On the Asymptotic Expansion of Complete Ricci-flat Kähler metrics on quasi-projective manifolds

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Abstract

In this work, we describe the asymptotic behavior of complete metrics with prescribed Ricci curvature on open Kähler manifolds that can be compactified by the addition of a smooth and ample divisor. First, we construct a explicit sequence of Kähler metrics with special approximating properties. Using those metrics as starting point, we are able to work out the asymptotic behavior of the solutions given in [TY1], in particular obtaining their full asymptotic expansion.

1 Introduction

In 1978, Yau [Y] proved the Calabi Conjecture by showing the existence and uniqueness of Kähler metrics with prescribed Ricci curvature on compact complex manifolds.

Following this work, Tian and Yau [TY1] settled the non-compact version of Calabi’s Conjecture on quasi-projective manifolds that can be compactified by adding a smooth, ample divisor. In a subsequent work [TY2], their result was extended to the case where the divisor has multiplicity greater than one and orbifold-type singularities. This generalization was independently done by Bando [B] and Kobayashi [K].

Once the existence problem is solved, an interesting question that arises concerns the behavior of these complete metrics near the divisor. This question is also addressed to by Tian and Yau ([TY1]).

In a subsequent work, Tian and Yau ([TY2]) obtain existence results, as well as the asymptotics of their solution, for the case in which the divisor has multiplicity strictly greater than one. These techniques, however, make an essential use of the higher multiplicity of the divisor and thus they do not work when this multiplicity equals one which can be thought of as the generic case. In particular the asymptotics properties of the solutions found in ([TY1]) remained ignored.

The aim of this paper is to provide an answer to this question, therefore refining the main result in [TY1]. More precisely, we shall first construct a sequence of complete Kähler metrics with special approximating properties on a quasi-projective manifold (in our case, the complement of a smooth, ample divisor on a compact complex manifold). Then by using these approximating metrics, we are going to study the solution of a complex Monge-Ampère equation on the open manifold. A careful analysis of the complex Monge-Ampère operator will allow us to describe the asymptotic properties of the solution. As a matter of fact, the reader will note that our results apply equally well to divisors having orbifold-type singularities.

In a subsequent work, we expect to remove the smoothness assumption on the divisor so as to include divisors having normal crossings.

To state the main results of this paper, let us consider a compact, complex manifold $\overline{M}$ of complex dimension $n$. Let $D$ be an admissible divisor in $\overline{M}$, ie, a divisor satisfying the following conditions:

- $\text{Sing } \overline{M} \subset D$.
- $D$ is smooth in $\overline{M} \setminus \text{Sing } \overline{M}$.
- For every $x \in \text{Sing } \overline{M}$, the corresponding local uniformization $\Pi_x : \tilde{U}_x \to U_x$, with $\tilde{U}_x \subset \mathbb{C}^n$, is such that $\Pi_x^{-1}(D)$ is smooth in $\tilde{U}_x$. 


Let \( \Omega \) be a smooth, closed \((1,1)\)-form in the cohomology class \( c_1(K^{-1}_M \otimes L^{-1}_D) \), where \( K_M \) stands for the Canonical Line Bundle of \( M \), and \( L_D \) for the line bundle associated to \( D \). Let \( S \) be a defining section of \( D \) on \( L_D \) and let \( M \) be the open manifold \( M = \overline{M} \setminus D \). Consider a hermitian metric \( ||.|| \) on \( L_D \).

Fefferman, in his paper \([F]\), developed inductively an \( n \)-th order approximation to a complete Kähler-Einstein metric on strictly pseudoconvex domains in \( \mathbb{C}^n \) with smooth boundary, and he suggested that higher order approximations could be obtained by considering log terms in the formal expansion of the solution to a certain complex Monge-Ampère equation. This idea was used by Lee and Melrose \([LM]\), where they constructed the full asymptotic expansion of the solution to the Monge-Ampère equation introduced by Fefferman.

Motivated by this work, we construct inductively a sequence of rescalings \( \|\cdot\|_{\phi_m} := e^{\phi_m/2}||.|| \) of a fixed hermitian metric \( ||.|| \) on \( L_D \), which will be the main ingredient of the proof of the following result.

**Theorem 1.1** Let \( M, \Omega \) and \( D \) be as above. Then, for every \( \varepsilon > 0 \), there exists an explicitly given complete Kähler metric \( g_\varepsilon \) such that

\[
\text{Ric}(g_\varepsilon) - \Omega = \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} f_\varepsilon \quad \text{on } M,
\]

where \( f_\varepsilon \) is a smooth function on \( M \) such that all its covariant derivatives decay to the order of \( O(||S||^{\varepsilon}) \). Furthermore, for any \( k \geq 0 \), the norm of the \( k \)-th covariant derivative of the Riemann curvature tensor \( \text{R}(g_\varepsilon) \) of the metric \( g_\varepsilon \) decays to the order of \( O((\varepsilon n \log ||S||)^{-\frac{k+2}{2n+2}}) \).

**Remark:** In the above statement, it should be emphasized that the metric in question is constructed inductively in an explicit manner. In other words, this result provides complete metrics that are “approximate solutions” to the Calabi problem, but that have the advantage of being explicitly described.

So far, there has been a large amount of work concerned with deriving asymptotic expansions for Kähler-Einstein metrics in different contexts: after Cheng and Yau \([CY1]\) proved existence and uniqueness of Kähler-Einstein metrics on strictly pseudoconvex domains in \( \mathbb{C}^n \) with smooth boundary (in addition to results on the regularity of the solution), Lee and Melrose \([LM]\) derived an asymptotic expansion for the Cheng-Yau solution, which completely determines the form of the singularity and improves the regularity result of \([CY1]\). On the setting of quasi-projective manifolds, Cheng and Yau \([CY2]\) and Tian and Yau \([TY3]\) showed the existence of Kähler-Einstein metrics under certain conditions on the divisor, and Wu developed the asymptotic expansion to the Cheng-Yau metric on a quasi-projective manifold (also assuming some conditions on the divisor), as the parallel part to the work of Lee and Melrose \([LM]\).

However the asymptotic description of complete Kähler metrics with prescribed Ricci curvature, which are not of Kähler-Einstein type, was still lacking, for example in the context of quasi-projective manifolds (also assuming some conditions on the divisor), as the parallel part to the work of Lee and Melrose \([LM]\).

In \([TY1]\), the result of existence of a complete Kähler metric (in a given Kähler class) with prescribed Ricci curvature is achieved by solving the following complex Monge-Ampère equation

\[
\begin{cases}
\left( \omega + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u \right)^n = e^f \omega^n, \\
\omega + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u > 0, \quad u \in C^\infty(M, \mathbb{R}),
\end{cases}
\]  

where \( f \) is a given smooth function satisfying the integrability condition

\[
\int_M (e^f - 1)w^n = 0. \tag{3}
\]

Our main result describes the asymptotic behavior of the solution to (2), by showing that the approximate metrics given in Theorem 1.1 are asymptotically as close to the actual solution as possible.

We should point out here that the underlying analysis of the case we are considering, as well as the methods used in our work, differs fundamentally from Wu’s work \([W]\). Namely, it is not trivial to show, for example, that the solution \( u(x) \) to (2) vanishes uniformly when \( x \) approaches infinity. In the Kähler-Einstein context considered by Wu, it is not hard to see it directly from the defining equation (as
observed by Cheng and Yau in [CY1]. Also, the log-filtration of the Cheng-Yau Hölder ring considered by Wu is not preserved in our case.

**Theorem 1.2** For each \( \varepsilon > 0 \), let \( g_\varepsilon \) and \( f_\varepsilon \) be given by Theorem 1.1

Consider the problem

\[
\begin{align*}
\left( \omega_{g_\varepsilon} + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_\varepsilon \right)^n &= e^{f_\varepsilon} \omega^n_{g_\varepsilon}, \\
\omega_{g_\varepsilon} + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_\varepsilon &> 0, \\
\end{align*}
\]

(4)

Then, there exists a solution \( u_\varepsilon(x) \) which decays to the order of at least \( O(||S||^x(x)) \) for \( x \) sufficiently close to \( D \).

Moreover, the norm of the \( k \)-th covariant derivative \( |\nabla^k \omega_{g_\varepsilon}|_{g_\varepsilon} \) of \( \omega_{g_\varepsilon} \) decays as \( O(||S||^x(x)\rho_{g_\varepsilon}^{-\frac{k+2}{n+1}}) \), where \( \rho_{g_\varepsilon}(x) \) denotes the distance, with respect to the metric \( g_\varepsilon \), from a fixed point \( x_0 \in M \) to \( x \).

This theorem has an important, straightforward corollary.

**Corollary 1.1** Let \( \overline{M} \) be a compact Kähler manifold of complex dimension \( n \), and let \( D \) be a smooth anti-canonical divisor. Then for any \( \varepsilon > 0 \), there exists a complete Ricci-flat Kähler metric on \( M = \overline{M} \setminus D \) that can be described as

\[
\omega = \omega_{g_\varepsilon} + \omega_{u_\varepsilon},
\]

where \( g_\varepsilon \) is the Kähler metric constructed in Theorem 1.1 and \( \omega_{u_\varepsilon} \) is a Kähler form that decays at least to the order of \( O(||S||^x) \) when \( x \) approaches the divisor. Therefore, \( \omega_{g_\varepsilon} \) provides the asymptotics of the Ricci-flat metric \( \omega \).

The structure of the paper is as follows. In Section 2 we construct inductively a sequence of hermitian metrics \( \{|\cdot|\}_m \) on \( L_D \) such that the closed \((1,1)\)-form

\[
\omega_m = \frac{\sqrt{-1}}{2\pi} \left( n^{1+1/n} + \partial \bar{\partial} (\log ||S||^2_m) \right)^{\frac{n+1}{n}}
\]

(5)

is positive definite on a tubular neighborhood \( V_m \) of \( D \) in \( \overline{M} \).

The Kähler form \( \omega_m \) defines a Kähler metric \( g_m \) on \( V_m \) such that \( \text{Ric}(g_m) - \Omega = \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} f_m \), for a smooth function \( f_m \) on \( M \) that decays to the order of \( ||S||^m \). An important technical result for this construction is Lemma 2.2, whose proof is the object of Section 3.

In Section 4 we use the constructions of Section 2 to complete the proof of Theorem 1.1. First, we shall obtain the necessary estimates on the decay of the Riemann curvature tensor of the metrics \( g_m \). Then we shall proceed to the construction of approximating metrics that are defined on the whole manifold (and not only on a neighborhood of the divisor at infinity).

Finally, Section 5 is devoted to the asymptotic study of the Monge-Ampère equation (2). By using the maximum principle for the complex Monge-Ampère operator, along with the construction of a suitable barrier, we shall complete the proof of Theorem 1.2.

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## 2 Approximating Kähler metrics

Let \( \overline{M} \) be a compact Kähler manifold of complex dimension \( n \), and let \( D \) be an admissible divisor in \( \overline{M} \).

The divisor \( D \) induces a line bundle \( L_D \) on \( \overline{M} \). We will assume that the restriction of \( L_D \) to \( D \) is ample, so that there exists an orbifold hermitian metric \( ||\cdot|| \) on \( L_D \) such that its curvature form \( \tilde{\omega} \) is positive definite along \( D \).
Consider a closed $(1, 1)$-form $\Omega$ in the Chern class $c_1(-K_M - L_D)$. The goal of this section is to construct a complete \( \text{kähler} \) metric \( g \) such that

\[
\text{Ric}(g) - \Omega = \frac{\sqrt{-1}}{2\pi} \partial\bar{\partial}f \text{ on } M,
\]

for a smooth function \( f \) with sufficiently fast decay, where \( M = \overline{M} \setminus D \) and \( \text{Ric}(g) \) stands for the Ricci form of the metric \( g \).

Fix an orbifold hermitian metric \( ||.|| \) on \( L_D \) such that its curvature form \( \tilde{\omega} \) is positive definite along \( D \). We shall need to rescale the metric by a suitable factor which will be determined in the following discussion. Let us begin by observing that the restriction \( \Omega|_D \) of \( \Omega \) to \( D \) belongs to \( c_1(D) \) since, by assumption, \( \Omega \in c_1(-K_M - L_D) \). Hence, there exists a function \( \varphi \) such that \( \tilde{\omega}|_D + \frac{\sqrt{-1}}{2\pi} \partial\bar{\partial}\varphi \) defines a metric \( g_D \) verifying \( \text{Ric}(g_D) = \Omega|_D \). So, by rescaling \( ||.|| \) by an appropriate factor, we may assume that \( \tilde{\omega} \), when restricted to the infinity \( D \), defines a metric \( g_D \) such that \( \text{Ric}(g_D) = \Omega|_D \).

