



3.2

# ANNALES

DE

# L'INSTITUT FOURIER

Thomas BLOOM, Norman LEVENBERG & Yu. LYUBARSKII

**A Hilbert Lemniscate Theorem in  $\mathbb{C}^2$**

Tome 58, n° 6 (2008), p. 2191-2220.

[http://aif.cedram.org/item?id=AIF\\_2008\\_\\_58\\_6\\_2191\\_0](http://aif.cedram.org/item?id=AIF_2008__58_6_2191_0)

© Association des Annales de l'institut Fourier, 2008, tous droits réservés.

L'accès aux articles de la revue « Annales de l'institut Fourier » (<http://aif.cedram.org/>), implique l'accord avec les conditions générales d'utilisation (<http://aif.cedram.org/legal/>). Toute reproduction en tout ou partie cet article sous quelque forme que ce soit pour tout usage autre que l'utilisation à fin strictement personnelle du copiste est constitutive d'une infraction pénale. Toute copie ou impression de ce fichier doit contenir la présente mention de copyright.

cedram

*Article mis en ligne dans le cadre du*  
*Centre de diffusion des revues académiques de mathématiques*  
<http://www.cedram.org/>

## A HILBERT LEMNISCATE THEOREM IN $\mathbb{C}^2$

by Thomas BLOOM,  
Norman LEVENBERG & Yu. LYUBARSKII (\*)

---

ABSTRACT. — For a regular, compact, polynomially convex circled set  $K$  in  $\mathbb{C}^2$ , we construct a sequence of pairs  $\{P_n, Q_n\}$  of homogeneous polynomials in two variables with  $\deg P_n = \deg Q_n = n$  such that the sets  $K_n := \{(z, w) \in \mathbb{C}^2 : |P_n(z, w)| \leq 1, |Q_n(z, w)| \leq 1\}$  approximate  $K$  and if  $K$  is the closure of a strictly pseudoconvex domain the normalized counting measures associated to the finite set  $\{P_n = Q_n = 1\}$  converge to the pluripotential-theoretic Monge-Ampère measure for  $K$ . The key ingredient is an approximation theorem for subharmonic functions of logarithmic growth in one complex variable.

RÉSUMÉ. — Pour un compact  $K$  dans  $\mathbb{C}^2$ , régulier, pôlynomialement convexe et cerclé, on construit une suite de paires  $\{P_n, Q_n\}$  avec  $P_n, Q_n$  pôlynomes homogènes en deux variables et  $\deg P_n = \deg Q_n = n$  tel que les ensembles  $K_n := \{(z, w) \in \mathbb{C}^2 : |P_n(z, w)| \leq 1, |Q_n(z, w)| \leq 1\}$  font une approximation de  $K$  et quand  $K$  est la fermeture d'un domaine strictement pseudoconvexe les mesures de comptage normalisées associées à l'ensemble fini  $\{P_n = Q_n = 1\}$  tendent vers la mesure de Monge-Ampère pour  $K$ . L'élément principal est un théorème d'approximation pour les fonctions sousharmoniques de croissance logarithmique à une variable.

### 1. Introduction

Let  $K \subset \mathbb{C}$  be a compact set with connected complement. The *Hilbert lemniscate theorem* in one variable says that for such sets, given any  $\epsilon > 0$ , there exists a polynomial  $p$  with

(1.1)

$$K \subset \mathcal{K}_p := \{z : |p(z)| \leq \|p\|_K := \sup_{z \in K} |p(z)|\} \subset K^\epsilon := \{z : \text{dist}(z, K) \leq \epsilon\}.$$

---

*Keywords:* Logarithmic potential, Monge-Ampère measure, subharmonic functions, atomization.

*Math. classification:* 32U05, 32W20.

(\*) Supported in part by an NSERC grant (TB) and by the Norwegian Research Council project 160192/V30 (YuL).

The set  $\mathcal{K}_p$  is called a *lemniscate*. In general, given  $\epsilon > 0$ , one can take  $p$  to be a *Fekete polynomial* of sufficiently large degree. A Fekete polynomial of degree  $n$  for  $K$  is a monic polynomial  $F_n(z) = \prod_{j=1}^n (z - a_{nj})$  with  $a_{nj} \in K$  chosen so that

$$\prod_{j < k}^n |a_{nj} - a_{nk}| = \max_{z_1, \dots, z_n \in K} \prod_{j < k}^n |z_j - z_k|.$$

The condition that  $K$  have connected complement is equivalent to the *polynomial convexity* of  $K$ : this means that  $K = \hat{K}$  where

$$\hat{K} := \{z \in \mathbb{C} : |p(z)| \leq \|p\|_K := \sup_{\zeta \in K} |p(\zeta)| \text{ for all polynomials } p\}.$$

