{p_{a,b,\beta}(w_1)}{w_2^{m+1-b}} \cdot \frac{\partial^{a+b}}{\partial w_1^a \partial w_2^b}. \]

We see that \( p_{a,b,\beta}(w_1) \) is obviously a polynomial of degree at most \( m + 1 \), and \( D_\beta^z \) has the form in (8.3).

When \( |\beta| \leq k \), all the possible combinations of derivatives in \( D_\beta^z \) are finite, so there are finitely many different coefficients in all of the \( p_{a,b,\beta}(w_1) \)'s. Note that \( |w_1| \leq 1 \) on \( \mathbb{D} \) and \( a, b \leq m \leq k \). So we see that \( |p_{a,b,\beta}(w_1)| \leq C_k \) on \( \mathbb{D} \) as desired. \[ \blacksquare \]

Now we transfer \( \mathbb{H} \) to the product model \( \mathbb{D} \times \mathbb{D}^* \) by the biholomorphism \( \Phi \), combine (8.2) and (8.3), and we see the right hand side of (8.1) becomes

\[ \sum_{|\beta|\leq k} \int_{\mathbb{D} \times \mathbb{D}^*} \left| \int_{\mathbb{D} \times \mathbb{D}^*} K_{a,b,\beta}(w, \eta) f(\Psi(\eta)) |\eta_2|^2 \ dV(\eta) \right|^p |w_2|^{pk+2} \ dV(w), \quad (8.4) \]

where

\[ K_{a,b,\beta}(w, \eta) = \frac{p_{a,b,\beta}(w_1)}{w_2^{|\beta|-b}} \cdot \frac{\partial^a}{\partial w_1^a} \left( \frac{1}{(1-w_1\eta_1)^2} \right) \cdot \frac{\partial^b}{\partial w_2^b} \left( \frac{1}{w_2\eta_2} \cdot \frac{1}{(1-w_2\eta_2)^2} \right). \]

### 8.3 Convert the Differential Operators on \( \mathbb{D}^* \)

Since \( \mathbb{D}^* \) is a Reinhardt domain, we can apply a result from [Str86].

**Lemma 8.3.1** As in (8.4), for the last factor in \( K_{a,b,\beta}(w, \eta) \) we have

\[ \frac{\partial^b}{\partial w_2^b} \left( \frac{1}{w_2\eta_2} \cdot \frac{1}{(1-w_2\eta_2)^2} \right) = \frac{\eta_2^b}{w_2^b} \cdot \frac{\partial^b}{\partial \eta_2^b} \left( \frac{1}{w_2\eta_2} \cdot \frac{1}{(1-w_2\eta_2)^2} \right). \quad (8.5) \]
By (3.1) in Chapter 3, we see that the kernel in (8.5) is the weighted Bergman kernel on $(\mathbb{D}^*, |z|^2)$. So we can argue step by step as in [Str86, Lemma 2.1] and its following remark in [Str86, Remark 2.3] to complete the proof.

Now we focus on the integration over $\mathbb{D}^*$ in (8.4). We first define a "tangential" operator.

**Definition 8.3.1** Let $S_w = w \frac{\partial}{\partial w}$ be the complex normal differential operator on a neighborhood of $\partial \mathbb{D}$. We define the tangential operator by

$$T_w = \Im(S_w) = \frac{1}{2i} \left( w \frac{\partial}{\partial w} - \overline{w} \frac{\partial}{\partial \overline{w}} \right).$$

**Remark 8.3.2** Indeed, $T_w$ is well-defined on a neighborhood of $\overline{\mathbb{D}}$. Moreover, for any disk $\mathbb{D}_r = \{|w| < r\}$ of radius $r < 1$ with defining function $\rho_r(w) = |w|^2 - r^2$, we have

$$T_w(\rho_r) = 0 \quad (8.6)$$
on $\partial \mathbb{D}_r$. That is, $T_w$ is tangential on $\partial \mathbb{D}_r$ for all $r < 1$.

In order to make use of integration by parts, we need the following lemma.

