1. Introduction

Let \((M, g)\) be a compact Hermitian manifold (without boundary) of complex dimension \(n \geq 2\) and write \(\omega\) for the corresponding real \((1, 1)\)-form

\[
\omega = \sqrt{-1} \sum_{i,j} g_{i \bar{j}} dz^i \wedge d\bar{z}^j.
\]

For a smooth real-valued function \(F\) on \(M\), consider the complex Monge-Ampère equation

\[
(\omega + \sqrt{-1} \partial \bar{\partial} \varphi)^n = e^F \omega^n, \quad \text{with}
\]

\[
\omega + \sqrt{-1} \partial \bar{\partial} \varphi > 0, \quad \sup_M \varphi = 0,
\]

for a real-valued function \(\varphi\).

Our main result is as follows.

**Main Theorem.** Let \(\varphi\) be a smooth solution of the complex Monge-Ampère equation (1.1). Then there are uniform \(C^\infty\) a priori estimates on \(\varphi\) depending only on \((M, \omega)\) and \(F\).

A corollary of this is that we can solve (1.1) uniquely after adding a constant to \(F\), or, equivalently, up to scaling the volume form \(e^F \omega^n\).

**Corollary 1.** For every smooth real-valued function \(F\) on \(M\) there exist a unique real number \(b\) and a unique smooth real-valued function \(\varphi\) on \(M\) solving

\[
(\omega + \sqrt{-1} \partial \bar{\partial} \varphi)^n = e^{F+b} \omega^n, \quad \text{with}
\]

\[
\omega + \sqrt{-1} \partial \bar{\partial} \varphi > 0, \quad \sup_M \varphi = 0.
\]

In the case of \(\omega\) Kähler, that is, when \(d\omega = 0\), this result is precisely the celebrated Calabi Conjecture [Ca] proved by Yau [Ya]. We note here that if \(\omega\) satisfies

\[
\partial \bar{\partial} \omega^k = 0, \quad \text{for } k = 1, 2
\]
(in particular if $\omega$ is closed), then the constant $b$ must equal

$$b = \log \frac{\int_M \omega^n}{\int_M e^F \omega^n}.$$  

(1.4)

In fact, one can easily see that (1.3) implies that $\partial \bar{\partial} \omega^k = 0$ for all $1 \leq k \leq n - 1$ (see for example [GL]), and integrating (1.2) over $M$ and repeatedly using Stokes’s Theorem, one sees that indeed $b$ equals (1.4).

We mention now some special cases where the results of the Main Theorem and Corollary 1 are already known. Cherrier [Ch] gave a proof when the complex dimension is two or if $\omega$ is balanced, that is, $d(\omega - 1) = 0$ (an alternative proof was very recently given in [TW]). In addition, Cherrier [Ch] dealt with the case of conformally Kähler and considered a technical assumption which is slightly weaker than balanced; see also the related work of Hanani [Ha]. Guan and Li [GL] gave a proof under the assumption (1.3). For further background we refer the reader to [TW] and the references therein.

As the reader will see in the proof below, we note that the key $L^\infty$ bound of $\varphi$ in the Main Theorem follows from combining a lemma of [Ch] with some recent estimates of the authors [TW].

Finally, we remark that one can give a geometric interpretation of (1.2) in terms of the first Chern class $c_1(M)$ of $M$. We denote by $\text{Ric}(\omega)$ the first Chern form of the Chern connection of $\omega$, which is a closed form cohomologous to $c_1(M)$. We then consider the real Bott-Chern space $H^1_{BC}(X, \mathbb{R})$ of closed real $(1,1)$-forms modulo the image of $\sqrt{-1} \partial \bar{\partial}$ acting on real functions. It has a natural surjection to the familiar space $H^1(X, \mathbb{R})$, which is an isomorphism if and only if $b_1(M) = 2h^{0,1}$ (in particular if $M$ is Kähler). The form $\text{Ric}(\omega)$ determines a class $c_1^{BC}(M)$ in $H^1_{BC}(M, \mathbb{R})$ which maps to the usual first Chern class $c_1(M)$ via the above surjection. Then from our Main Theorem we get the following Hermitian version of the Calabi Conjecture (see also a related question of Gauduchon [G2 IV.5]):

**Corollary 2.** Every representative of the first Bott-Chern class $c_1^{BC}(M)$ can be represented as the first Chern form of a Hermitian metric of the form $\omega + \sqrt{-1} \partial \bar{\partial} \varphi$.