(Here and in the entire paper “polynomial” means *holomorphic* polynomial). We call  $K$  *regular* if the extremal function

$$(1.2) \quad V_K(z) := \max \left[ 0, \sup \left\{ \frac{1}{\deg p} \log |p(z)| : p \text{ polynomial, } \deg p \geq 1, \|p\|_K \leq 1 \right\} \right]$$

is continuous on  $\mathbb{C}$ . For the lemniscate  $\mathcal{K}_p$  in (1.1),

$$V_{\mathcal{K}}(z) = \max \left[ \frac{1}{\deg p} \log [|p(z)| / \|p\|_K], 0 \right].$$

If  $K$  is regular, in choosing, e.g., a sequence of Fekete polynomials  $\{F_n\}$ , the functions

$$(1.3) \quad \frac{1}{n} \log [|F_n(z)| / \|F_n\|_K] \rightarrow V_K(z)$$

locally uniformly outside of  $K$ . We also have the normalized counting measure of the zeros

$$(1.4) \quad \mu_n := \frac{1}{n} \sum_{j=1}^n \delta_{a_{nj}} \rightarrow \frac{1}{2\pi} \Delta V_K$$

weak-\* as measures. Here,  $\Delta V_K$ , the Laplacian of  $V_K$ , is to be interpreted as a positive distribution, i.e., a positive measure. Another example of a sequence of polynomials for which (1.3) and (1.4) hold is gotten by taking the interval  $K = [-1, 1]$  and the classical Chebyshev polynomials  $\{T_n\}$ . Here  $T_n(x) = \cos n(\arccos x)$  for  $x \in \mathbb{R}$ ;  $V_K(z) = \log |z + \sqrt{z^2 - 1}|$  and the normalized counting measure of the zeros approximate the arcsine distribution  $\frac{dx}{\sqrt{1-x^2}} = \Delta V_K$ .

In several complex variables, given a compact set  $K \subset \mathbb{C}^N$ ,  $N > 1$ , we can define the extremal function  $V_K$  as in (1.2) where  $p(z) = p(z_1, \dots, z_N)$  is a polynomial of the complex variables  $z_1, \dots, z_N$ . The definitions of regularity

and polynomial convexity are defined as in the one-variable case; however this latter definition is no longer equivalent to the complement of  $K$  being connected. It follows from the definition of  $V_K$  and  $\hat{K}$  that  $V_K = V_{\hat{K}}$  and that  $\hat{K} = \{z : V_K(z) = 0\}$  so that an assumption of polynomial convexity is a natural one. In this paper, we will prove a version of Hilbert’s lemniscate theorem for circled compact sets in  $\mathbb{C}^2$ , including a convergence of measures result in the spirit of (1.4).

To motivate this result, we note that in several complex variables, sublevel sets  $\{z : |p(z)| \leq M\}$  for a polynomial  $p$  are unbounded; in general, one needs at least  $N$  polynomials  $p_1, \dots, p_N$  to have hopes of a sublevel set  $\{z \in \mathbb{C}^N : |p_1(z)| \leq M_1, \dots, |p_N(z)| \leq M_N\}$  being compact. Moreover, the topology of such sublevel sets can be complicated. A *polynomial polyhedron* is a set  $P$  which is the closure of the union of a finite number of connected components of

$$\mathcal{P} := \{z \in \mathbb{C}^N : |p_1(z)| < 1, \dots, |p_m(z)| < 1\}$$

where  $p_1, \dots, p_m$  are polynomials. It is an easy exercise to see that given any *polynomially convex compact set*  $K \subset \mathbb{C}^N$ , and any open neighborhood  $\Omega$  of  $K$ , there exists a set of the form  $\mathcal{P}$  with  $K \subset \mathcal{P} \subset \Omega$  (cf. [11]). What is not at all obvious is a deep result of Bishop [4]: there exists a **special polynomial polyhedron**  $P$  with the same property. We call a polynomial polyhedron  $P \subset \mathbb{C}^N$  *special* if it can be defined by exactly  $N$  polynomials. We emphasize that not all components of  $\mathcal{P}$  need be included in  $P$ . It is known (cf. [13], Theorem 5.3.1) that if the set

$$\mathcal{P} := \{z \in \mathbb{C}^N : |p_1(z)| < 1, \dots, |p_N(z)| < 1\},$$

consisting of the union of all components of a special polynomial polyhedron defined by  $p_1, \dots, p_N$  with  $\deg p_1 = \dots = \deg p_N =: n$  is compact, and if  $(p_1, \dots, p_N) : \mathbb{C}^N \rightarrow \mathbb{C}^N$  is proper, then we have

$$V_{\mathcal{P}}(z) = \max\left[\frac{1}{n} \log |p_1(z)|, \dots, \frac{1}{n} \log |p_N(z)|, 0\right].$$