**Lemma 8.3.3** Let $T_w$ be as above. For $b \in \mathbb{Z}^+ \cup \{0\}$, we have

$$T_w^b \equiv \sum_{j=0}^{b} c_j w^j \frac{\partial^j}{\partial \overline{w}^j} \left( \mod \frac{\partial}{\partial \overline{w}} \right), \quad (8.7)$$

where the $c_j$'s are constants, $c_b \neq 0$, and $T_w^b$ denotes the composition of $b$ copies of the $T_w$'s.

**Proof** We prove (8.7) by induction on $b$. The case $b = 0$ is trivial. When $b = 1$, it is easy to see that

$$T_w \equiv -\frac{1}{2i} \overline{w} \frac{\partial}{\partial \overline{w}} \left( \mod \frac{\partial}{\partial \overline{w}} \right).$$
Suppose that (8.7) holds for some $b$. Then we see that

$$T^b_w = \sum_{j=0}^b c_j \overline{w}^j \frac{\partial^j}{\partial \overline{w}^j} + A \circ \frac{\partial}{\partial w},$$

for some operator $A$. So, for the case $b + 1$, we have

$$T_w \circ T^b_w = \frac{1}{2i} \left( w \frac{\partial}{\partial w} - \overline{w} \frac{\partial}{\partial \overline{w}} \right) \circ \left( \sum_{j=0}^b c_j \overline{w}^j \frac{\partial^j}{\partial \overline{w}^j} + A \circ \frac{\partial}{\partial w} \right)$$

$$= \frac{1}{2i} \left( \sum_{j=0}^{b+1} c_j \overline{w}^j \frac{\partial^j}{\partial \overline{w}^j} - j c_j \overline{w}^j \frac{\partial^j}{\partial \overline{w}^j} - c_j \overline{w}^{j+1} \frac{\partial^{j+1}}{\partial \overline{w}^{j+1}} \right) + T_w \circ A \circ \frac{\partial}{\partial w}$$

$$= \sum_{j=0}^{b+1} c'_j \overline{w}^j \frac{\partial^j}{\partial \overline{w}^j} + A' \circ \frac{\partial}{\partial w},$$

for some constants $c'_j$'s with $c'_{b+1} = -\frac{1}{2} c_b \neq 0$ and some operator $A'$. Therefore, (8.7) holds for $T^{b+1}_w$.

Combining (8.5) and (8.7), we note that the kernel in (8.5) is anti-holomorphic in $\eta_2$. The inside integration over $\mathbb{D}^*$ with respect to variable $\eta_2$ in (8.4) denoted by $I$ becomes

$$I = \int_{\mathbb{D}^*} \frac{\partial^b}{\partial w^b} \left( \frac{1}{w^b_2} \cdot \frac{1}{(1-w^b_2)^2} \right) f(\Psi(\eta)) |\eta_2|^2 dV(\eta_2)$$

$$= \int_{\mathbb{D}^*} \frac{\partial^b}{\partial \overline{w}^b} \left( \frac{1}{w^b_2} \cdot \frac{1}{(1-w^b_2)^2} \right) f(\Psi(\eta)) |\eta_2|^2 dV(\eta_2)$$

$$= \frac{1}{w^b_2} \sum_{j=0}^b c_j T^j_{\eta_2} \left( \frac{1}{w^j_2} \cdot \frac{1}{(1-w^j_2)^2} \right) f(\Psi(\eta)) |\eta_2|^2 dV(\eta_2)$$

$$= \frac{1}{w^b_2} \sum_{j=0}^b c_j \lim_{\epsilon \to 0^+} \int_{D - D_\epsilon} T^j_{\eta_2} \left( \frac{1}{w^j_2} \cdot \frac{1}{(1-w^j_2)^2} \right) f(\Psi(\eta)) |\eta_2|^2 dV(\eta_2).$$