To see why this holds, just notice that (1.2) holds for some constant $b$ if and only if

$$\text{Ric}(\omega + \sqrt{-1} \partial \bar{\partial} \varphi) = \text{Ric}(\omega) - \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} F$$

and that by definition every form representing $c_1^{BC}(M)$ can be written as $\text{Ric}(\omega) - \frac{\sqrt{-1}}{2\pi} \partial \bar{\partial} F$ for some function $F$. We note here that in the case $n = 2$, Corollary 2 of [TW] gives a criterion to decide which representatives of $c_1(M)$ can be written in this form.

2. **Proof of the Main Theorem**

By the results of [Ch], [GL], [Zh] it suffices to obtain a uniform bound of $\varphi$ in the $L^\infty$ norm. Indeed, by extending the second-order estimate on $\varphi$ of Yau [Yau] (and Aubin [Au]), Cherrier [Ch] has shown, for general $\omega$, that a uniform $L^\infty$ bound on $\varphi$ implies that the metric $\omega + \sqrt{-1} \partial \bar{\partial} \varphi$ is uniformly equivalent to $\omega$. Moreover, generalizing Yau’s third-order estimate [Yau], Cherrier shows that given this one can then bound $\omega + \sqrt{-1} \partial \bar{\partial} \varphi$ in $C^1$. Higher-order estimates then follow from standard
elliptic theory. A similar second-order estimate was also proved by Guan and Li [GL] and Zhang [Zh] for general $\omega$ and sharpened in [TW] in the cases of $n = 2$ or $\omega$ balanced. It is also possible to avoid the third-order estimate by using the Evans-Krylov theory, as in [GL] and [TW].

We remark that our $L^\infty$ bound on $\phi$ depends only on $(M, \omega)$ and sup$_M F$, as in Yau’s estimate for the Kähler case [Ya]. In particular, the $L^\infty$ bound does not depend on inf$_M F$. In the course of the proof, we say that a constant is uniform if it depends only on the data $(M, \omega)$ and sup$_M F$. We will often write such a constant as $C$, which may differ from line to line. If we say that a constant depends only on a quantity $Q$, then we mean that it depends only on $Q$, $(M, \omega)$, and sup$_M F$.

Our goal is thus to give a uniform bound for $\phi$. We begin with a lemma which can be found in [Ch]. For the convenience of the reader, we provide a proof. We use the notation of exterior products instead of the multilinear algebra calculations of [Ch].

**Lemma 2.1.** There are uniform constants $C$, $p_0$ such that for all $p \geq p_0$ we have

$$\int_M |\partial e^{-\frac{p}{2}\phi}|^2 g_\omega n \leq C p \int_M e^{-p\phi} \omega_n.$$  

**Proof.** From now on we will use the shorthand notation $\omega_\phi = \omega + \sqrt{-1} \partial \bar{\partial} \phi$. Let $\alpha$ be the $(n-1,n-1)$-form given by

$$\alpha = \sum_{k=0}^{n-1} \omega_\phi^k \land \omega^{n-k-1}.$$  

We compute, using the equation (1.1) and integrating by parts,

$$C \int_M e^{-p\phi} \omega_n \geq \int_M e^{-p\phi} (\omega_\phi^n - \omega^n) = \int_M e^{-p\phi} \sqrt{-1} \partial \bar{\partial} \phi \land \alpha + \int_M e^{-p\phi} \sqrt{-1} \partial \phi \land \partial \phi \land \omega_\phi^k \land \omega^{n-k-1}.$$  