Thus, it will be helpful to know when a compact set  $K$  can be approximated not just by a special polynomial polyhedron  $P$ , but by the full component set  $\mathcal{P}$  of such an object. It turns out that if we work in  $\mathbb{C}^2$  with variables  $(z, w)$  and we assume, in addition to  $K = \hat{K}$ , that  $K \subset \mathbb{C}^2$  is *circled*; i.e.,  $z \in K$  if and only if  $e^{it}z \in K$ , then such an approximation is possible. Moreover, in this case, utilizing one-variable techniques, we can construct Bishop-type approximants which satisfy an analogue of (1.3) and (1.4).

THEOREM 1.1. — *Let  $K \subset \mathbb{C}^2$  be a regular, circled, polynomially convex compact set. Then there exists a sequence of pairs of homogeneous polynomials  $\{P_n, Q_n\}$ ,  $\deg P_n = \deg Q_n = n$  with no common linear factors such that*

$$\tilde{u}_n(z, w) := \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)|, 0 \right]$$

uniformly approximates  $V_K$  on  $\mathbb{C}^2$ ;

$$U_n(z, w) := \max \left[ \frac{1}{n} \log |P_n(z, w) - 1|, \frac{1}{n} \log |Q_n(z, w) - 1| \right]$$

locally uniformly approximates  $V_K$  on  $\mathbb{C}^2 \setminus \partial K$ ; and

$$(dd^c \tilde{u}_n)^2 \rightarrow (dd^c V_K)^2$$

weak-\* as measures in  $\mathbb{C}^2$ . Moreover, if  $K$  is the closure of a strictly pseudoconvex domain (e.g., a ball), then

$$(dd^c U_n)^2 \rightarrow (dd^c V_K)^2.$$

Here, for certain plurisubharmonic (psh) functions  $u$  in  $\mathbb{C}^2$ , the complex Monge-Ampère measure  $(dd^c u)^2$  associated to  $u$  is well-defined. We discuss this issue in section 4. In particular, for regular compact sets  $K \subset \mathbb{C}^2$ ,  $(dd^c V_K)^2$  plays a role analogous to  $\Delta V_K$  in one variable. In Theorem 1.1,

- the function  $\tilde{u}_n$  is the extremal function for the set

$$(1.5) \quad \mathcal{K}_n := \{(z, w) \in \mathbb{C}^2 : |P_n(z, w)| \leq 1, |Q_n(z, w)| \leq 1\};$$

- the Monge-Ampère measure  $(dd^c U_n)^2$  is supported on the finite point set (see section 4)

$$(1.6) \quad K_n := \{(z, w) : P_n(z, w) = Q_n(z, w) = 1\};$$

- the measures  $\{(dd^c \tilde{u}_n)^2\}_{n=1, \dots}$ ,  $\{(dd^c U_n)^2\}_{n=1, \dots}$  are supported in a fixed compact set in  $\mathbb{C}^2$ .

The distinction between the sequences  $\{\tilde{u}_n\}$  and  $\{U_n\}$  can easily be seen even in one variable: take  $K = \mathbb{D} := \{t \in \mathbb{C} : |t| \leq 1\}$ , the closed unit disk. Then  $V_{\mathbb{D}}(t) = \max[\log |t|, 0]$  and, taking  $p_n(t) = t^n$ , we have

$$\tilde{v}_n(t) := \max \left[ \frac{1}{n} \log |p_n(t)|, 0 \right] \equiv V_{\mathbb{D}}(t)$$

while

$$V_n(t) := \frac{1}{n} \log |p_n(t) - 1| = \frac{1}{n} \log |t^n - 1|$$

converges locally uniformly to  $V_{\mathbb{D}}$  in  $\mathbb{C} \setminus \{|t| = 1\}$  but we clearly do not have  $V_n \rightarrow V_{\mathbb{D}}$  pointwise, or even “in capacity” (cf. [17]) on the circle  $\{|t| = 1\}$ . However, we do have  $V_n \rightarrow V_{\mathbb{D}}$  in  $L^1_{\text{loc}}(\mathbb{C})$ . Thus, we can utilize elementary

distribution theory to conclude that the normalized counting measure of the zeros of these Fekete polynomials  $p_n(t)$  converge weak- $*$  to  $\Delta V_{\mathbb{D}}$ . Of course, in this example, the convergence of these measures is trivial (and, as mentioned earlier, always holds for Fekete polynomials). We discuss the analogous example of the unit bidisk in  $\mathbb{C}^2$  in section 4.