Let us assume in addition for a moment that $f(\Psi(\eta))$ belongs to $C^\infty(\mathbb{D} \setminus \{0\})$ in the variable $\eta_2$. Then, by (8.6), we see that
\[ I = \frac{1}{w_2^b} \sum_{j=0}^{b} c_j \lim_{\epsilon \to 0^+} \int_{D - D_\epsilon} T_{\eta_2}^j \left( \frac{1}{w_2 \eta_2} \cdot \frac{1}{(1 - w_2 \eta_2)^2} \right) f(\Psi(\eta)) \eta_2^2 \, dV(\eta_2) \]
\[ = \frac{1}{w_2^b} \sum_{j=0}^{b} c_j (-1)^j \lim_{\epsilon \to 0^+} \int_{D - D_\epsilon} \frac{1}{w_2 \eta_2^2} \cdot \frac{1}{(1 - w_2 \eta_2)^2} T_{\eta_2}^j \left( f(\Psi(\eta)) \eta_2^2 \right) dV(\eta_2) \tag{8.8} \]
\[ = \frac{1}{w_2^b} \sum_{j=0}^{b} (-1)^j c_j \int_{D^*} \frac{1}{w_2 \eta_2} \cdot \frac{1}{(1 - w_2 \eta_2)^2} T_{\eta_2}^j \left( f(\Psi(\eta)) \right) \eta_2^2 \, dV(\eta_2), \]
where the last line follows from the fact \( T_{\eta_2} \left( |\eta_2|^2 \right) = 0. \)

**Definition 8.3.2** We use the following notation:

\[ F_j(\eta) = T_{\eta_2}^j \left( f(\Psi(\eta)) \right) \cdot \eta_2, \]
\[ \mathcal{B}_{0,a}(g)(w_1) = \int_{D} \frac{\partial^a}{\partial w_1^a} \left( \frac{1}{(1 - w_1 \eta_1)^2} \right) g(\eta_1) \, dV(\eta_1), \]
for any \( g \) whenever the integral is well-defined, and
\[ \mathcal{B}_0(h)(w_2) = \int_{D^*} \frac{h(\eta_2)}{(1 - w_2 \eta_2)^2} \, dV(\eta_2), \]
for any \( h \) whenever the integral is well-defined.

By (8.8) and the notation above, we see that (8.4) becomes

\[ \sum_{|\beta| \leq k} \int_{D \times D^*} \left| \sum_{a + b \leq |\beta|} \frac{p_{a,b,\beta}(w_1)}{w_2^{|\beta|+1}} \sum_{j=0}^{b} (-1)^j c_j \mathcal{B}_{0,a}(\mathcal{B}_0(F_j))(w) \right|^p \eta_2^{|p|k+2} \, dV(w). \tag{8.9} \]

### 8.4 Proof of Theorem 13

To prove Theorem 13, we first need two propositions.

**Proposition 8.4.1** The Bergman projection on \( \mathbb{D} \) is bounded from \( L^p_k(\mathbb{D}) \) to itself for \( p \in (1, \infty) \) and all \( k \in \mathbb{Z}^+ \cup \{0\} \).
Proof This is a special case of the classical result, the regularity of Bergman projection on bounded smooth domains with strongly pseudoconvex boundary. See [PS77] for details, or [KR14] for treatment of domains with more general boundary.

**Proposition 8.4.2** The integral operator $B_0$, defined as in Definition 8.3.2, is bounded from $L^p(D^*, |w|^2 - p)$ to itself for $p \in \left(\frac{4}{3}, 4\right)$, where $w \in D^*$.

Proof This statement is equivalent to the assertion that the weighted Bergman projection on the weighed space $(D^*, |w|^2)$ is bounded from $L^p(D^*, |w|^2)$ to itself for $p \in \left(\frac{4}{3}, 4\right)$. See Theorem 2.

Now we are ready to prove Theorem 13 under the additional assumption $f(\Psi(\eta)) \in C^\infty(\overline{D} \setminus \{0\})$ in the variable $\eta_2$.

**Theorem 13** The Bergman projection $B_{\mathbb{H}}$ on the Hartogs triangle $\mathbb{H}$ maps continuously from $L^p_k(\mathbb{H})$ to $L^p_k(\mathbb{H}, |z_2|^{pk})$ for $p \in \left(\frac{4}{3}, 4\right)$.

Proof [Under the additional assumption $f(\Psi(\eta)) \in C^\infty(\overline{D} \setminus \{0\})$ in the variable $\eta_2$.]