(2.1)

The first term on the right-hand side of (2.1) is positive, and we are going to use part of it to deal with the second one. Notice that

$$\partial \alpha = n \sum_{k=0}^{n-2} \omega_\phi^k \land \omega^{n-k-2} \land \partial \omega.$$  

Since $\partial \omega$ is a fixed tensor, there is a constant $C$ so that for any $\varepsilon > 0$ and any $k$ we have the elementary pointwise inequality

$$\frac{\sqrt{-1} \partial \phi \land \partial \omega \land \omega_\phi^k \land \omega^{n-k-2}}{\omega^n} \leq C \frac{\sqrt{-1} \partial \phi \land \partial \phi \land \omega_\phi^k \land \omega^{n-k-1}}{\omega^n} + \varepsilon C \frac{\omega_\phi^k \land \omega^{n-k}}{\omega^n}.$$  

(2.2)
that the reader can verify by choosing local coordinates at a point that make \( \omega \) the identity and \( \omega_\varphi \) diagonal. Applying (2.2), we have for any \( \varepsilon > 0 \) and any \( p \),

\[
- \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \alpha = -n \sum_{k=0}^{n-2} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \omega_\varphi^k \wedge \omega^{n-k-2} \wedge \partial \omega \\
\leq \frac{C}{\varepsilon} \sum_{k=0}^{n-2} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \omega_\varphi^k \wedge \omega^{n-k-1} \\
+ \varepsilon C \sum_{k=0}^{n-2} \int_M e^{-p\varphi} \omega_\varphi^k \wedge \omega^{n-k}.
\]

Now if we choose \( p_0/2 \geq C/\varepsilon \), we see that if \( 0 < \varepsilon \leq 1 \), then for \( p \geq p_0 \),

\[
- \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \alpha \leq \frac{p}{2} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \alpha + C \int_M e^{-p\varphi} \omega^n + \varepsilon C \sum_{k=1}^{n-2} \int_M e^{-p\varphi} \omega_\varphi^k \wedge \omega^{n-k}.
\]

Combining this with (2.1), we see that for any \( 0 < \varepsilon < 1 \) there exists \( p_0 \) depending only on \( \varepsilon \) such that for \( p \geq p_0 \),

\[
(2.3) \quad \frac{p}{2} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \alpha \leq C \int_M e^{-p\varphi} \omega^n + \varepsilon C \sum_{k=1}^{n-2} \int_M e^{-p\varphi} \omega_\varphi^k \wedge \omega^{n-k}.
\]

We now claim the following. There exist uniform constants \( C_2, \ldots, C_n \) and \( \varepsilon_0 \) such that for all \( \varepsilon \) with \( 0 < \varepsilon \leq \varepsilon_0 \), there exists a constant \( p_0 \) depending only on \( \varepsilon \) such that for all \( p \geq p_0 \) we have for \( i = 2, \ldots, n \),

\[
(2.4) \quad \frac{p}{2^{i-1}} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \alpha \leq C_i \int_M e^{-p\varphi} \omega^n + \varepsilon C_i \sum_{k=1}^{n-i} \int_M e^{-p\varphi} \omega_\varphi^k \wedge \omega^{n-k}.
\]

Given the claim, the lemma follows. Indeed once we have the statement with \( i = n \), then, fixing \( \varepsilon = \varepsilon_0 \), we have for \( p \geq p_0 \),

\[
\int_M |\partial e^{-\frac{\varphi}{2}} g|_g^2 \omega^n = \frac{np^2}{4} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \omega^{n-1} \\
\leq \frac{np^2}{4} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \partial \varphi \wedge \alpha \\
\leq n^{2n-3} C_n p \int_M e^{-p\varphi} \omega^n,
\]

as required.