Next denote by \( S \) the defining section of \( D \), and write \( ||.||_\varphi = e^{-\varphi/2}||.|| \) for the rescaling of \( ||.|| \), where \( \varphi \) is any smooth function on \( \overline{M} \).

We define

\[
\omega_\varphi = \frac{\sqrt{-1}}{2\pi} n^{1+1/n} \partial\bar{\partial}(-\log ||S||^2_\varphi)^{\frac{n+1}{n}}.
\]

Then it follows that

\[
\omega_\varphi = (-n \log ||S||^2_\varphi)^{1/n} \tilde{\omega}_\varphi + \frac{1}{(-n \log ||S||^2_\varphi)^{(n-1)/n}} \frac{\sqrt{-1}}{2\pi} \partial\log ||S||^2_\varphi \wedge \bar{\partial}\log ||S||^2_\varphi,
\]

where \( \tilde{\omega}_\varphi \) is the curvature form of the metric \( ||.||_\varphi \). From this expression, we can see that, as long as \( \tilde{\omega}_\varphi \) is positive definite along \( D \), \( \omega_\varphi \) is positive definite near \( D \).

We state here the main result of this section.

**Proposition 2.1.** Let \( \overline{M} \) be a compact \( \text{kähler} \) manifold of complex dimension \( n \), and let \( D \) be an admissible divisor in \( \overline{M} \). Consider also a form \( \Omega \in c_1(-K_M - L_D) \), where \( L_D \) is the line bundle induced by \( D \).

Then there exist sequences of neighborhoods \( \{V_m\}_{m \in \mathbb{N}} \) of \( D \) along with complete \( \text{kähler} \) metrics \( \omega_m \) on \( (V_m \setminus D, \partial(V_m \setminus D)) \) (as defined in (7)) such that

\[
\text{Ric}(\omega_m) - \Omega = \frac{\sqrt{-1}}{2\pi} \partial\bar{\partial}f_m \text{ on } V_m \setminus D
\]

where \( f_m \) are smooth functions on \( M = \overline{M} \setminus D \). Furthermore each \( f_m \) decays to the order of \( O(||S||^m) \). In addition the curvature tensors \( R(g_m) \) of the metrics \( g_m \) decay at least to the order of \( (-n \log ||S||^2)^{\frac{1}{n}} \) near the divisor.

The remainder of this section will be devoted to the proof of Proposition 2.1.

If \( \tilde{\omega} = -\frac{\sqrt{-1}}{2\pi} \partial\bar{\partial}\log ||S||^2 \) is the curvature form of \( ||.|| \), then for any \( \text{kähler} \) metric \( g' \) on \( \overline{M} \), \( \text{Ric}(g') - \tilde{\omega} \in c_1(-K_M - L_D) \). Hence, up to constant, there is a unique function \( \Psi \) such that

\[
\Omega = \text{Ric}(g') - \tilde{\omega} + \frac{\sqrt{-1}}{2\pi} \partial\bar{\partial}\Psi.
\]

**Definition 2.1.** For \( x \) in the set where \( \omega_\varphi \) is positive definite (\( x \) near \( D \)), write

\[
f_\varphi(x) = -\log ||S||^2 - \log\left(\frac{\omega^n_\varphi}{\overline{\omega^n_\varphi}}\right) - \Psi,
\]

where \( \omega' \) is the \( \text{kähler} \) form of \( g' \).

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Lemma 2.1 The function \( f_0(x) \) converges uniformly to a constant if and only if \( \text{Ric}(g_D) = \Omega|_D \).

Proof: Choose a coordinate system \((z_1, \ldots, z_n)\) around a point \(x\) near \(D\) such that the local defining section \(S\) of \(D\) is given by \(\{z_n = 0\}\). In these coordinates, write \(\tilde{\omega} = \tilde{\omega}_0^{1/2} \text{det} g' \), \(g'\) as \(g'_{ij} \), and \(h_{ij}^{1/2} \text{det} g' \), \(h_{ij}^{1/2} \text{det} g'\), and \(||.||\) as a positive function \(a\).

By definition we have
\[
f_0(x) = -\log \left( \frac{|S|^2 \omega_0^n}{\omega^n} \right) - \Psi(x) = -\log \left( \frac{a \text{det}(h_{ij})^{1/2}}{\text{det}(g'_{ij})^{1/2}} \right) (x) - \Psi(x) + O(||S(x)||),
\]
for \(x\) near \(D\).

Since \(a^{-1} \text{det}(g'_{ij})^{1/2} \) is a well-defined volume form on \(D\), it makes sense to set
\[
f_0(x) = -\log \left( \frac{a \text{det}(h_{ij})^{1/2}}{\text{det}(g'_{ij})^{1/2}} \right) (z', 0) + O(||S(x)||),
\]
for \(x = (z', z_n)\). Hence, \(\lim_{x\to D} f_0(x)\) is a constant if and only if \(\frac{a \text{det}(h_{ij})^{1/2}}{\text{det}(g'_{ij})^{1/2}} (z', 0)\) is constant. In other words, \(\lim_{x\to D} f_0(x)\) is a constant if and only if
\[
\sqrt{-1} \frac{1}{2\pi} \partial \bar{\partial} \Psi = -\log \left( \frac{a \text{det}(h_{ij})^{1/2}}{\text{det}(g'_{ij})^{1/2}} \right) (z', 0) - \log a \text{det}(g'_{ij})^{1/2} \text{det}(g'_{ij})^{1/2}.
\]
Since \(\Omega = \text{Ric}(g') - \tilde{\omega} + \sqrt{-1} \frac{1}{2\pi} \partial \bar{\partial} \Psi\), \(\lim_{x\to D} f_0(x)\) is a constant if and only if \(\text{Ric}(g_D) = \Omega|_D\). \(\square\)

An appropriate choice of \(\Psi\) allows us to assume in the sequel that \(f_0(x)\) converges uniformly to zero as \(x \to D\).

The function \(f_0(x)\) was only defined for \(x\) near \(D\), but we can extend it smoothly to be zero along \(D\) since \(|S|^2 \omega_0^n\) is a well-defined volume form over all \(M\). Hence, there exists a \(\delta_0 > 0\) such that, in the neighborhood \(V_0 := \{x \in M; ||S(x)|| < \delta_0\}\), \(f_0\) can be written as
\[
f_0 = S \cdot u_1 + \overline{S} \cdot \overline{u}_1,
\]
where \(u_1\) is a \(C^\infty\) local section in \(\Gamma(V_0, L^{-1}_D)\).

Our goal now would be to construct a function \(\phi_1\) of the form \(S \cdot \theta_1 + \overline{S} \cdot \overline{\theta}_1\), so that the corresponding \(f_\phi_1 = f_1\) vanishes at order \(2\) along \(D\), and then proceed inductively to higher order. Unfortunately, there is an obstruction to higher approximation that lies in the kernel of the laplacian on \(L^{-1}_D\) restricted to \(D\). In order to deal with this difficulty, one must introduce \((-\log ||S||^2)\)-terms in the expansion of \(\phi_1\), as pointed out in [F] and [LM] where the similar problem of finding expansions for the solutions of the Monge-Ampère equation on a strictly pseudoconvex domain was treated. Further details can be found below.

Following the techniques in [TY2], we are going to construct inductively a sequence of hermitian metrics \(\{||.||_m\}_{m>0}\) on \(L_D\) such that, for any \(m > 0\), there exists a \(\delta_m > 0\) satisfying:

1. The corresponding Kähler form \(\omega_m\) associated to \(|.|_m\) (as defined in [T]) is positive definite in \(V_m := \{x \in M; ||S(x)|| < \delta_m\}\).
2. The function \(f_m\) associated to \(\omega_m\) (as in the Definition [24]) can be expanded in \(V_m\) as
   \[
f_m = \sum_{k \geq m+1} \sum_{\ell=0}^{\ell_k} u_{k\ell} (-\log ||S||^2_m)^\ell,
   \]
   where \(u_{k\ell}\) are smooth functions on \(\nabla_m\) that vanish to order \(k\) on \(D\). In particular the function \(u_{k\ell}\) can be written as
   \[
u_{k\ell} = \sum_{i+j=k} \theta_{ij} + \theta_{ij},
   \]
   for \(\theta_{ij} \in \Gamma(V_m, L^{-1}_D \otimes L^{-j}_D)\).
We define $\|\cdot\|_0 = \|\cdot\|$, and it is clear that $\|\cdot\|_0$ satisfies the Conditions 1 and 2 above. Now we proceed on the inductive step: assuming the existence of $\|\cdot\|_m$, we construct $\|\cdot\|_{m+1}$. The next lemma gives a relation between $f_m$ and $f_\phi$, where $\|\cdot\|_\phi = e^{-\phi/2}\|\cdot\|_m$, and $f_\phi$ is associated to a smooth function $\phi$ on $V_m$ of the form

$$
\phi = (\sum_{i+j=k} S^{ij} \theta_{ij} + S^{ij} \bar{\theta}_{ij})(-\log \|S\|^2_m)^k, \quad \text{for } k \geq m + 1.
$$

**Lemma 2.2** Let $f_\phi(x)$ be defined as in Definition 2.1, associated to

$$
\omega_\phi = \frac{\sqrt{-1}}{2\pi} \frac{n}{n+1} n^{1/n} \partial \bar{\partial}(-\log \|S\|^2_m) \frac{\phi}{2(\phi)}.\n$$

Similarly let $f_m$ be associated to $\omega_m$. Then

$$
f_\phi = f_m + nm\phi + \frac{k\phi}{(-\log \|S\|_m^2)(-\log \|S\|_m^2) + (m - 1)} + \sum_{i+j=m+1} \left( i_j \left( S^{ij} \theta_{ij} + S^{ij} \bar{\theta}_{ij} \right) \right) + \left( -\log \|S\|_m^2 \right) \left( 2(n+1)j \left( S^{ij} S^{ij} \theta_{ij} + S^{ij} \bar{\theta}_{ij} \right) + S^{ij} \square_m \theta_{ij} + S^{ij} \square_m \bar{\theta}_{ij} \right)
$$

$$
+ \sum_{k' \geq m+2} \sum_{k' \geq m+2} u_{k'\ell} (-\log \|S\|_m^2)^{\ell} \tag{13}
$$

where $\square_m = \text{tr}_{\omega_m}(\square_m D_m)$ is the Laplacian of the bundle $L_D^{-1} \otimes L_D^{-j}$ on $D$ with respect to the hermitian metric $\|\cdot\|_m$, and the functions $u_{k'\ell}$ decay as $O(\|S\|^{k'})$.

The proof of this lemma will be postponed to the next section so that we can now proceed to our inductive construction.

**Proof of Proposition 2.1** We want to find a function $\phi$ such that $\|\cdot\|_{m+1}^2 = e^{-\phi/2}\|\cdot\|_m^2$ satisfies the Conditions 1 and 2, i.e., we need to eliminate the terms $\sum_{\ell=0}^{\ell_{m+1}} u_{m+1,\ell}(-\log \|S\|_m^2)^\ell$ from the expansion of $f_m$. Each of the $u_{m+1,\ell}$, $0 \leq \ell \leq m + 1$ will be eliminated successively, as follows.

Step 1: Write $u_{m+1,\ell_{m+1}}$ as

$$
u_{m+1,\ell_{m+1}} = \sum_{i+j=m+1} S^{ij} (v_{ij} + v'_{ij}) + S^{ij} (\bar{v}_{ij} + \bar{v}'_{ij}),
$$

where $v'_{ij} \in D \in \text{Ker}(\square_m + (n+1)m - 1 - 2(n+1))$ and $v_{ij} \in D$ is perpendicular to that kernel. If there is some $i, j$ ($i + j = m + 1$) such that $v'_{ij} \notin D \neq 0$, we use Lemma 2.2 with $k = \ell_{m+1} + 1$ and $\theta_{ij} = \omega_{2, k_{m+1}}$. Note that the constant $k_{m+1}$ was chosen so as to eliminate the kernel term from the expression of $u_{m+1,\ell_{m+1}}$.