By (8.1), (8.4), (8.9) and Lemma 8.2.2, we obtain

\[
\|B(f)\|^p_{p,k, pk} \leq \sum_{|\beta| \leq k} \sum_{a+b \leq |\beta|} C_{p,k} \int_{D^*} |B_{0,a}(B_0(F_j))(w)|^p |w_2|^{pk+2-p(|\beta|+1)} dV(w) \\
\leq C_{p,k} \sum_{a+b \leq k} \int_{D^*} |B_{0,a}(B_0(F_b))(w)|^p |w_2|^{2-p} dV(w).
\]

By Proposition 8.4.1 and Definition 8.3.2, we see that $B_{0,a}$ is bounded from $L^p_a(D)$ to $L^p(D)$. Therefore, for $p \in (1, \infty)$, we have
\[ \|B(f)\|_{p,k,pk}^p \leq C_{p,k} \sum_{|\beta| \leq k} \int_{D^*} \left( \int_D \left| \sum_{|\beta| \leq n} D_{w_1,w_1}^\beta (B_0(F_b))(w) \right|^p dV(w_1) \right) |w_2|^{2-p} dV(w_2) \]
\[ \leq C_{p,k} \sum_{|\beta| \leq k} \int_{D^*} \left( \int_D \left| B_0(D_{w_1,w_1}^\beta (F_b))(w) \right|^p |w_2|^{2-p} dV(w_2) \right) dV(w_1). \]

Similarly, by Proposition 8.4.2 and Definition 8.3.2, for \( p \in (\frac{4}{3}, 4) \) we have

\[ \|B(f)\|_{p,k,pk}^p \leq C_{p,k} \sum_{|\beta| \leq k} \int_{D^*} \left( \int_D \left| D_{w_1,w_1}^\beta (F_b)(w) \right|^p |w_2|^{2-p} dV(w_2) \right) dV(w_1) \]
\[ = C_{p,k} \sum_{|\beta| \leq k} \int_{D^*} \left| D_{w_1,w_1}^\beta T_{w_1} (f(\Psi(w))) \cdot w_2 \right|^p |w_2|^{2-p} dV(w) \]
\[ \leq C_{p,k} \sum_{|\beta| \leq k} \int_{D^*} \left| D_{w_1,w_1}^\beta T_{w_1} D_{w_2,w_2}^\beta \left( f(\Psi(w)) \right) \right|^p |w_2|^2 dV(w), \]

where the last line follows from \( T_{w_2} = \frac{1}{2i} \left( w_2 \frac{\partial}{\partial w_2} - \overline{w_2} \frac{\partial}{\partial \overline{w_2}} \right) \), \(|w_2| < 1\) for \( w_2 \in D^* \), and an equation similar to (8.7).

Note that, under the biholomorphism \( \Psi(w) = z \) defined in §8.2, we have

\[ \frac{\partial}{\partial w_1} = w_2 \frac{\partial}{\partial z_1} \quad \text{and} \quad \frac{\partial}{\partial \overline{w_1}} = \overline{w_2} \frac{\partial}{\partial \overline{z}_1}, \]

and also

\[ \frac{\partial}{\partial w_2} = w_1 \frac{\partial}{\partial z_1} + \frac{\partial}{\partial z_2} \quad \text{and} \quad \frac{\partial}{\partial \overline{w}_2} = \overline{w}_1 \frac{\partial}{\partial \overline{z}_1} + \frac{\partial}{\partial \overline{z}_2}. \]

Again, since \((w_1, w_2) \in D \times D^*\), we see that \(|w_1|, |w_2| < 1\). Therefore, by (8.10) and the transfer of \( D \times D^* \) back to \( \mathbb{H} \), we finally arrive at

\[ \|B(f)\|_{p,k,pk}^p \leq C_{p,k} \sum_{|\alpha| \leq k} \int_{\mathbb{H}} \left| D_{z,\overline{z}}^\alpha (f)(z) \right|^p dV(z) \]
as desired.
To remove the additional assumption \( f(\Psi(\eta)) \in C^\infty(\overline{\mathbb{D} \setminus \{0\}}) \) in variable \( \eta_2 \), we need the following lemma.