We prove the first part of Theorem 1.1 by reducing it to a one-variable approximation problem in section 2. Given a measure  $\mu$  in  $\mathbb{C}$  with  $\mu(\mathbb{C}) = 1$  consider its logarithmic potential

$$(1.7) \quad V(t) = \int_{\mathbb{C}} \log \left| 1 - \frac{t}{\zeta} \right| d\mu(\zeta).$$

We assume that

$$(1.8) \quad \lim_{|t| \rightarrow \infty} [V(t) - \log |t|] \text{ exists,}$$

$$(1.9) \quad \int_{\mathbb{C}} |\log |t|| d\mu(t) < \infty,$$

and that  $V(t)$  is continuous in  $\mathbb{C}$ . Under these assumptions, we will prove the following theorem, which is of interest in its own right, in section 3:

**THEOREM 1.2.** — *Given  $V$  satisfying (1.7), (1.8) and (1.9), for each  $\epsilon > 0$  there exist a number  $N$  and polynomials  $P(t)$  and  $Q(t)$  of degree  $N$  such that*

$$(1.10) \quad \left| V(t) - \frac{1}{N} \max\{\log |P(t)|, \log |Q(t)|\} \right| < \epsilon, \quad t \in \mathbb{C}.$$

The construction is based on techniques developed in [14]. There the authors construct an  $L^1$ -approximant to an arbitrary subharmonic function  $u$  in  $\mathbb{C}$  of the form  $\log |f|$  with a (single) entire function  $f$ . The proof utilizes a clever partition of  $\mathbb{C}$  related to the measure  $\mu$  and its support, due to Yulmukhametov [19]. The precise version of the result that we use in section 3 is labeled Lemma A. We remark that the genesis of Theorem 1.2 occurred during an Oberwolfach meeting attended by the second and third authors in February 2004.

In the final section of the paper, we turn to the proof of Monge-Ampère convergence, the second part of Theorem 1.1. For the sequence  $\{\tilde{u}_n\}$  this convergence is automatic; but for the sequence  $\{U_n\}$ , which is *not* locally bounded, a non-trivial argument is required. This is given as Theorem 4.3. We would like to thank Urban Cegrell for pointing out an error in our proof of this result in a previous version.

We remark that from Bishop’s theorem one can construct sequences of psh functions with the same properties as the sequence  $\{U_n\}$  in Theorem 1.1 for general regular, polynomially convex compact sets  $K \subset \mathbb{C}^N$  which are not necessarily circled. However, this work of Bishop is technically complicated and the construction may not yield psh functions which are the maximum of exactly  $N$  functions of the form  $c \log |p|$  where  $p$  is a polynomial. Our methods in constructing the polynomials in Theorem 1.1 are purely one-variable in nature and provide, via the sets  $\{K_n\}$  in (1.6), discrete approximations to the Monge-Ampère measure  $(dd^c V_K)^2$ .

We thank the referee for a careful reading of our paper.

### 2. Reduction to one-variable

For  $N = 1, 2, \dots$ , let

$$L(\mathbb{C}^N) := \{u \text{ psh in } \mathbb{C}^N : u(z) \leq \log^+ |z| + C\}$$

denote the class of psh functions of logarithmic growth on  $\mathbb{C}^N$  where the constant  $C$  can depend on  $u$ . For example, given a polynomial  $p$ ,  $u(z) := \frac{1}{\deg p} \log |p(z)| \in L(\mathbb{C}^N)$ . We also consider the class

$$L^+(\mathbb{C}^N) := \{u \in L(\mathbb{C}^N) : \log^+ |z| + C_1 \leq u(z) \leq \log^+ |z| + C_2, \text{ some } C_1, C_2\}.$$

Note functions in this class are locally bounded.

For a bounded Borel set  $E$  in  $\mathbb{C}^N$ , one can define

$$(2.1) \quad V_E(z) := \sup\{u(z) : u \in L(\mathbb{C}^N), u \leq 0 \text{ on } E\}.$$

The uppersemicontinuous (usc) regularization  $V_E^*(z) := \limsup_{\zeta \rightarrow z} V_E(\zeta)$  is called the global extremal function of  $E$ ; either  $V_E^* \equiv +\infty$  – this occurs precisely when  $E$  is pluripolar; i.e.,  $E \subset \{u = -\infty\}$  for some  $u \neq -\infty$  psh on a neighborhood of  $E$  – or else  $V_E^* \in L^+(\mathbb{C}^N)$ . It is well-known that if  $E$  is a compact set in  $\mathbb{C}^N$ , then  $V_E$  defined in (2.1) coincides with  $V_E$  in formula (1.1) (cf. [13] Theorem 5.1.7) and hence  $V_E$  is lowersemicontinuous. Thus for compact sets  $E$ ,  $E$  is regular if and only if  $V_E = V_E^*$ .