Now Lemma 2.2 implies

$$
f'_m := f_\phi = \left( \sum_{i+j=m+1} S^{ij} v_{ij} + S^{ij} \bar{v}_{ij} \right)(-\log \|S\|_m^2)^{\ell_{m+1}} + \sum_{\ell=0}^{\ell_{m+1}-1} u_{m+1,\ell} (-\log \|S\|_m^2)^\ell + \sum_{k' \geq m+1} \sum_{\ell=0}^{\ell_{k'}} u_{k'\ell} (-\log \|S\|_m^2)^\ell. \tag{14}
$$

After Step 1, we can assume (by replacing $f_m$ by $f'_m$ in (14)) that $f_m$ has an expansion of the form

$$
u_{m+1,\ell_{m+1}} = \sum_{i+j=m+1} S^{ij} (v_{ij} + \bar{v}_{ij}).
$$
Step 2: Now we can solve
\[(\Box, + n(m + 1) - 2(n + 1)j) \theta_{ij} = v_{ij}|_{D} \text{ on } D,\]
for \(\theta_{ij} \in \Gamma(V_{m}, L_{D}^{-j} \bigotimes L_{D}^{j}).\) Next let us extend \(\theta_{ij}\) to \(\overline{M},\) and then apply again Lemma 2.2 with \(k = \ell_{m+1}\) and \(\theta_{ij}\) as above. The new \(f_{m}\) will have an expansion of the form
\[f_{m} = \sum_{\ell=0}^{\ell_{m+1} - 1} u_{m+1, \ell} (-\log ||S||_{m}^{2})^{\ell} + O(||S||^{m+2}).\]

By repeating Steps 1 and 2 above, we are able to eliminate all the terms \(\sum_{\ell=0}^{\ell_{m+1}} u_{m+1, \ell} (-\log ||S||_{m}^{2})^{\ell}\) from the expansion of \(f_{m}\). Finally, let \(\phi_{m}\) be the sum of all functions used in steps 1 and 2, and define the new metric \(||.||_{m+1}\) by letting \(||.||_{m+1} = e^{-\phi/2}||.||_{m}||.\) Clearly the resulting metric satisfies Conditions 1 and 2 of \(\text{(12)}\). This completes the proof of the proposition.

3 Proof of Lemma 2.2

This section is entirely devoted to proving Lemma 2.2 therefore completing the inductive construction of the metrics \(||.||_{m}\).

According to Definition 2.1 we have \(f_{\phi}(x) = f_{m} - \log \left(\frac{\omega_{m}^{n}}{\omega_{m}}\right)\). Hence, we just need to compute the quotient \(\frac{\omega_{m}^{n}}{\omega_{m}}\).

Denote by \(D_{m}\) (resp. \(D_{\phi}\)) the covariant derivative of the metric \(||.||_{m}\) (resp. \(||.||_{\phi}\)). Similarly, let \(\tilde{\omega}_{m}\) and \(\tilde{\phi}_{m}\) denote the corresponding curvature forms. The following relations are well-known:

\[D_{\phi}S = D_{m}S - S\partial \phi\]

\[\tilde{\omega}_{m} = \tilde{\omega}_{m} + \frac{\sqrt{-1}}{2\pi} \partial \tilde{\phi}\] (15)

For simplicity, set \(\alpha_{m} = (-n \log ||S||_{m}^{2})\) and \(\alpha_{\phi} = (-n \log ||S||_{\phi}^{2}) = \alpha_{m} + n \phi\). Then,

\[\omega_{m}^{n} = \alpha_{m} \tilde{\omega}_{m}^{n-1} \wedge \left(\tilde{\omega}_{m} + \frac{n\sqrt{-1}}{2\pi \alpha_{m}} D_{m}S \wedge \overline{D_{m}S} / |S|^{2}\right).\] (16)

\[\omega_{\phi}^{n} = \alpha_{\phi} \tilde{\omega}_{m}^{n-1} \wedge \left(\tilde{\omega}_{m} + \frac{n\sqrt{-1}}{2\pi \alpha_{\phi}} D_{\phi}S \wedge \overline{D_{\phi}S} / |S|^{2}\right) = (\alpha_{m} + n \phi) \left(\tilde{\omega}_{m} + \frac{\sqrt{-1}}{2\pi} \partial \tilde{\phi}\right)^{n-1} \wedge \left(\tilde{\omega}_{m} + \frac{\sqrt{-1}}{2\pi} \partial \tilde{\phi}\right) \wedge \left(D_{m}S \wedge \overline{D_{m}S} / |S|^{2} - \partial \phi \wedge \overline{D_{m}S} / S - \partial \phi \wedge \overline{D_{m}S} / S + \partial \phi \wedge \overline{\partial \phi}\right).\] (17)

Some calculations using the definition of \(\phi\) lead to

\[\partial \phi = \sum_{i+j=m+1} (-\log ||S||_{m}^{2})^{k} \left(D_{m}S^{ij} \theta_{ij} + D_{m}S^{ij} \overline{\theta_{ij}} + S^{ij} D_{m} \theta_{ij} + + S^{ij} D_{m} \overline{\theta_{ij}}\right) + k(-\log ||S||_{m}^{2})^{k-1} \left(S^{ij} \theta_{ij} + S^{ij} \overline{\theta_{ij}}\right) \left(-\frac{D_{m}S}{S}\right).\] (18)
We will also need the expression for $\partial \bar{\partial} \phi$. After some computations using (18), it follows that

$$\partial \bar{\partial} \phi = (- \log ||S||^2_m)^k \sum_{i+j=m+1} \left\{ i_j(S^*S_i' \theta_{ij} + S^S \bar{\theta}_{ij}) \left( \frac{D_m S \wedge D_m S}{S} \right) + 
+ (j S^*S_j D_m \theta_{ij} + i S^S \bar{D}_m \bar{\theta}_{ij}) \wedge \frac{D_m S}{S} + \frac{D_m S}{S} \wedge (i S^*S_i' \bar{D}_m \bar{\theta}_{ij} + j S^S \bar{D}_m \bar{\theta}_{ij}) + 
+ (S^*S_j D_m \theta_{ij} + S^S \bar{D}_m \bar{\theta}_{ij} + k(- \log ||S||^2_m)^{-1} \left( (S^*S_j D_m \theta_{ij} + S^S \bar{D}_m \bar{\theta}_{ij}) \wedge \frac{D_m S}{S} + 
(S^*S_j D_m \theta_{ij} + S^S \bar{D}_m \bar{\theta}_{ij}) \wedge \frac{D_m S}{S} \right) \right\} + \left(\frac{k(n+1) \phi}{(- \log ||S||^2_m)^2} + \frac{k(n-1) \phi}{(- \log ||S||^2_m)^2} \right) \frac{D_m S \wedge D_m S}{S}. \quad (19)$$

We can therefore conclude from a simple analysis of (19) that

$$||S||^2_m (\partial \bar{\partial} \phi)^\ell \wedge \omega^n_m = \omega^n_m O(||S||^{2m+2}) \quad \text{for } \ell \geq 2. \quad (20)$$

The above ingredients are going to be needed in the proof of Lemma 2.2.

**Proof of Lemma 2.2** Recall that we only need to compute the quotient $\omega^n_m / \omega^n_m$. Formulas (19) and (17) then provide

$$\omega^n_m = \alpha_m ||S||^2_m \omega_m^{\alpha_\phi} \left\{ \left( \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi \right)^n - \left( \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi \right) \right\} + \left(\frac{n \sqrt{-1} \log ||S||^2_m}{2 \pi \alpha_\phi} \left( \frac{D_m S \wedge D_m S}{S} - \partial \phi \wedge \frac{D_m S}{S} + \bar{\partial} \phi \wedge \frac{D_m S}{S} \right) \right\} \wedge \left[ \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi + \frac{n \sqrt{-1} \log ||S||^2_m}{2 \pi \alpha_\phi} \left( \frac{D_m S \wedge D_m S}{S} + \partial \phi \wedge \bar{\partial} \phi \right) \right] + O(||S||^{m+2}). \quad (21)$$

Direct calculations using (18) and its analogous formula for $\bar{\partial} \phi$ lead to (further details can be found in [S])

$$\partial \phi \wedge \frac{D_m S}{S} + \bar{\partial} \phi \wedge \frac{D_m S}{S} = \left( (m+1) \phi + \frac{2k \phi}{\log ||S||^2_m} \right) \frac{D_m S \wedge D_m S}{S}. \quad (22)$$

Thus it follows that

$$\omega^n_m = \alpha_m ||S||^2_m \omega_m^{\alpha_\phi} \left\{ \left( \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi \right)^n - \left( \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi \right) \right\} + \left(\frac{n \sqrt{-1} \log ||S||^2_m}{2 \pi \alpha_\phi} \left( 1 - (m+1) \phi - \frac{2k \phi}{\log ||S||^2_m} \right) \frac{D_m S \wedge D_m S}{S} + \partial \phi \wedge \bar{\partial} \phi \right\} + O(||S||^{m+2}). \quad (23)$$

On the other hand, (22) implies that the summand with $\partial \phi \wedge \bar{\partial} \phi$ in (23) can be bounded by a multiple of $||S||^{m+3} \omega^n_m$. So, we obtain

$$\omega^n_m = \alpha_m ||S||^2_m \omega_m^{\alpha_\phi} \left\{ \left( \omega_m + \sqrt{-1} \frac{\varphi}{2 \pi} \partial \bar{\partial} \phi + \frac{n \sqrt{-1} \log ||S||^2_m}{2 \pi \alpha_\phi} \left( 1 - (m+1) \phi - \frac{2k \phi}{\log ||S||^2_m} \right) \frac{D_m S \wedge D_m S}{S} \right) + 
+ (n-1) \omega_m^{\alpha_\phi} \left( \frac{\sqrt{-1}}{2 \pi} \partial \bar{\partial} \phi \right) \wedge \left( \omega_m + \frac{n \sqrt{-1} D_m S \wedge D_m S}{|S|^2} \right) \right\} + O(||S||^{m+2}). \quad (24)$$
Also, the definitions of $\alpha_\phi$ and $\alpha_m$ give

$$\alpha_\phi||S||^2 \tilde{\omega}_m^{-1} \wedge \left( \tilde{\omega}_m + \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) = ||S||^2 \tilde{\omega}_m^n \left( \alpha_m + \frac{||D_m S||^2}{||S||^2} \right) + O(||S||^{m+2}_m) \tilde{\omega}_m^n. \quad (25)$$

Therefore,

$$\frac{\omega^n_\phi}{\omega^n_m} = 1 + \frac{||S||^2 \alpha_\phi}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left\{ n \tilde{\omega}_m^{n-1} \wedge \left( \frac{-1}{2\pi} \partial \phi \right) - \phi \left( m + 1 \right) + \frac{2k}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left[ \tilde{\omega}_m^{n-1} \wedge \left( \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) \right] + O(||S||^{m+2}_m) = \right.$$  

$$= 1 - \left( m + 1 \right) + \frac{2k}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \phi + \frac{||S||^2 \alpha_\phi}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left( n \tilde{\omega}_m^{n-1} \wedge \left( \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) \right) + \phi \left( m + 1 \right) + \frac{2k}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left[ \tilde{\omega}_m^{n-1} \wedge \left( \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) \right] + O(||S||^{m+2}_m). \quad (26)$$

The last term of (26) can be simplified by using (25), yielding

$$\frac{\omega^n_\phi}{\omega^n_m} = 1 + \left( m + 1 \right) + \frac{k(m - 1)}{(-\log ||S||^2_m)^2} + \frac{(k - 1)k}{(-\log ||S||^2_m)^2} \phi + \frac{\alpha_\phi ||S||^2_m}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left\{ \left( S^i S^j \theta_{ij} + S^j S^i \bar{\theta}_{ij} \right) \tilde{\omega}_m^{n-1} \wedge \left( \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) \right\} + \phi \left( m + 1 \right) + \frac{2k}{\alpha_m (||S||^2_m + 1/\alpha_m ||D_m S||^2_2) \tilde{\omega}_m^n} \left[ \tilde{\omega}_m^{n-1} \wedge \left( \frac{n\sqrt{-1} \, D_m S \wedge D_m S}{2\pi \alpha_\phi \, ||S||^2} \right) \right] + O(||S||^{m+2}_m). \quad (27)$$