**Lemma 8.4.3** The subspace \( C^\infty(\mathbb{D} \setminus \{0\}) \cap L^p_k(\mathbb{D}^*, |w|^2) \) is dense in \( L^p_k(\mathbb{D}^*, |w|^2) \) with respect to the weighted norm in \( L^p_k(\mathbb{D}^*, |w|^2) \).

**Proof** The argument is based on the ideas from [Eva98, §5.3 Theorem 2 and Theorem 3].

Given any \( g \in L^p_k(\mathbb{D}^*, |w|^2) \), we fix a \( \delta > 0 \). On \( V_0 = \mathbb{D} \setminus \overline{D_{\frac{1}{2}}} \), the weighted norm \( L^p_k(V_0, |w|^2) \) is equivalent to the unweighted norm \( L^p_k(V_0) \). Arguing as in the proof of [Eva98, §5.3 Theorem 2], we see that there is a \( g_0 \in C^\infty(V_0) \), so that

\[
\| g_0 - g \|_{L^p_k(V_0, |w|^2)} < \delta.
\]

Define \( U_j = \mathbb{D}_{\rho_{j+1}} \setminus \overline{D_{\frac{1}{2}}} \) for some \( 1 > \rho > \frac{1}{2} \) and for \( j \in \mathbb{Z}^+ \) (\( U_1 = \emptyset \)). Let \( V_j = U_{j+3} \setminus \overline{U_{j+1}} \).

Then we see that \( \bigcup_{j=1}^\infty V_j = \mathbb{D}_\rho \setminus \{0\} \). Arguing as in the proof of [Eva98, §5.3 Theorem 2], we can find a smooth partition of unity \( \{ \psi_j \}_{j=1}^\infty \) subordinate to \( \{ V_j \}_{j=1}^\infty \), so that \( \sum_{j=1}^\infty \psi_j = 1 \) on \( \mathbb{D}_\rho \setminus \{0\} \). Moreover, for each \( j \), the support of \( \psi_j g \) lies in \( V_j \) (so \( |w| > \frac{1}{j+3} \)), and hence \( \psi_j g \in L^p_k(\mathbb{D}_\rho \setminus \{0\}) \). Therefore we can find smooth function \( g_j \), with support in \( U_{j+4} \setminus \overline{U_j} \), so that

\[
\| g_j - \psi_j g \|_{L^p_k(\mathbb{D}_\rho \setminus \{0\})} \leq \frac{\delta}{2^j},
\]

see [Eva98, §5.3 Theorem 2] for details. Write \( \tilde{g}_0 = \sum_{j=1}^\infty g_j \). It is easy to see that \( \tilde{g}_0 \in C^\infty(\mathbb{D}_\rho \setminus \{0\}) \) and

\[
\| \tilde{g}_0 - g \|_{L^p_k(\mathbb{D}_\rho \setminus \{0\}, |w|^2)} \leq \| \tilde{g}_0 - g \|_{L^p_k(\mathbb{D}_\rho \setminus \{0\})} \leq \delta,
\]

since \( |w| < 1 \) on \( \mathbb{D}_\rho \setminus \{0\} \).
Let $V'_0$ be an open set so that $\partial \mathbb{D} \subset V'_0$ and $V'_0 \cap \mathbb{D} = V_0$. Then $V'_0 \cup D_\rho$ cover $\overline{\mathbb{D}}$. Take a smooth partition of unity $\{\tilde{\psi}_1, \tilde{\psi}_2\}$ on $\overline{\mathbb{D}}$ subordinate to $\{V'_0, D_\rho\}$. Then $h = \tilde{\psi}_1 g_0 + \tilde{\psi}_2 \tilde{g}_0$ belongs to $C^\infty(\overline{\mathbb{D}} \setminus \{0\})$, and

$$
\|h - g\|_{L^p(\mathbb{D}^*, |w|^2)} \leq C \left( \|g_0 - g\|_{L^p(V_0, |w|^2)} + \|	ilde{g}_0 - g\|_{L^p(D_\rho \setminus \{0\}, |w|^2)} \right) < 2C\delta
$$

as desired.