We will prove the claim by induction on \( i \). By (2.3) we have already proved the statement for \( i = 2 \). So we assume the induction statement (2.4) for \( i \) and prove it
for \(i+1\). We compute
\[
\varepsilon C_i \sum_{k=1}^{n-i} \int_M e^{-p\varphi} \omega_p^k \wedge \omega^{n-k} = \varepsilon C_i \sum_{k=1}^{n-i} \int_M e^{-p\varphi} \omega_p^{k-1} \wedge \omega^{n-k+1}
\]
\[
+ \varepsilon C_i \sum_{k=1}^{n-i} \int_M e^{-p\varphi} \sqrt{-1} \partial \bar{\partial} \varphi \wedge \omega_p^{k-1} \wedge \omega^{n-k}
\]
(2.5)
\[
= A_1 + A_2,
\]
where
\[
A_1 = \varepsilon C_i \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \omega_p^k \wedge \omega^{n-k},
\]
\[
A_2 = \varepsilon C_i \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \sqrt{-1} \partial \bar{\partial} \varphi \wedge \omega_p^k \wedge \omega^{n-k-1}.
\]

The term \(A_1\) is already acceptable for the induction. For \(A_2\) we integrate by parts to obtain
\[
A_2 = \varepsilon C_i p \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \bar{\partial} \varphi \wedge \omega_p^k \wedge \omega^{n-k-1}
\]
\[
+ \varepsilon C_i \sum_{k=0}^{n-i-1} k \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \omega_p^{k-1} \wedge \omega^{n-k-1} \wedge \partial \omega
\]
\[
+ \varepsilon C_i \sum_{k=0}^{n-i-1} (n-k-1) \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \omega_p^k \wedge \omega^{n-k-2} \wedge \partial \omega
\]
(2.6)
\[
= B_1 + B_2 + B_3,
\]
where
\[
B_1 = \varepsilon C_i p \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \bar{\partial} \varphi \wedge \omega_p^k \wedge \omega^{n-k-1}
\]
\[
B_2 = \varepsilon C_i \sum_{k=0}^{n-i-2} (k+1) \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \omega_p^k \wedge \omega^{n-k-2} \wedge \partial \omega
\]
\[
B_3 = \varepsilon C_i \sum_{k=0}^{n-i-1} (n-k-1) \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \omega_p^k \wedge \omega^{n-k-2} \wedge \partial \omega.
\]
Choosing \(\varepsilon_0\) such that \(\varepsilon_0 C_i < 2^{-i-1}\), we have for \(\varepsilon \leq \varepsilon_0\) and \(p \geq p_0\),
\[
B_1 \leq \frac{p}{2^{i+1}} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \bar{\partial} \varphi \wedge \alpha.
\]
(2.7)
For the terms \(B_2\) and \(B_3\) we use again (2.2) to obtain
\[
B_2 + B_3 \leq nC_i C \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \bar{\partial} \varphi \wedge \omega_p^k \wedge \omega^{n-k-1}
\]
\[
+ \varepsilon^2 nC_i C \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \omega_p^k \wedge \omega^{n-k}.
\]
(2.8)
Notice that the second term on the right-hand side of (2.8) is acceptable for the induction. Moreover, we may assume that $p_0 \geq 2^{i+1} nC_i C$ and thus for $p \geq p_0$,

$$B_2 + B_3 \leq \frac{p}{2^{i+1}} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \overline{\partial} \varphi \wedge \alpha + \varepsilon^2 nC_i C \sum_{k=0}^{n-i-1} \int_M e^{-p\varphi} \omega^k \wedge \omega^{n-k}.$$  

(2.9)

Combining the inductive hypothesis (2.4) with (2.5), (2.6), (2.7), (2.9), we obtain for $p \geq p_0$,

$$\frac{p}{2^i} \int_M e^{-p\varphi} \sqrt{-1} \partial \varphi \wedge \overline{\partial} \varphi \wedge \alpha \leq C_{i+1} \int_M e^{-p\varphi} \omega^n + \varepsilon C_{i+1} \sum_{k=1}^{n-i-1} \int_M e^{-p\varphi} \omega^k \wedge \omega^{n-k},$$

completing the inductive step. This finishes the proof of the claim and thus the lemma. □