Now observe that the relations

$$\begin{align*}
D_m D_m S^j &= -D_m D_m S^j + j S^j \tilde{\omega}_m \\
D_m D_m \theta_{ij} &= -D_m D_m \theta_{ij} - (i - j) \theta_{ij} \tilde{\omega}_m
\end{align*} \quad (28)$$

imply that

$$\sum_{i+j=m+1} \left( S^i S^j D_m D_m \theta_{ij} + S^j S^i D_m D_m \bar{\theta}_{ij} \right) = \sum_{i+j=m+1} \left\{ \left( S^i S^j D_m D_m \theta_{ij} + S^j S^i D_m D_m \bar{\theta}_{ij} \right) - \left( S^i S^j \theta_{ij} - S^j S^i \bar{\theta}_{ij} \right) (i - j) \tilde{\omega}_m \right\}. \quad (29)$$
Hence,
\[
\frac{\omega^n}{\omega^m} = 1 + \left(-m + 1 + \frac{k(m-1)}{(\log ||S||^2_m)^k} + \frac{k(k-1)}{(\log ||S||^2_m)^2}\right) \phi + \frac{\alpha_m||S||^2_m}{\alpha_m(||S||^2_m + 1/\alpha_m||D_m S||^2_m)} \omega^m.
\]
\[
\left\{(-\log ||S||^2_m)^k \sum_{i+j=m+1} \left[ \alpha_m \phi (S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij}) \right] \omega^m \right\} + (n-1)\omega^{n-2} \wedge \left( \frac{n \sqrt{-1} D_m S \wedge D_m S}{|S|^2} \right) \wedge \left[ - (S^i S^j D_m S \theta_{ij} + S^i S^j D_m S \bar{\theta}_{ij}) \right]
\]
\[
+ \left( S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij} \right) + O(||S||^m+2).
\]

Notice that we can replace the term involving \(\alpha_m\) from the last formula by the analogous term involving \(\alpha_m\), since the function \(\phi\) is assumed to be of order \(O(||S||^m+1)\). This implies that the residual term of this substitution will lie in the term \(O(||S||^m+2)\). Therefore, we conclude
\[
\frac{\omega^n}{\omega^m} = 1 + \left(-m + 1 + \frac{k(m-1)}{(\log ||S||^2_m)^k} + \frac{k(k-1)}{(\log ||S||^2_m)^2}\right) \phi
\]
\[
- (-\log ||S||^2_m)^k \sum_{i+j=m+1} \left[ \alpha_m \phi (S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij}) \right] + (-\log ||S||^2_m)^k
\]
\[
\cdot \sum_{i+j=m+1} \alpha_m \phi + (n-1)(m+1)-2j \left( S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij} \right) + O(||S||^m+2) =
\]
\[
= 1 + n(m+1)\phi + \frac{k}{(-\log ||S||^2_m)^k} \left[ \frac{k-1}{(-\log ||S||^2_m)} - (m-1) \right] + 
\]
\[
+ \sum_{i+j=m+1} \left( S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij} \right) + (n-1)(-\log ||S||^2_m)^k \sum_{i+j=m+1} j \left( S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij} \right) +
\]
\[
+ (\log ||S||^2_m)^{k-1} \sum_{i+j=m+1} i j \left( S^i S^j \theta_{ij} - S^i S^j \bar{\theta}_{ij} \right) + O(||S||^m+2).
\]

Finally,
\[
f_\phi = f_m - \log \left( \frac{\omega^n}{\omega^m} \right) = nm \phi + \frac{k \phi}{(-\log ||S||^2_m)^k} \left[ \frac{k-1}{(-\log ||S||^2_m)} - (m-1) \right] + 
\]
\[
+ (-\log ||S||^2_m)^k \sum_{i+j=m+1} \left[ \left( S^i S^j \theta_{ij} + S^i S^j \bar{\theta}_{ij} \right) + 2(n+1)j \left( S^i S^j \theta_{ij} - S^i S^j \bar{\theta}_{ij} \right) \right] +
\]
\[
+ (-\log ||S||^2_m)^{k-1} \sum_{i+j=m+1} i j \left( S^i S^j \theta_{ij} - S^i S^j \bar{\theta}_{ij} \right) + O(||S||^m+2),
\]
which proves the lemma. The inductive construction of the metrics \(||.||^n\) is also completed. \(\square\)

### 4 Complete Kähler Metrics on \(M\)

In this section we shall finish the proof of Theorem 1.1. In particular it is going to be necessary to consider the asymptotic behavior of the Riemann curvature tensor.

For each \(m \geq 1\), consider the function \(f_m\) constructed in Section 2. For this choice, let the corresponding
\[
\omega_m = \frac{\sqrt{-1}}{2\pi(n+1)} \partial \bar{\partial}(-n \log ||S||^2_m)^{\frac{n+1}{n}}
\]
define a \((1,1)\)-form on \(M\). If \(\delta_m\) is sufficiently small, \(\omega_m\) is positive definite on \(V_m = \{||S(x)|| \leq \delta_m\}\), and defines a Kähler metric \(g_m\). 

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Lemma 4.1  The Kähler manifolds \((V_m, \partial V_m, g_m)\) are all complete, equivalent to each other near \(D\), and for each \(m > 0\), the function

\[
\rho = \frac{2}{n+1} (\partial \log ||S||_m^2)^{\frac{n+1}{n}}
\]
is equivalent to any distance function from a fixed point in \(V_m\) near \(D\).

Proof: Fix \(m > 0\). We have

\[
|\nabla_m \rho|^2_{g_m} = \frac{1}{2\pi} \partial \rho \wedge \bar{\partial} \rho \wedge \omega_{m}^{n-1}
\]
Since

\[
\partial \rho = n \frac{\omega_{m}^{n-1}}{(n \log ||S||_m^2)^{\frac{n+1}{n}}} \frac{D_m S}{S}
\]
it follows that

\[
\frac{\sqrt{-1}}{2\pi} \partial \rho \wedge \bar{\partial} \rho \wedge \omega_{m}^{n-1} = (n \log ||S||_m^2)^{\frac{n}{n+1}} \frac{D_m S}{S}
\]
Therefore, we conclude that

\[
|\nabla_m \rho|^2_{g_m} = \frac{1}{n} (n \log ||S||_m^2)^{\frac{n}{n+1}} \frac{D_m S}{S}
\]
Now, recall that \(||D_m S||_m^2\) is never zero, and that \(\lim_{||S||_m \to 0} (n \log ||S||_m^2)^{\frac{n}{n+1}} = 0\). Hence

\[
|\nabla_m \rho|^2_{g_m} = \frac{1}{n} \lim_{||S||_m \to 0} (n \log ||S||_m^2)^{\frac{n}{n+1}} \frac{D_m S}{S}
\]
proving that \(\rho\) is equivalent to any distance function from the boundary near \(D\).

Also, since \(\rho \to \infty\) when \(x \to D\), the Kähler manifold \((V_m, \partial V_m, g_m)\) is complete.

We claim that all the metrics \(g_m\) are equivalent near \(D\). To check the claim, note first that each \(\tilde{\omega}_m\) is the curvature form of the metric \(||.||_m\), hence, for every \(m, \ell \in \mathbb{N}\), \(\tilde{\omega}_m\) is equivalent to \(\tilde{\omega}_\ell\) near \(D\). The claim then follows from (3), that relates the expressions for \(\omega_m\) and \(\tilde{\omega}_m\).

Finally here is a remark about the volume growth of \((V_m, \partial V_m, g_m)\): since \(\omega_{m}^{n}\) is equivalent to \(\tilde{\omega}_{m}^{n}(n \log ||S||_m^2)^{\frac{n}{n+1}}\), it suffices to consider the integral

\[
\int_{||S(x)||_m \geq e^{-1/2\rho m}} (n \log ||S||_m^2)^{\frac{n}{n+1}} \tilde{\omega}_{m}^{n}
\]
which is of order \(\rho^{\frac{2n}{n+1}}\).

In the sequel we are going to carry out the estimates of the Riemann curvature tensor \(R(g_m)\) corresponding to the metric \(g_m\) which are involved in the statement of Theorem (11). Let us begin with the following lemma:

Lemma 4.2  Let \((V_m, \partial V_m, g_m)\) be complete, Kähler manifolds with boundary defined as in Lemma 4.1. Then the norm of \(R(g_m)\) with respect to the metric \(g_m\) decays at the order of at least \((n \log ||S||_m^2)^{\frac{n}{n+1}}\) near \(D\).

Proof: We shall prove the statement in local coordinates, as follows. There exists a finite covering \(U_t\) of \(D\) in \(\bar{M}\) such that for each \(t\), there is a local uniformization \(\Pi_t: U_t \to U_t\) such that \(\Pi_t^{-1}(D)\) is smooth in \(U_t\). The covering \(U_t\) can, in addition, be chosen so that given a local coordinate system \((z_1, \ldots, z_n)\) in \(U_t\), with \(S = z_n\) and \(z' = (z_1, \ldots, z_{n-1})\) defining coordinates along \(D\), we have

\[
\sum_{i,j,k,l=1}^{n} R_{ijkl}(g_{m}) = (-n \log |z_n|^2)^{1/n} \sum_{i,j,k,l=1}^{n} R_{ijkl}(g_D|_{\Pi_t^{-1}(D)}) + O((-n \log |z_n|^2)^{-1/n})
\]
for every $g_m$-unit vector $(\xi^1, \ldots, \xi^n)$, where $g_D$ is the Kähler metric defined by the restriction of the curvature form $\tilde{\omega}$ to the divisor.

Without loss of generality, we assume that $U_t \cap \overline{M}$ is smooth.

For every $x \in U_t \cap M$, consider local coordinates $(z_1, \ldots, z_n)$ for a neighborhood of $x$ which satisfy the conditions below:

- The defining section $S$ of the divisor is given by $z_n$.
- The curvature form $\tilde{\omega}_m$ of $||.||_m$ is represented in the mentioned coordinates by the tensor $(h_{ij})$ where $(h_{ij})$ satisfies

\[
\delta_{ij}(x) = \partial h_{\bar{i} \bar{j}}(x) = 0 \text{ if } j < n; \quad \partial h_{\bar{i} \bar{j}}(x) = 0 \text{ if } i < n;
\]

- The hermitian metric $||.||_m$ is represented by a positive function $a$ with $a(x) = 1$, $da(x) = 0$ and $d(\partial g_j/\partial z_i)(x) = 0$.

In order to simplify notation, let us write $B = B(|z_n|) = (-n \log |z_n|^2)$, and let us drop the subscripts for the metric $g_{mn}$ to be denoted by $g$ from now on.

Formula (S) implies that

\[
g_{\bar{i}\bar{j}}(x) = \begin{cases} O(B^{-1/n}) & \text{if } i = j \text{ and } i < n \\ o(B^{-1/n}) & \text{if } i \neq j \text{ and } i, j < n \\ O(|z_n|^2B^{-1/n}) & \text{if } i = j = n, \end{cases}
\]

and computations give (check [S] for further details)

\[
\frac{\partial g_{\bar{i}\bar{j}}}{\partial z_k} = B^{1/n} \left[ \frac{\partial h_{\bar{i}\bar{j}}}{\partial z_k} - \frac{1}{z_n B} \left( \delta_{kn} h_{\bar{i}\bar{j}} + \delta_{in} h_{\bar{k}\bar{j}} + \delta_{in} \delta_{jn} \delta_{kn} \left( \frac{n-1}{B} + \frac{1}{|z_n|^2} \right) \right) \right]
\]

and

\[
\frac{\partial^2 g_{\bar{i}\bar{j}}}{\partial z_k \partial \bar{z}_l} = B^{1/n} \left\{ \frac{\partial^2 h_{\bar{i}\bar{j}}}{\partial z_k \partial \bar{z}_l} - \frac{1}{z_n B} \left( \delta_{kn} \delta_{in} h_{\bar{i}\bar{j}} + \delta_{in} h_{\bar{m}\bar{k}} + \delta_{in} \delta_{jn} \delta_{kn} \left( \frac{n-1}{B} + \frac{1}{|z_n|^2} \right) \right) \right\} + \frac{1-n}{|z_n|^2 B^2} \left( \delta_{in} (\delta_{kn} h_{\bar{i}\bar{j}} + \delta_{in} h_{\bar{k}\bar{j}}) + \delta_{jn} (\delta_{kn} h_{\bar{i}\bar{j}} + \delta_{in} h_{\bar{k}\bar{j}}) \right) + \delta_{in} \delta_{jn} \delta_{kn} \delta_{ln} \left( \frac{1}{|z_n|^4 B^3} \right) \left( |z_n|^2 (n-1)(1-2n) + (1-n)B + B^2 \right).
\]