Now we are ready to remove the extra assumption and prove Theorem 13.

**Proof of Theorem 13:**

For any $f \in L^p_k(\mathbb{H})$, we have $f(\Psi(w)) \in L^p_k(\mathbb{D}^*, |w_2|^2)$ in the variable $w_2$. Then, by Lemma 8.4.3, we can find a sequence $\{h_j(w)\} \subset C^\infty(\overline{\mathbb{D}} \setminus \{0\})$ tending to $f(\Psi(w))$ in the variable $w_2$ with respect to the norm in $L^p_k(\mathbb{D}^*, |w_2|^2)$. We have already seen that (8.10) holds for each $h_j(w)$ replacing $f(\Psi(w))$. Indeed, if we focus on the integration over $\mathbb{D}^*$, by comparing with (8.4), we see that (8.10) is just the following. For each $b = 0, 1, \ldots, k$,

$$
\int_{\mathbb{D}^*} \left| w_2^b \frac{\partial}{\partial w_2^b} (B_2(h_j)) \right|^p |w_2|^2 dV(w_2) \leq C_{p,k} \|h_j\|_{L^p_k(\mathbb{D}^*, |w_2|^2)}, \quad (8.11)
$$

where $B_2$ is the weighted Bergman projection on the weighted space $(\mathbb{D}^*, |w_2|^2)$.

Now let $j \to \infty$. In view of the boundedness of $B_2$ (by Theorem 2 (a)), we see that $w_2^b \frac{\partial}{\partial w_2^b} (B_2(h_j))$ indeed tends to $w_2^b \frac{\partial}{\partial w_2^b} (B_2(f(\Psi)))$ in $L^p(\mathbb{D}^*, |w_2|^2)$ for each $b = 0, 1, \ldots, k$. Therefore (8.11) is valid for general $f(\Psi(w)) \in L^p_k(\mathbb{D}^*, |w_2|^2)$, which completes the proof for general $f \in L^p_k(\mathbb{H})$.

**Remark 8.4.4** If we consider a general weighted space $L^p_k(\mathbb{H}, |z_2|^s)$ rather than $L^p_k(\mathbb{H}, |z_2|^{pk})$, we can use the same idea and apply the two-weight inequality in Chapter 4 to derive the boundedness of $\mathcal{B}$ for $p \in (\frac{1}{3}, \frac{s+1}{k+1})$ and $s \leq pk$. When $s = 0$ and $k = 1$, we see that we
cannot derive the boundedness even for $p = 2$. This coincides with the fact that $B$ is not bounded from $W^1(\mathbb{H})$ to itself for the unweighted case, see [CS13].

**Remark 8.4.5** We may also consider the weighted Sobolev space with weights inhomogeneous with respect to derivatives of different orders.

To be precise, for each $k \in \mathbb{Z}^+ \cup \{0\}$, $p \in (1, \infty)$, and $t = \{t_m\}_{m=0}^\infty \in \mathbb{R}^\omega$, we define the inhomogeneous weighted Sobolev space by

$$L^p_k(|z_2|^t) = \{ f \in L^1_{\text{loc}}(\mathbb{H}) : \|f\|_{p,k,t} < \infty \},$$

where the norm is defined as

$$\|f\|_{p,k,t} = \left( \int_{\mathbb{H}} \sum_{|\alpha| \leq k} |D^\alpha (f)(z)|^p |z_2|^t |dz| \right)^{\frac{1}{p}}.$$

Then a variant of Theorem 13 can be stated as follows. (The proof is almost the same.)

For each $k \in \mathbb{Z}^+ \cup \{0\}$ and $p \in \left( \frac{1}{3}, 4 \right)$, suppose that $t = \{t_m\}_{m=0}^\infty \in \mathbb{R}^\omega$ and $t_m = mp$. Then there exists a constant $C_{p,k} > 0$ so that

$$\|B(f)\|_{p,k,t} \leq C_{p,k} \|f\|_{p,k}$$

for any $f \in L^p_k(\mathbb{H})$.

---

8.5 **Generalization to $n$-dimensional Hartogs Triangle**

The method also applies to the $n$-dimensional Hartogs triangle. Using the notation in (1.1), we have the following result.