We now complete the proof of the Main Theorem. Using Lemma 2.1 and the Sobolev inequality, we have for $\beta = \frac{n}{n-1} > 1$,

$$\left(\int_M e^{-p\varphi} \omega^n\right)^{1/\beta} \leq C \left(\int_M |\partial e^{-\frac{\varphi}{2}}|^2 \omega^n + \int_M e^{-p\varphi} \omega^n\right) \leq Cp \int_M e^{-p\varphi} \omega^n,$$

for all $p \geq p_0$. Thus

$$\|e^{-\varphi}\|_{L^{p\beta}} \leq C^{1/p} \|e^{-\varphi}\|_{L^p}.$$

Since this holds for all $p \geq p_0$, we can iterate this estimate in a standard way to obtain

$$\|e^{-\varphi}\|_{L^\infty} \leq C \|e^{-\varphi}\|_{L^{p_0}},$$

which is equivalent to

$$e^{-p_0 \inf_M \varphi} \leq C \int_M e^{-p_0 \varphi} \omega^n.$$

We now make use of a result from [TW]:

**Lemma 2.2.** Let $f$ be a smooth function on $(M, \omega)$. Write $d\mu = \omega^n / \int_M \omega^n$. If there exists a constant $C_1$ such that

$$e^{-\inf_M f} \leq e^{C_1} \int_M e^{-f} d\mu,$$

then

$$|\{f \leq \inf_M f + C_1 + 1\}| \geq \frac{e^{-C_1}}{4},$$

(2.11)

where $| \cdot |$ denotes the volume of the set with respect to $d\mu$.

**Proof.** See [TW] Lemma 3.2. □

Applying this lemma to $f = p_0 \varphi$, we see that there exist uniform constants $C$, $\delta > 0$ so that

$$|\{\varphi \leq \inf_M \varphi + C\}| \geq \delta.$$  

(2.12)
We remark that, in [TW], the bound (2.12) is established whenever one has the improved second-order estimate,

\[(2.13) \quad \text{tr}_\omega \omega \varphi \leq C e^{A(\varphi - \inf_M \varphi)},\]

for uniform $A$ and $C$. It is shown in [TW] that (2.13) holds if $n = 2$ or $\omega$ is balanced.

The $L^\infty$ bound on $\varphi$, and hence the Main Theorem, now follow from the arguments of [TW]. However, we include an outline of these arguments for the reader’s convenience. Recall that, from [G1], if $(M, \omega)$ is a compact Hermitian manifold, then there exists a unique smooth function $u : M \to \mathbb{R}$ with $\sup_M u = 0$ such that the metric $\omega_G = e^u \omega$ is Gauduchon, that is, it satisfies

\[(2.14) \quad \partial \bar{\partial} (\omega^n_G - 1) = 0.\]

Writing $\Delta_G$ for the complex Laplacian associated to $\omega_G$ (which differs from the Levi-Civita Laplacian in general), we have the following lemma (cf. [TW, Lemma 3.4]).

**Lemma 2.3.** Let $M$ be a compact complex manifold of complex dimension $n$ with a Gauduchon metric $\omega_G$. If $\psi$ is a smooth nonnegative function on $M$ with $\Delta_G \psi \geq -C_0$,

then there exist constants $C_1$ and $C_2$ depending only on $(M, \omega_G)$ and $C_0$ such that

\[(2.15) \quad \int_M |\partial \psi^{p+1}|^2 \omega^n_G \leq C_1 p \int_M \psi^p \omega^n_G \quad \text{for all } p \geq 1\]

and

\[(2.16) \quad \sup_M \psi \leq C_2 \max \left\{ \int_M \psi \omega^n_G, 1 \right\}.\]