If $(\xi^1, \ldots, \xi^n)$ is a $g$-unit tangent vector, then

\[
\begin{align*}
\{ \xi^i \}^2 & \leq CB^{-1/n} \quad \text{if } i < n, \\
\{ \xi^n \}^2 & \leq C|z_n|^2B^{(n-1)/n},
\end{align*}
\]

where $C$ is a constant that does not depend neither on the unit vector $(\xi^1, \ldots, \xi^n)$ nor on the point $x \in D$. Hence, in local coordinates, we have

\[
R(g)_{\bar{i}\bar{j}k\ell}(x)(\xi^\ell \overline{\xi}^k \xi^\bar{k} \overline{\xi}^\ell)(x) = \left[ \frac{\partial^2 g_{\bar{i}\bar{j}}}{\partial z_k \partial \bar{z}_l}(x) + \sum_{u,v=1}^n g^{uv}(x) \frac{\partial g_{uv}}{\partial z_k}(x) \frac{\partial g_{uv}}{\partial \bar{z}_l}(x) \right] (\xi^\ell \overline{\xi}^k \xi^\bar{k} \overline{\xi}^\ell) =
\]

\[
= -B^{1/n} \left\{ \frac{\partial^2 h_{\bar{i}\bar{j}}}{\partial z_k \partial \bar{z}_l}(x)(\xi^\ell \overline{\xi}^k \xi^\bar{k} \overline{\xi}^\ell) + \frac{4(1-n)|\xi^n|^2}{|z_n|^2 B^2} \left( \sum_{i=1}^n |\xi^i|^2 \right) \right. + |\xi^n|^4 \left/ |z_n|^4 B^3 \right. \left( |z_n|^2 (n-1)(1-2n) + (1-n)B + B^2 \right) \right\} + \]

\[
+ B^{2/n} \sum_{u,v=1}^n g^{uv}(x) \left[ -\frac{\xi^n}{z_n B} \left( 2\xi^i h_{\bar{i}u} + \xi^n \delta_{iu} \left( \frac{n-1}{B} + \frac{1}{|z_n|^2} \right) \right) \right.
\]

\[
\cdot \left. \left[ -\frac{\bar{\xi}^n}{z_n B} \left( 2\bar{\xi}^\ell h_{\bar{\ell}u} + \bar{\xi}^n \delta_{\bar{\ell}u} \left( \frac{n-1}{B} + \frac{1}{|z_n|^2} \right) \right) \right] \right) \right) \right) \right)
\]

\[
(37)
\]
Next let us separately bound each of the above terms. By using (34) and our previous choice of local coordinates, we obtain, when $z_n$ approaches zero, 

$$
\frac{4(1-n)|\xi^n|^2}{|z_n|^2B^2} \left( \sum_{i=1}^{n} |\xi^i|^2 \right) \leq \frac{C|z_n|^2B^{(n-1)/2}}{|z_n|^2B^2} (B^{-1/n} + |z_n|^2B^{(n-1)/n}) \leq CB^{-(n+2)/n},
$$

where $C$ denotes a uniform constant. Also, we have that 

$$
\frac{|\xi^n|^4}{|z_n|^4B^3} \left( |z_n|^2(n-1)(1-2n) + (1-n)B + B^2 \right) \leq CB^{-1/n}(B^{-1} + 1) \leq CB^{-1/n}.
$$

Now, notice that the expression 

$$
\frac{\xi^n}{z_nB} \left( 2\xi^i_{h} + \xi^n_{\delta i} \left( \frac{n-1}{B} + \frac{1}{|z_n|^2} \right) \right) \leq C(B^{-(n+2)/2n} + |z_n|^{-1}B^{-1/n}), \tag{38}
$$

needs special attention due to the presence of a term involving $|z_n|^{-1}$. However our estimate for 

$$
g^{\bar{u}\bar{v}} = B^{-1/n} \left[(1-\delta_{uv}\delta_{ev})O(1) + \delta_{uv}\delta_{ev})O(|z_n|^2)\right]
$$

shows that this term is compensated by the last term of the above expression. The estimate for the decay of the last term in (37) is analogous to the case discussed above, and will be omitted. For details, please refer to [S].

In conclusion, we have 

$$
R(g)_{i\bar{j}k\bar{l}}(x)(\xi^i\bar{\xi}^j\xi^k\bar{\xi}^l)(x) = B^{1/n} \frac{\partial^2 h_{i\bar{j}}}{\partial z_k \partial \bar{z}_l}(x)(\xi^i\bar{\xi}^j\xi^k\bar{\xi}^l) + O(B^{-1/n}),
$$

which implies (35), and concludes the proof of the lemma. \qed

The reader may also notice that Lemma 4.2 completes the proof of Proposition 2.1.

**Lemma 4.3** For the manifold $(V_m, \partial V_m, g_m)$ defined in Lemma 4.1, we have 

$$
||\nabla^k R(g_m)||_{g_m}(x) = O \left( \rho_m^{-\frac{k+2}{2k+1}}(x) \right), \tag{39}
$$

where $\rho_m(x)$ is the distance function from a fixed point associated to $g_m$.

**Proof:** The proof of this lemma will follow the same idea as the proof of [TY2], Lemma 2.5.

We start by fixing $m$, and fixing a small $\delta > 0$ such that $V_\delta := \{ x \in M; ||S||_m < \delta \} \subset V_m$. In order to prove the result, we are going to introduce a suitable new coordinate system on $V_\delta$.

Because $D$ is admissible, it follows that the total space of the unit sphere bundle of $L_D|_D$ (with respect to the metric $||.||_m$) is a smooth manifold of real dimension $2n+1$, to be denoted by $M_1$.

Since $L_D$ is simply the normal bundle of $D$ in $M$, there exists a diffeomorphism 

$$
\Psi : M_1 \times (0, \delta) \rightarrow V_\delta
$$

induced by the exponential map of $(M, ||.||_m)$ along $D$.

It is also known that the Kähler form of $g_m$ is given by 

$$
\omega_m = \frac{\sqrt{-1}}{2\pi} \frac{n^{1+1/n}}{n+1} \partial \bar{\partial}(-\log(||S||^2_2e^{2\phi_m}))^{\frac{n+1}{n}},
$$

where $\phi_m$ is a smooth function on $M$, that can be written as $\sum_{\kappa \geq m} \sum_{\ell=0}^{\kappa_n} u_{\kappa \ell}(-\log ||S||^2_2)^\ell$, where $u_{\kappa \ell}$ are smooth functions on $V_m$ that vanish to order $\kappa$ on $D$. 

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Combining the facts above, the pull-back of \( g_m \) under \( \Psi \) on \( M_1 \times (0, \delta) \) is given by

\[
\Psi^* g_m = \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} g(||S||, ||S|| \log(||S||)) + \\
+ \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} d \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} h(||S||, ||S|| \log(||S||)) + \\
+ \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} u(||S||, ||S|| \log(||S||)) .
\]

(40)

Here \( g(\cdot, \cdot) \) (resp. \( h(\cdot, \cdot), u(\cdot, \cdot) \)) is a \( C^\infty \) family of metrics (resp. \( 1 \)-tensors, functions) on \( M_1 \), such that for each fixed integer \( \ell > 0 \), there exists a constant \( K_\ell \) that bounds all covariant derivatives (with respect to a fixed metric \( \tilde{h} \) on \( M_1 \)) of \( g(t_0, t_1) \) (resp. \( h(t_0, t_1), u(t_0, t_1) \)) up to order \( \ell \), for every \( t_0 \in [0, \delta] \) and \( t_1 \in [0, \delta \log(\delta)] \).

Setting \( \rho = \left( -n \log(||S||^2) \right)^{\frac{1}{n+1}} \), (40) becomes

\[
\Psi^* g_m = \rho^{\frac{2(1-\lambda)}{n+1}} g(\cdot, \cdot) + \rho^{\frac{2(1-\lambda)}{n+1}} d(\rho^{\frac{2(1-\lambda)}{n+1}}) h(\cdot, \cdot) + \rho^{\frac{2(1-\lambda)}{n+1}} (\rho^{\frac{2(1-\lambda)}{n+1}})^2 u(\cdot, \cdot),
\]

and hence we can regard \( \Psi^* g_m \) as being a metric defined on \( M_1 \times \left( -n \log \delta^2 \right)^{\frac{1}{n+1}}, \infty \).

It is easy to see that, if \( g \) is any Riemannian metric, and \( \tilde{g} = \lambda^2 g \) is a rescaling of \( g \), then the norm of the covariant derivatives of the new metric, taken with respect to the new metric \( \tilde{g} \), satisfy \( ||\tilde{\nabla}^k R(\tilde{g})||_\delta = \lambda^{-2(k+2)} ||\nabla^k R(g)||_g \). Therefore, if we define a new metric \( \tilde{g} \) on \( M_1 \times \left( -n \log \delta^2 \right)^{\frac{1}{n+1}}, \infty \)
by \( \tilde{g} = \rho_m^{\frac{2}{n+1}}(x) \Psi^* g_m \), showing (39) is equivalent to showing that \( ||\tilde{\nabla}^k R(\tilde{g})||_\delta(x) = O(1) \).

But this last statement follows clearly from the assertions on \( g(\cdot, \cdot), h(\cdot, \cdot) \) and \( u(\cdot, \cdot) \). \( \square \)

In the same lines of Lemma 4.3 one can show

**Lemma 4.4** For a fixed \( m \), let \( f_m \) be the smooth function constructed in Section 2. Then,

\[
||\nabla^k f_m||_{g_m} = O(||S||^m||S||^m_{m+1} \rho_m^{-\frac{2}{n+1}}),
\]

(42)

where we recall that \( \rho_m(\cdot) \) is the distance function associated to the metric \( g_m \).

**Proof:** We will use the same notation and objects defined on the proof of Lemma 4.3

Begin by observing that (42) is equivalent to showing that

\[
||\tilde{\nabla}^k f_m||_{\rho_m^{\frac{2}{n+1}} \Psi^* g_m} (\Psi^{-1}(x)) = O_k(1)(||S||^m_{m+1})(x),
\]

(43)

where \( 0_k(1) \) is a quantity bounded by a constant that depends on \( k \), and \( \tilde{\nabla} \) is the covariant derivative associated to the metric \( \rho_m^{\frac{2}{n+1}} \Psi^* g_m \) on \( M_1 \times (0, \delta) \).

Also, recall that the function \( f_m \) satisfies \( \text{Ric}(g_m) = -\Omega \), for a fixed \( \Omega \in c_1(-K_{\mathcal{M}}) \). Hence, (43) follows clearly from the estimates on the covariant derivatives of the curvature tensor \( R(\rho_m^{\frac{2}{n+1}} \Psi^* g_m) \) given by Lemma 4.3 and the observation on the local expression of the metric \( \rho_m^{\frac{2}{n+1}} \Psi^* g_m \).

\( \square \)

We are finally able to prove Theorem 1.1

**Proof of Theorem 1.1** In what follows we keep the preceding setting and notations.

Since the divisor \( D \) is assumed to be ample in \( \mathcal{M} \), there exists a hermitian metric \( ||\cdot||' \) on \( L_D \) whose curvature form \( \tilde{\omega}' \) is positive definite on \( D \).
Fix an integer \( k \geq \varepsilon \), and write, for \( \varepsilon > 0 \),

\[
\omega_{g_\varepsilon} = \omega_k + C_\varepsilon \frac{1}{2\pi} \partial \bar{\partial} (-|S|')^\varepsilon,
\]

where \( \omega_k \) is the Kähler form defined on Section 2. The Kähler form \( \omega_{g_\varepsilon} \) is positive definite on \( M \), and gives rise to a complete Kähler metric \( g_\varepsilon \) on \( M \).

Let \( \delta > 0 \) be such that \( V_\delta = \{ ||S(x)|| < \delta \} \subset V_k \). On \( V_\delta \), \( \omega_{g_\varepsilon} \) satisfies \( \text{Ric}(g_\varepsilon) - \Omega = \frac{\sqrt{\varepsilon}}{2\pi} \partial \bar{\partial} f \), and we want to estimate the decay of \( f \) at infinity.

On the other hand, on \( V_\delta \), we have \( \text{Ric}(g_\varepsilon) - \Omega = \frac{\sqrt{\varepsilon}}{2\pi} \partial \bar{\partial} f_k \) which, in turn, implies that

\[
f = f_k - \log \frac{\omega^{n}_{g_k}}{\omega_k^{n}} = f_k - \log \left( \frac{\omega^{n}_{k} + C_\varepsilon|S|'^{(\varepsilon-1)}w^{n-1}_{k} \wedge \frac{n\sqrt{\varepsilon}}{2\pi}(D'S \wedge D'S)}{\omega_k^{n}} \right) = f_k - C_\varepsilon|S|'^{(\varepsilon-1)}|D'S||g_k|,
\]

where \( D'S \) denotes the covariant derivative of the metric \( ||.||' \). Hence, in order to estimate the decay of \( f \), it suffices to study the decay of \( |D'S||g_k| \).