**Theorem 14** The Bergman projection on the $n$-dimensional Hartogs triangle $\mathbb{H}^n_{\phi_j}$ maps continuously from $L^p_k(\mathbb{H}^n_{\phi_j})$ to $L^p_k(\mathbb{H}^n_{\phi_j}, |z_1^p|)$ for $p \in \left( \frac{2n}{n+1}, \frac{2n}{n-1} \right)$.

---

2See also [Zey13] for variants of Hartogs triangle.
The idea of the proof remains the same, but requires more complicated computations. We outline it very briefly here.

**Proof** Using the same argument as in the proof of Theorem 5 in Chapter 3, it suffices to prove the theorem for the domain

\[ \mathbb{H}^n = \{ (z', z'') \in \mathbb{C}^{m_1 + \cdots + m_l + d} : \max_{1 \leq j \leq l} |z_j''| < |z_1''| < \cdots < |z_d''| < 1 \}. \]

As in §8.2, we transfer \( \mathbb{H}^n \) to a product model by \( \Phi : \mathbb{H}^n \to \mathbb{B}_{m_1} \times \cdots \times \mathbb{B}_{m_l} \times (\mathbb{D}^\times)^d \), with

\[ \Phi(z', z'') = \left( \frac{z_1'}{z_2'}, \frac{z_2'}{z_3'}, \ldots, \frac{z_{l-1}'}{z_l'}, \frac{z_l'}{z_d'} \right) = (w', w_1'', \ldots, w_d''). \]

By induction, (8.3) becomes

\[ D_z^\beta = \sum_{|a| + |b| \leq |\beta|} \frac{p_{a,b}(w)}{w^n} \cdot \frac{\partial^{a+b}}{\partial w^a \partial w^b}, \tag{8.12} \]

where \( \beta \) is an \( n \)-dimensional multi-index, \( a \) is \( m \)-dimensional, and both \( b \) and \( \tilde{b} \) are \( d \)-dimensional with \( \tilde{b}_j + b_j \leq |\beta| \) for \( j = 1, \ldots, d - 1 \) and \( \tilde{b}_d + b_d = |\beta| \).

While converting the differential operators on \( \mathbb{D}^\times \), (8.5) applies to the weighted Bergman kernel on the weighted space \( (\mathbb{D}^\times, |w|^{2(j-1)}) \), for \( j = n - d + 1, n - d + 2, \ldots, n \). By using (8.5), (8.6), (8.7), and integration by parts, we arrive at a similar expression as (8.9).

Classical result tells us that, for \( j = 1, \ldots, l \), the \( L_p^k \) boundedness of the Bergman projection on \( \mathbb{B}^{m_j} \) holds for \( p \in (1, \infty) \). Thus we only need to take care of the \( L_p^k \) boundedness of the weighted Bergman projection on \( (\mathbb{D}^\times, |w|^{2(j-1)}) \), for \( j = n - d + 1, n - d + 2, \ldots, n \). By Theorem 2, all these projections will be bounded when \( p \in \left( \frac{2n}{n+1}, \frac{2n}{n-1} \right) \).

The proof will be complete once we pass from \( C^\infty(\overline{\mathbb{D}} \setminus \{0\}) \) to \( L_p^k(\mathbb{D}^\times, |w|^{2(j-1)}) \) for \( j = n - d + 1, n - d + 2, \ldots, n \), by applying a general version of Lemma 8.4.3. \( \blacksquare \)
Remark 8.5.1 The reason we consider the weight $|z_1|^{pk}$ rather than $|z_d|^{pk}$ is that, if we look at (8.12) and apply (8.5), then we will obtain a factor $\frac{1}{|\tilde{\omega}_j|^{b_j+b_j}}$ with $\tilde{\beta}_j + b_j \leq |\beta| \leq k$ for $j = 1, \ldots, d$. For each $j$, the equality will hold in some cases. Therefore, for each $j$, it is required to consider a weight $|\omega_j|^{pk}$ to cancel out with the factor. By transferring the product model back to $\mathbb{H}^n$, we obtain a weight $|z_1|^{pk}$. 

REFERENCES