**Proof.** Compute for $p \geq 1$,

\[
\int_M |\partial \psi^{p+1}|^2 \omega^n_G = \frac{n(p+1)^2}{4} \int_M \sqrt{-1} \psi^{p-1} \partial \psi \wedge \overline{\partial} \psi \wedge \omega^{n-1}_G
\]

\[= \frac{n(p+1)^2}{4p} \int_M \sqrt{-1} \psi^{p} \wedge \overline{\partial} \psi \wedge \omega^{n-1}_G
\]

\[= \frac{(p+1)^2}{4p} \int_M \psi^p (-\Delta_G \psi) \omega^n_G
\]

\[+ \frac{n(p+1)}{4p} \int_M \sqrt{-1} \partial \psi^{p+1} \wedge \partial \omega^{n-1}_G
\]

\[\leq C \frac{(p+1)^2}{4p} \int_M \psi^p \omega^n_G,
\]

thus establishing (2.15). The inequality (2.16) then follows by a standard iteration argument, using the Sobolev inequality for the metric $\omega_G$. Indeed, writing $q = p + 1$ and $\beta = \frac{n}{n-1}$, we obtain for $q \geq 2$,

\[
\left( \int_M \psi^q \omega^n_G \right)^{1/\beta} \leq C \max \left\{ \int_M \psi^q \omega^n_G, 1 \right\}.
\]
By repeatedly replacing $q$ by $q\beta$ and iterating, we have, after setting $q = 2$,
\[
\sup_M \psi \leq C \max \left\{ \left( \int_M \psi^2 \omega^n_G \right)^{1/2}, 1 \right\} \leq C \max \left\{ \sup_M \psi \right\} \left( \int_M \psi \omega^n_G \right)^{1/2}, 1 \right\},
\]
and (2.16) follows.

We apply Lemma 2.3 to the function $\psi = \varphi - \inf_M \varphi$, which satisfies $\Delta_G \psi = e^{-u} \Delta \psi > -C$, where $\Delta$ is the complex Laplacian with respect to $\omega$. In light of (2.16), once we bound the $L^1$ norm of $\psi$, the Main Theorem follows. Denoting by $\bar{\psi}$ the average of $\psi$ with respect to $\omega^n_G$, we obtain from the Poincaré inequality and (2.15) with $p = 1$
\[
(2.17) \quad \| \psi - \bar{\psi} \|_{L^2} \leq C \left( \int_M |\partial \psi|^2 \omega^n_G \right)^{1/2} \leq C \| \psi \|_{L^1}^{1/2}.
\]
In (2.17) and the following we are using $L^q$ norms with respect to the volume form $\omega^n_G$, which are equivalent to $L^q$ norms with respect to $d\mu$. Using (2.12), we see that the set $S := \{ \psi \leq C \}$ satisfies $|S| \geq \delta$ for a uniform $\delta > 0$, where $|\cdot|_G$ denotes the volume of a set with respect to $\omega^n_G$. Hence
\[
\delta \int_M \omega^n_G = \delta \leq \int_S \omega^n_G \leq \int_S (|\psi - \bar{\psi}| + C) \omega^n_G \leq \int_M (|\psi - \bar{\psi}| + C).
\]
Then,
\[
\| \psi \|_{L^1} \leq C(\| \psi - \bar{\psi} \|_{L^2} + 1) \leq C(\| \psi - \bar{\psi} \|_{L^1} + 1) \leq C(\| \psi \|_{L^2}^{1/2} + 1),
\]
which shows that $\psi$ is uniformly bounded in $L^1$. This completes the proof of the Main Theorem.

Finally we mention that Corollary 1 follows from the argument of Cherrier [Ch], which uses results from [De], or for another proof, see [TW, Corollary 1].

Acknowledgements

The authors thank S.-T. Yau for many useful discussions over the last few years on the complex Monge-Ampère equation. The authors also express their gratitude to D. H. Phong for his support, encouragement, and helpful suggestions. In addition the authors thank G. Székelyhidi for some helpful discussions.

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