In what follows, we will use the notation defined in the proof of Lemma 4.3; recall that \( \Psi \) is the map between a tubular neighborhood of \( D \) inside \( \overline{M} \) induced by the exponential map of \( ||.|| \) along \( D \).

Let the function \( \gamma := \Psi^*(||S||')^\varepsilon \) be defined on \( M_1 \times \left( (-n \log \delta^2) \frac{2n}{n-1}, \infty \right) \). Our goal is to understand the decay of \( |D'S||g_k| \), which is equivalent to studying the decay of \( |\tilde{\nabla} \gamma|_{\rho^{-2/(n+1)}\Psi^*g_k}(\Psi^{-1}(x)) \), where \( \tilde{\nabla} \) denotes the covariant derivative of the metric \( \rho^{-2/(n+1)}\Psi^*g_k \).

Notice that on \( M_1 \times \left( (-n \log \delta^2) \frac{2n}{n+1}, \infty \right) \), the function \( \gamma \) can be written under the form

\[
e^\tilde{\gamma}(., \exp\{\rho_{\frac{2n}{n-1}}\}) \exp\left\{ \frac{\varepsilon}{n} \rho_{\frac{2n}{n-1}} \right\},
\]

where \( \tilde{\gamma} \) is a smooth function on \( M_1 \times \left( (-n \log \delta^2) \frac{2n}{n-1}, \infty \right) \) with all derivatives bounded in terms of a fixed product metric.

Hence, from (41), it follows that

\[
|\tilde{\nabla} \gamma|_{\rho^{-2/(n+1)}\Psi^*g_k}(\Psi^{-1}(x)) = O(\exp\left\{ \frac{\varepsilon}{n} \rho_{\frac{2n}{n-1}} \right\}),
\]

since the curvature tensor of \( \rho^{-2/(n+1)}\Psi^*g_k \) is bounded near \( \Psi^{-1}(x) \).

Note also that (40) is equivalent to

\[
|D'S||g_k| = O(||S||^\varepsilon),
\]

which shows that the metric \( g_\varepsilon \), with corresponding Kähler form \( \omega_{g_\varepsilon} \), satisfies the equation \( \text{Ric}(g_\varepsilon) - \Omega = \partial \bar{\partial} f_\varepsilon \), for \( f_\varepsilon \) a smooth function that decays at least to the order of \( O(||S||^\varepsilon) \).

To close the proof of Theorem 1.1, it only remains to note that the curvature estimates for the new metric \( g_\varepsilon \) follow easily from the estimates on the curvature tensor \( R(g_m) \), described in Lemma 4.2.

5 Asymptotics of the Monge-Ampère Equation on \( M \)

This last section is intended to provide the proof of Theorem 1.2.

Let \((M, g)\) be a complete Kähler manifold, with Kähler form \( \omega \). Consider the following Monge-Ampère equation on \( M \):

\[
\begin{cases}
\left( \omega + \frac{\sqrt{\varepsilon}}{2\pi} \partial \bar{\partial} u \right)^n = e^f \omega^n, \\
\omega + \frac{\sqrt{\varepsilon}}{2\pi} \partial \bar{\partial} u > 0, \\
u \in C^\infty(M, \mathbb{R}),
\end{cases}
\]
where \( f \) is a given smooth function satisfying the integrability condition
\[
\int_M (e^f - 1)w^n = 0. \tag{48}
\]

Whenever \( u \) is a solution to \([17]\), the \((1,1)\)-form \( \omega + \sqrt{-1} \partial \bar{\partial} u \) satisfies \( \text{Ric}(\omega + \sqrt{-1} \partial \bar{\partial} u) = f \). So, in order to define metrics with prescribed Ricci curvature, it is enough to determine a solution to \([47]\).

In \([TY1]\), Tian and Yau proved that \([47]\) has, in fact, solutions modulo assuming certain conditions on the volume growth of \( g \) as well as on the decay of \( f \) at infinity. For the convenience of the reader, we state here their main result.

**Theorem 5.1 (Tian, Yau, \([TY1]\))** Let \((M, g)\) be a complete Kähler manifold, satisfying:

- The sectional curvature of the metric \( g \) is bounded by a constant \( K \).
- \( \text{Vol}_g(B_R(x_0)) \leq CR^2 \) for all \( R > 0 \) and \( \text{Vol}_g(B_1(x_0)) \geq C^{-1}(1 + \rho(x))^{-\beta} \), for a constant \( \beta \), where \( \text{Vol}_g \) denotes the volume associated to the metric \( g \), \( B_R(x_0) \) is the geodesic ball of radius \( R \) about a fixed point \( x_0 \in M \), and \( \rho(x) \) denotes the distance (with respect to \( g \)) from \( x_0 \) to \( x \).
- There are positive numbers \( r > 0, r_1 > r_2 > 0 \) such that for every \( x \in M \), there exists a holomorphic map \( \phi_x : U_x \subset (\mathbb{C}^n, 0) \to B_r(x) \) such that \( \phi_x(0) = x \). Here one has \( B_{r_2} \subset U_x \subset B_{r_1} \), where \( B_r := \{ z \in \mathbb{C}^n; |z| \leq r \} \). Furthermore \( \phi_x^* g \) is a Kähler metric in \( U_x \) whose metric tensor has derivatives up to order \( 2 \) bounded and \( 1/2 \)-Hölder-continuously bounded.

Let \( f \) be a smooth function, satisfying the integrability condition \((48)\) and such that
\[
\sup_M \{ |\nabla_g f|, |\Delta_g f| \} \leq C \quad |f(x)| \leq C(1 + \rho(x))^{-N}, \tag{49}
\]
for some constant \( C \), for all \( x \) in \( M \), where \( N \geq 4 + 2\beta \).

Then there exists a bounded, smooth solution \( u \) for \((47)\), such that \( \omega + \sqrt{-1} \partial \bar{\partial} u \) defines a complete Kähler metric equivalent to \( g \).

An interesting question addressed by Tian and Yau in the same paper is that whether or not the resulting metric is asymptotically as close to \( g \) as possible modulo assuming further conditions on the decay of \( f \). We provide an answer to this problem in the remainder of this paper.

We are interested in studying the Monge-Ampère equation \((47)\) for the Kähler manifold \((M, \omega_x)\) constructed in Section 4. More precisely, given \( \varepsilon > 0 \), we want to understand the asymptotic behavior of a solution \( u \) to the problem
\[
\begin{align*}
\left( \omega_x + \sqrt{-1} \partial \bar{\partial} u \right)^n &= e^{f_x} \omega^n_x, \\
\omega_x + \sqrt{-1} \partial \bar{\partial} u &> 0, \quad u \in C^\infty(M, \mathbb{R}). \tag{50}
\end{align*}
\]

To guarantee the existence of a solution to \((50)\), we need to check that the function \( f_x \) (defined on \( M \)) satisfies the integrability condition \((48)\).

**Lemma 5.1** There exists a number \( \lambda > 0 \) such that, by replacing \( \phi \) by \( \phi + \lambda \) in Definition \((24)\) of \( \phi \), we have
\[
\int_M (e^{f_x} - 1)\omega^n_x = 0. \tag{51}
\]

**Proof:** Recall the definition of \( \omega_{g_x} \):
\[
\omega_{g_x} = \omega + C_\varepsilon \sqrt{-1} \partial \bar{\partial}(-\|S\|^\varepsilon), \tag{52}
\]
where \( \omega_\phi = \frac{\sqrt{-1}}{2\pi} n^{1+1/n} \partial \bar{\partial} ( - \log ||S||^{2/n}_\phi )^{n+1} \). We choose \( \phi \) (as in Section 2) so that the corresponding \( f_\phi \) decays faster than \( O(||S||^r) \).

A direct computation using integration by parts shows that \( \int_M \omega^n_{g_\phi} - \omega^n_\phi = 0 \). Also, the definitions of \( \omega_g \) and \( \omega_\phi \) imply that \( e^{f_\phi} \omega^n_{g_\phi} = e^{f_\phi} \omega^n_\phi \). Therefore, \( \int_M (e^{f_\phi} - 1) \omega^n_{g_\phi} = \int_M (e^{f_\phi} - 1) \omega^n_\phi \). On the other hand, Definition 2.1 gives

\[
e^{f_\phi} \omega^n_\phi = e^{-\Psi} \omega^n_\phi \tag{53}
\]

Notice that the function \( \Psi \) remains unchanged if we replace \( \phi \) by \( \phi + \lambda \), since \( \bar{\omega}_\phi = \bar{\omega}_{\phi + \lambda} \). Therefore, the right-hand side of (53) is invariant under the transformation \( \phi \rightarrow \phi + \lambda \).

On the other hand, a straightforward computation using (7) shows that

\[
\omega^n_{\phi + \lambda} = \left( \frac{\sqrt{-1}}{2\pi} n^{1+1/n} \frac{1}{n+1} \partial \bar{\partial} ( - \log ||S||^{2/n}_{\phi + \lambda} )^{n+1} \right) - n \lambda \bar{\omega}^{n}_\phi, \tag{54}
\]

where \( \bar{\omega}^{n}_\phi \) is the curvature form of the hermitian metric \( ||.||_\phi \).

Therefore, by redefining \( f_\phi \) by \( f_\phi = - \log ||S||^2 - \log \frac{\omega^n_{\phi + \lambda}}{\omega^n_\phi} - \Psi \), we have that

\[
\int_M (e^{f_\phi} - 1) \omega^n_{g_\phi + \lambda} = \int_M \left( e^{-\Psi} \omega^n_\phi - \omega^n_\phi \right) - n \lambda \int_M \bar{\omega}^{n}_\phi. \tag{55}
\]

Since the first integral in the above expression is finite and independent on \( \lambda \), we can choose the number \( \lambda \) so as to make the right-hand side of (55) equal to zero. This establishes the lemma.

The previous lemma shows that each \( f_\phi \) satisfies the conditions in the existence theorem of Tian and Yau. Also, the estimates on the decay of the Riemann curvature tensor (Lemma 4.2) and the observation on the volume growth of the metric \( g_\phi \) (see the remark after Lemma 4.1) show that \( (M, g_\phi) \) is a complete \( \mathbb{K} \)ähler manifold in which Theorem 5.1 can be applied.

Therefore, for each \( \varepsilon > 0 \), there exists a bounded and smooth solution \( u_\varepsilon \) to the problem (50). Our goal now is to understand the asymptotic behavior of \( u_\varepsilon \).

Denote by \( \omega_\Omega \) the \( \mathbb{K} \)ähler form on \( M \) given by Theorem 5.1 when we use \( g_\varepsilon \) (given by Theorem 1.1) as the ambient metric:

\[
\omega_\Omega = \omega_{g_\varepsilon} + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_\varepsilon.
\]

Clearly, it suffices to prove the asymptotic assertions on \( u_\varepsilon \) for a small tubular neighborhood of \( D \) in \( M \).

Recall from Theorem 1.1 that on \( V_\varepsilon \setminus D \),

\[
\omega_{g_\varepsilon} = \omega_m + C \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} (||S||^r)^{2\varepsilon},
\]

for some \( m \geq \varepsilon \) fixed.

Since \( \omega_m \) and \( \omega_{g_\varepsilon} \) are cohomologous, there exists a function \( u_m \) such that we can write, in \( V_m \setminus D \),

\[
\omega_\Omega = \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_m. \tag{56}
\]

On the other hand, if \( f_m \) is the function defined by (2.1), (56) implies that \( u_m \) satisfies

\[
\left( \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_m \right)^n = e^{f_m} \omega^n_m \quad \text{on} \quad V_m \setminus D, \tag{57}
\]

where we remind the reader that \( |f_m|_{g_m} \) is of order of \( O(||S||^n_m) \).
Lemma 5.2  On the neighborhood \( V_m \setminus D = \{ 0 < ||S||_m < \delta_m \} \), we have

\[
\left\{ \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \overline{\partial} \left( C \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] (-n \log(||S||_m^2))^k \right) \right\}^n = \\
= \omega_m^n \left[ 1 + C(-n \log(||S||_m^2))^k + \frac{\sqrt{-1}}{2\pi} \left\{ ij(-n \log(||S||_m^2))^2 \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] - \\
-(-n \log(||S||_m^2)) \left[ (k(i + j) + (j(n - 1)) S^i S^j \theta_{ij} + (k(i + j) + (i(n - 1)) \overline{S}^i S^j \tilde{\theta}_{ij} \right] \\
+ k(k - n) + O(||S||_m^{i+j+1}) \right) , \quad (58)
\]

where \( \theta_{ij} \) is a \( C^\infty \) local section of \( L_D^1 \otimes L_D^{-j} \) on \( V_m \).

Proof: In order to simplify the notation, define \( B = (-n \log(||S||_m^2)) \). Computations (that can be found in detail in [S]) lead to

\[
\frac{\sqrt{-1}}{2\pi} \partial \overline{\partial} \left( CB^k \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] \right) = \tilde{\omega}_m \left\{ CB^{k-1} \left[ (-jB + k) S^i S^j \theta_{ij} \right] + \left[ (-iB + k) S^i S^j \tilde{\theta}_{ij} \right] \right\} + \\
+ \frac{\sqrt{-1}}{2\pi} \frac{D_m S \wedge D_m \overline{S}}{|S|^2} \left\{ CB^{k-2} \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] [ijF^2 - k(i + j)F + (k - 1)] \right\} + \\
+ CB^{k-1} \frac{\sqrt{-1}}{2\pi} \left[ (jB - k) S^i S^j D_m \theta_{ij} + (iB - k) \overline{S}^i S^j D_m \tilde{\theta}_{ij} \right] \wedge \frac{D_m S}{\overline{S}} + \\
+ CB^{k-1} \frac{\sqrt{-1}}{2\pi} \frac{D_m S}{|S|^2} \wedge \left[ (iB - k) S^i S^j D_m \theta_{ij} + (jB - k) \overline{S}^i S^j D_m \tilde{\theta}_{ij} \right] + \\
+ CB^{k} \frac{\sqrt{-1}}{2\pi} \left[ S^i S^j D_m D_m \theta_{ij} + \overline{S}^i S^j D_m D_m \tilde{\theta}_{ij} \right] , \quad (59)
\]

where \( D_m \) stands for the covariant derivative with respect to the hermitian metric \( ||.||_m \), and where \( \tilde{\omega}_m \) is its corresponding curvature form.

From (S), we have

\[
\omega_m = (-n \log(||S||_m^2))^\frac{1}{n} \tilde{\omega}_m + (-n \log(||S||_m^2))^\frac{1-n}{n} \frac{\sqrt{-1}}{2\pi} \frac{D_m S \wedge D_m \overline{S}}{|S|^2} .
\]

Thus

\[
\left\{ \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \overline{\partial} \left( CB^k \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] \right) \right\}^n = \left[ a \tilde{\omega}_m + b \frac{\sqrt{-1}}{2\pi} \frac{D_m S \wedge D_m \overline{S}}{|S|^2} + \\
\frac{\sqrt{-1}}{2\pi} (c_1 D_m \theta_{ij} + c_2 D_m \tilde{\theta}_{ij}) \wedge \frac{D_m S}{\overline{S}} + \frac{\sqrt{-1}}{2\pi} \frac{D_m S}{|S|^2} \wedge (d_1 \tilde{D}_m \theta_{ij} + d_2 \tilde{D}_m \tilde{\theta}_{ij}) + e \frac{\sqrt{-1}}{2\pi} \tilde{D}_m D_m \theta_{ij} \right]^n , \quad (60)
\]

where

\[
\begin{align*}
 a &= B^k \left[ 1 - CB^{k-\frac{n+1}{2}} [ijB - k) S^i S^j \theta_{ij} + (iB - k) \overline{S}^i S^j \tilde{\theta}_{ij}] \right] \\
 b &= B^{\frac{n+1}{2}} \left[ 1 + CB^{k-\frac{n+1}{2}} \left[ S^i S^j \theta_{ij} + \overline{S}^i S^j \tilde{\theta}_{ij} \right] [ijF^2 - k(i + j)F + (k - 1)] \right] \\
 c_1 &= CS^i S^j B^{k-1} [jB - k], \quad c_2 = CS^i S^j B^{k-1} [iB - k] \\
 d_1 &= CS^i S^j B^{k-1} [iB - k], \quad d_2 = CS^i S^j B^{k-1} [jB - k] \\
 e &= CS^i S^j B^k .
\end{align*}
\]

Now, we proceed on estimating each term on (60).

\[
a^n \tilde{\omega}_m^n = B^\frac{n+1}{2} \left[ 1 - CnB^{k-\frac{n+1}{2}} [ijB - k) S^i S^j \theta_{ij} + (iB - k) \overline{S}^i S^j \tilde{\theta}_{ij}] + O(||S||_m^{i+j+1}) \right] \tilde{\omega}_m^n . \quad (62)
\]
Also
\[ na^{n-1}b = \left[ 1 - C(n-1)B^{k-\frac{n+i}{2}} \left( (jB - k)SS^j\theta_{ij} + (iB - k)SS^j\bar{\theta}_{ij} \right) \right] \cdot \left[ 1 + CB^{k-\frac{n+i}{2}} \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) \right] (ijB^2 - k(i + j)B + k(k - 1)) = \]
\[ = 1 + CB^{k-\frac{n+i}{2}} \left\{ ijB^2 \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) - B \left( (k(i + j) + j(n - 1)) SS^j\theta_{ij} + (k(i + j) + i(n - 1)) SS^j\bar{\theta}_{ij} \right) + k(k - n) \right\} + O(||S||_{m+1}). \] (63)

The expressions for the other terms are analogous, and will henceforth be omitted.

From (7), we deduce that
\[ \tilde{\omega}_m^n = \omega_m^n \frac{||S||_{m}^2 B^{-1}}{||S||_{m}^2 + B^{-1}||D_m S||_{m}^2}, \]
and since
\[ \frac{||S||_{m}^2}{||S||_{m}^2 + B^{-1}||D_m S||_{m}^2} = \frac{||S||_{m}^2 B^{-1}}{||D_m S||_{m}^2} \left( \frac{1}{1 + \frac{B||S||_{m}^2}{||D_m S||_{m}^2}} \right) = O(||S||_{m}^2 B^{-1}), \]
all the terms in (60) will decay at the order of at least \( O(||S||_{m+1}^{i+j+1}) \), with the exception of the term (63), which will be written as:
\[ a^{n-1}b \left\{ \tilde{\omega}_m^{n-1} + \frac{n\sqrt{-1} D_m S \wedge D_m \bar{S}}{||S||^2} \right\} = a^{n-1}b \frac{||D_m S||_{m}^2}{||S||_{m}^2} \tilde{\omega}_m^n = \]
\[ = a^{n-1}b \left( \frac{||D_m S||_{m}^2}{||S||_{m}^2} \right) \frac{\omega_m^n ||S||_{m}^2 B^{-1}}{||S||_{m}^2 + B^{-1}||D_m S||_{m}^2} = \omega_m^n \left[ 1 + CB^{k-\frac{n+i}{2}} \left\{ ijB^2 \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) - B \left( (k(i + j) + j(n - 1)) SS^j\theta_{ij} + (k(i + j) + i(n - 1)) SS^j\bar{\theta}_{ij} \right) + k(k - n) \right\} + O(||S||_{m+1}^{i+j+1}) \right]. \] (64)

Therefore,
\[ \left[ \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} \left( C SS^j\theta_{ij} B^k \right) \right]^n = \omega_m^n \left[ 1 + CB^{k-\frac{n+i}{2}} \left\{ ijB^2 \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) - B \left( (k(i + j) + j(n - 1)) SS^j\theta_{ij} + (k(i + j) + i(n - 1)) SS^j\bar{\theta}_{ij} \right) + k(k - n) \right\} + O(||S||_{m+1}^{i+j+1}) \right], \] (65)
completing the proof of the lemma.

**Proposition 5.1** Let \( u_m \) be a solution to the Monge-Ampère equation \((5.7)\). If \( u_m(x) \) converges uniformly to zero as \( x \) approaches the divisor, then there exists a constant \( C = C(m) \) such that
\[ |u_m(x)| \leq C||S||_{m+1} \quad \text{on } V_m \setminus D. \] (66)

**Proof:** It suffices to prove (66) in a neighborhood of \( D \). Apply Lemma 5.2 for \( i = m + 2 \) and \( j = -1 \), and choose the section \( \theta_{ij} \) so that the function \( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \) is positive on \( V_m \setminus D \). Note that there is, in fact, a \( C^\infty \)-section \( \theta_{ij} \) satisfying this condition. Indeed, a local section on a trivializing coordinate can clearly be constructed by means of a bump function. In particular we can consider finitely many local sections as above such that the union of their supports covers the all of \( D \). Since the positivity condition is naturally respected by the cocycle relations arising from the change of coordinates, the desired section \( \theta_{ij} \) can simply be obtained by adding these local sections.

With the above choices, we have
\[ \left[ \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} C \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) \right]^n = \omega_m^n \left[ 1 - C(m + 2)(-n \log(||S||_{m}^2))^k \right] \left[ 1 + o(1) \right] \left( SS^j\theta_{ij} + SS^j\bar{\theta}_{ij} \right) + O(||S||_{m+2}). \] (67)
On the other hand,

\[ e^{f_m} \omega_m^n = [1 + O(||S||_m^{m+1})] \omega_m^n \quad \text{on } V_m \setminus D. \]  

(68)

More precisely, we can write on \( V_m \setminus D \)

\[ e^{f_m} \omega_m^n = [1 + \sum_{\ell=0}^{\ell_{m+1}} \{S^i S^j \theta_{ij} + \overline{S}^i S^j \overline{\theta}_{ij}\}(-\log ||S||_m^2)^\ell + O(||S||_m^{m+2})] \omega_m^n, \]  

(69)

for sections \( \theta_{ij} \in \Gamma(V_m \setminus D, L_D^{-1} \otimes L_D^m) \).

Let \( \varepsilon > 0 \), and define \( C_i = \frac{C_i'}{\varepsilon} \), where \( C_i' := \sup_{x \in V_m \setminus D} (|u_m| + 1) \), and \( C_2' = -C_1' \). Then, for all \( x \in V_m \setminus D \) verifying

\[ (S^{m+2} \overline{S}^{-1} \theta_{m+2,-1} + S^{m+2} \overline{S}^{-1} \overline{\theta}_{m+2,-1}(-n \log(||S||_m^2))^{\ell_{m+1}}) (x) = \varepsilon, \]  

(70)

it follows that

\[ C_1 (S^{m+2} \overline{S}^{-1} \theta_{m+2,-1} + S^{m+2} \overline{S}^{-1} \overline{\theta}_{m+2,-1}(-n \log(||S||_m^2))^{\ell_{m+1}}) (x) > |u_m(x)|. \]

Furthermore, if \( \varepsilon \) is sufficiently small, then on the subset

\[ \{x \in V_m \setminus D : (S^{m+2} \overline{S}^{-1} \theta_{m+2,-1} + S^{m+2} \overline{S}^{-1} \overline{\theta}_{m+2,-1}(-n \log(||S||_m^2))^{\ell_{m+1}}) (x) \leq \varepsilon\}, \]

we have (for \( i = m + 2 \) and \( j = -1 \))

\[ \left[ \varepsilon + \frac{\sqrt{-1}}{2\pi} \bar{\partial} \bar{\bar{\partial}} C_1 \left[ S^i S^j \theta_{ij} + S^i S^j \overline{\theta}_{ij}\right] (-n \log ||S||_m^2)^{\ell_{m+1} - \frac{n}{2} - \frac{1}{n}} \right]^n \leq e^{f_m} \omega_m^n, \quad \text{and} \]

\[ \left[ \varepsilon + \frac{\sqrt{-1}}{2\pi} \bar{\partial} \bar{\bar{\partial}} C_2 \left[ S^i S^j \theta_{ij} + S^i S^j \overline{\theta}_{ij}\right] (-n \log ||S||_m^2)^{\ell_{m+1} - \frac{n}{2} - \frac{1}{n}} \right]^n \geq e^{f_m} \omega_m^n. \]

Finally, by using the hypothesis on the uniform vanishing of \( u_m \) on \( D \), the proposition follows from the maximum principle for the complex Monge–Ampère operator: we obtain the following bound (write \( \ell = \ell_{m+1} - \frac{n}{2} - \frac{1}{n} \))

\[ C_2 \left[ S^i S^j \theta_{ij} + S^i S^j \overline{\theta}_{ij}\right] (-n \log ||S||_m^2)^{\ell} \leq u_m \leq C_1 \left[ S^i S^j \theta_{ij} + S^i S^j \overline{\theta}_{ij}\right] (-n \log ||S||_m^2)^{\ell} \]

(71)

on the neighborhood given in (70), which completes the proof of the proposition.

Now, let us deal with another step in the proof of Theorem 1.2 which consists of showing that the solution to the Monge–Ampère equation (47) actually converges uniformly to zero.

Proposition 5.2 For a fixed \( m \geq 2 \), let \( u_m \) be a solution to (47). Then \( u_m(x) \) converges uniformly to zero as \( x \) approaches the divisor \( D \).

Proof: In [TY1], the solution \( u_m \) to the Monge–Ampère equation (47) is obtained as the uniform limit, as \( \varepsilon \) goes to zero, of solutions \( u_{m,\varepsilon} \) of the perturbed Monge–Ampère equations

\[ \begin{cases} 
\left( \varepsilon + \frac{\sqrt{-1}}{2\pi} \bar{\partial} \bar{\bar{\partial}} C \left[ S^i S^j \theta_{ij} + S^i S^j \overline{\theta}_{ij}\right]\right)^n = e^{f_m} \omega_m^n, \\
\varepsilon + \frac{\sqrt{-1}}{2\pi} \bar{\partial} \bar{\bar{\partial}} u > 0, \\
u_m \in C^\infty (M, \mathbb{R}).
\end{cases} \]

(72)

On the neighborhood \( V_m \), Lemma (5.2) applied for \( i = 2, j = -1 \) and \( k = 0 \), gives

\[ \begin{align*}
\left[ \varepsilon + \frac{\sqrt{-1}}{2\pi} \bar{\partial} \bar{\bar{\partial}} \left[ C \left[ S^2 S^{-1} \theta_{2,-1} + S^2 S^{-1} \overline{\theta}_{2,-1}\right]\right]\right]^n &= \varepsilon \left[ 1 - 2C(-n \log ||S||_m^2)^{\ell_{m+1}} \left\{ (-n \log ||S||_m^2)^2 \left[ S^2 S^{-1} \theta_{2,-1} + S^2 S^{-1} \overline{\theta}_{2,-1}\right] - \right. \right.
\end{align*} \]

(73)
Again, we can choose appropriate local $C^\infty$-sections $\theta_{2,-1}$ such that

$$S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}$$

is a positive function on a neighborhood of the divisor, and use this function as a uniform barrier to the sequence of solutions $\{u_{m,\varepsilon}\}$.

Note that $e^{f_{m} + u_{m,\varepsilon}} = 1 + O(\|S\|_{m})$. Hence, as in the proof of Lemma 6.2 we can define, for a fixed $\delta > 0$, $C_{i} = \frac{C_{i}'}{\delta}$, where $C_{i}' := \sup_{x \in V_{m} \setminus D}(|u_{m,\varepsilon}| + 1)$ and $C_{i}'' = -C_{i}'$. A priori, $C_{i}'$ could depend on $\varepsilon$, but it turns out (see [TY1] for details) that $\sup_{M} |u_{m,\varepsilon}|$ can be bounded uniformly by a constant independent on $\varepsilon$. Then, for all $x \in V_{m} \setminus D$ such that

$$\left(S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right)(x) = \delta,$$

we have that

$$C_{1}\left(S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right)(x) > |u_{m,\varepsilon}(x)|.$$

In addition, in the neighborhood $\{x \in V_{m} \setminus D$: $\left(S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right)(x) \leq \delta\}$, for a fixed $\delta$ sufficiently small, we have

$$\left[\omega_{m} + \frac{\sqrt{-1}}{2\pi}\partial\bar{\partial}C_{1}\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right]\right]^{n} \leq e^{f_{m} + \varepsilon C_{1}\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right]\omega_{m}^{n}},$$

and

$$\left[\omega_{m} + \frac{\sqrt{-1}}{2\pi}\partial\bar{\partial}C_{2}\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right]\right]^{n} \geq e^{f_{m} + \varepsilon C_{1}\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right]\omega_{m}^{n}}.$$

Since $u_{m,\varepsilon}$ vanishes at $D$ (see [CY1]), we can apply the maximum principle to conclude that there exists a $C$ independent of $\varepsilon$ such that, near $D$,

$$-C\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right] \leq u_{m,\varepsilon} \leq C\left[S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right].$$

Now, since the neighborhood $\{x \in V_{m} \setminus D$: $\left(S^2\bar{S}^{-1}\theta_{2,-1} + \bar{S}^2S^{-1}\bar{\theta}_{2,-1}\right)(x) \leq \delta\}$ is a fixed set, independent of $\varepsilon$, and the constant $C$ above is also independent of $\varepsilon$, we can pass to the limit when $\varepsilon$ goes to zero, obtaining the claim. 

We can still provide further information about the decay of the covariant derivatives of the solution $u_{m}$ to (57).

**Proposition 5.3** For a fixed $m > 1$, let $u_{m}$ be a solution to (57). Then, there exists $C = C(k, m)$ such that, for all $x \in V_{m} \setminus D$,

$$|\nabla^{k}u_{m}|_{g_{m}}(x) \leq C\|S\|_{m}(x)^{-\frac{k\varepsilon + 2}{m - k\varepsilon}}.$$  \hspace{1cm} (74)

**Proof:** The strategy of this proof will be induction on $k$, and the use of Moser Iteration Technique. Recall that Lemma 4.3 gives

$$||\nabla^{k}R(g_{m})||_{g_{m}}(x) = O(\rho_{m}^{-\frac{k+2}{m+1}})$$

for all $x \in V_{m} \setminus D$.

In order to use Moser Iteration, we will need to localize on a small ball around a point $x \in V_{m} \setminus D$. Let us define a new rescaled Kähler metric on $B_{R}(x, g_{m})$ by $(\tilde{g}) = R^{-2}g_{m}$, where $R = \rho_{m}(x)$. Note that $B_{1}(x, \tilde{g}) = B_{R}(x, g_{m})$.

Then,

$$||\tilde{\nabla}^{k}R(\tilde{g})||_{\tilde{g}}(x) = ||\nabla^{k}R(g_{m})||_{g_{m}}(x)R^{k+2},$$

$$||\tilde{\nabla}^{k}R(\tilde{g})||_{\tilde{g}}(x) = ||\nabla^{k}R(g_{m})||_{g_{m}}(x)R^{k+2},$$

$$\text{for all } x \in V_{m} \setminus D.$$
and hence \( \sup\{||\tilde{\nabla}^k R(\tilde{g})||_{\tilde{g}}(x); x \in B_1(x, \tilde{g})\} \leq C. \)

By writing \( \tilde{u} = R^{-2}u_m \), we get that \( \tilde{u} \) satisfies
\[
\left( \omega_{\tilde{g}} + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} \tilde{u} \right)^n = e^{f_m} \omega_{\tilde{g}}^n \quad \text{on } B_1(x, \tilde{g})), \tag{75}
\]
and from Propositions 5.2 and 5.1 we also have that \( \sup\{||\tilde{u}|; x \in B_1(x, \tilde{g})\} \leq C||S||^m_m(x). \)

Lemma 4.1 also tells us that \( \nabla^k f_{m_n}(x) = O(||S||^{m+1}_m(x)\rho_m^{-k+1}(x)) \), hence there exists a constant \( C = C(k, m) \) such that \( \sup\{||\nabla^k f_{m_n}; x \in B_1(x, \tilde{g})\} \leq C||S||^m_m(x). \)

Now, we have all the ingredients to start the inductive proof. Since \( |\nabla^k u_m|_{g_m}(x) = R^{-k+2} |\nabla^k \tilde{u}|_{\tilde{g}}(x), \) it suffices to prove that there exists a constant \( C \) such that
\[
|\nabla^k \tilde{u}|_{\tilde{g}}(x) \leq C||S||^m_m(x). \tag{76}
\]

We will proceed by induction on \( k \). First, consider the case \( k = 1 \). By the second order estimate in \cite{Y} (see also \cite{TY1}), we have that the Kähler metric which solves the Monge-Ampère equation is equivalent to the chosen representative of the fixed Kähler class, i.e., there exists a constant \( C = C_m \) such that
\[
0 \leq \omega_m + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} u_m \leq C \omega_m.
\]

This implies that
\[
0 \leq \omega_{\tilde{g}} + \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} \tilde{u} \leq C \omega_{\tilde{g}} \quad \text{on } B_1(x, \tilde{g})).
\]

Let \( \eta \) be a cut-off function that vanishes outside the unit ball, and is identically one on \( B_{1/2}(x, \tilde{g}) \). By multiplying both sides of (75) by \( \eta^2 \tilde{u} \) and integrating by parts, we obtain the \( L^2 \)-estimate of \( |\nabla \tilde{u}| \):
\[
\int_{B_{1/2}(x, \tilde{g}))} |\nabla \tilde{u}|_{\tilde{g}}^2 \omega_{\tilde{g}}^n \leq C \int_{B_1(x, \tilde{g}))} |e^{f_m} - 1||\tilde{u}|_{\tilde{g}}^n \leq ||S||^2_m(x). \tag{77}
\]

Now, differentiating (75) with respect to \( z_k, 1 \leq k \leq n \), we obtain
\[
\tilde{g}^{ij} \left( \frac{\partial \tilde{u}}{\partial z_k} \right)_{i \bar{j}} = (e^{f_m} - 1) \tilde{g}^{ij} \left( \frac{\partial \tilde{g}_{i \bar{j}}}{\partial z_k} \right)_{\bar{k}} + \frac{\partial f_m}{\partial z_k} e^{f_m} + O(|\nabla^2 \tilde{u}|), \tag{78}
\]
where \( O(|\nabla^2 \tilde{u}|) \) denotes the terms that can be bounded by \( |\nabla^2 \tilde{u}| \).

Our estimates on the \( L^2 \)-norm of \( |\nabla \tilde{u}| \) on the ball \( B_{1/2}(x, \tilde{g}) \) allow us to apply Theorem 8.17, \cite{GT} (the Moser Iteration Method) to conclude that
\[
|\nabla \tilde{u}|_{\tilde{g}}(x) \leq C||S||^m_m(x). \tag{79}
\]

Recall that \( x \) was a point chosen arbitrarily, so this estimate holds for all \( x \in V_m \setminus D \).

Now, the next step is to multiply both sides of (79) by \( \eta^2 \frac{\partial u}{\partial z_k} \) (for \( \eta \) an adequate cut-off function defined on \( B_1(x, \tilde{g}) \)) and integrate by parts, in order to obtain the estimate on the \( L^2 \)-estimate on the norm of \( \nabla^2 \tilde{u} \):
\[
\int_{B_{1/2}(x, \tilde{g}))} |\nabla^2 \tilde{u}|_{\tilde{g}}^2 \omega_{\tilde{g}}^n \leq C||S||^{2m}_m(x). \tag{80}
\]

Since it is analogous to our previous step, we will omit further explanations. We note that the pointwise estimate on \( |\nabla \tilde{u}| \) allow us to obtain the \( L^2 \)-estimate on \( |\nabla^2 \tilde{u}| \). This completes the first step on the induction (for \( k = 1 \)).

Now, assume that the following is true for all \( j \leq k - 1 \):
\[
|\nabla^j \tilde{u}|_{\tilde{g}}(x) \leq C||S||^m_m(x), \quad \text{and} \tag{81}
\]

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\[
\int_{B_{1/2}(x, \tilde{g})} |\nabla^k \tilde{u}|^2_{\tilde{g}} \leq C \| S \|^m_m(x). \quad (82)
\]

Differentiating (75) \(k\) times, we obtain
\[
\tilde{g}^{ij} \left( \frac{\partial^k \tilde{u}}{\partial z^{i_1} \ldots \partial z^{i_k}} \right)_{ij} = \frac{\partial^k f_m}{\partial z^{i_1} \ldots \partial z^{i_k}} e^f_m + O(\| S \|^m_m(x)). \quad (83)
\]

Our estimates on the decay of \(|\nabla^k f_m|_{\tilde{g}}\) (given by Lemma 4.4) allow us to use again Moser Iteration to conclude that
\[
|\nabla^k \tilde{u}|_{\tilde{g}}(x) \leq C \| S \|^m_m(x), \quad (84)
\]
completing the proof of the Proposition.

**Proof of Theorem 1.2** It follows immediately from the combination of Propositions 5.1, 5.2 and 5.3.

□

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