As well as the classes  $L(\mathbb{C}^N)$  and  $L^+(\mathbb{C}^N)$ , we will consider the class

$$H(\mathbb{C}^N) := \{u \in L(\mathbb{C}^N) : u(\lambda z) = u(z) + \log |\lambda| \text{ for } \lambda \in \mathbb{C}, z \in \mathbb{C}^N\}$$

of logarithmically homogeneous psh functions.

Given  $u : \mathbb{C}^N \rightarrow \mathbb{R}$  in  $L(\mathbb{C}^N)$  we define the Robin function of  $u$  to be

$$\rho_u(z) := \limsup_{|\lambda| \rightarrow \infty} [u(\lambda z) - \log |\lambda|].$$

Note that for  $\lambda \in \mathbb{C}$ ,  $\rho_u(\lambda z) = \log |\lambda| + \rho_u(z)$ ; i.e.,  $\rho_u$  is logarithmically homogeneous. It is known (cf. [6], Proposition 2.1) that for  $u \in L(\mathbb{C}^N)$ , the Robin function  $\rho_u(z)$  is plurisubharmonic in  $\mathbb{C}^N$ ; indeed, either  $\rho_u \in H(\mathbb{C}^N)$  or  $\rho_u \equiv -\infty$ . As an example, if  $p$  is a polynomial of degree  $d$  so that  $u(z) := \frac{1}{d} \log |p(z)| \in L(\mathbb{C}^N)$ , then  $\rho_u(z) = \frac{1}{d} \log |\hat{p}(z)|$  where  $\hat{p}$  is the top degree ( $d$ ) homogeneous part of  $p$ . For a compact set  $K$ , we denote by  $\rho_K$  the Robin function of  $V_K^*$ ; i.e.,  $\rho_K := \rho_{V_K^*}$ .

Suppose now that  $K$  is circled; i.e.,  $z \in K$  if and only if  $e^{it}z \in K$ . Then the extremal function  $V_K$  in (1.1) can be gotten via

$$\begin{aligned} V_K(z) &= \max[0, \sup\{u(z) : u \in H(\mathbb{C}^N), u \leq 0 \text{ on } K\}] \\ &= \max[0, \sup\{\frac{1}{\deg p} \log |p(z)| : p \text{ homogeneous polynomial, } \|p\|_K \leq 1\}] \end{aligned}$$

(cf. [13], Theorem 5.1.6). Moreover, we have the following.

LEMMA 2.1. — *Let  $K \subset \mathbb{C}^N$  be compact, circled, and nonpluripolar. Then*

$$(2.2) \quad V_K^*(z) = \max[0, \rho_K(z)]$$

and

$$(2.3) \quad \text{supp}(dd^c V_K^*)^N \subset \{\rho_K = 0\}.$$

*Proof.* — Equation (2.2) follows from the above equation for  $V_K$ , which shows that  $V_K^*(\lambda z) = V_K^*(z) + \log |\lambda|$  provided  $z, \lambda z \notin \hat{K}$ , and the definition of  $\rho_K$ : if  $V_K^*(z) > 0$ , then

$$\begin{aligned} \rho_K(z) &:= \limsup_{|\lambda| \rightarrow \infty} [V_K^*(\lambda z) - \log |\lambda|] \\ &= \limsup_{|\lambda| \rightarrow \infty} [V_K^*(z) + \log |\lambda| - \log |\lambda|] = V_K^*(z). \end{aligned}$$

We have  $\rho_K \in H(\mathbb{C}^N)$  and  $\rho_K(z) = V_K^*(z)$  if  $V_K^*(z) > 0$ ; since the set  $\{z \in \mathbb{C}^N : \rho_K(z) \leq 0\}$  differs from  $\hat{K} = \{z \in \mathbb{C}^N : V_K(z) = 0\}$  by at most a pluripolar set, (2.2) follows (cf. Corollary 5.2.5 [13]). The Robin function  $\rho_K$  is locally bounded away from the origin which implies, by the logarithmic homogeneity, that  $(dd^c \rho_K)^N = 0$  on  $\mathbb{C}^N \setminus \{0\}$  (see section 4 for a discussion of the complex Monge-Ampère operator). This gives (2.3).  $\square$

Let  $u \in L(\mathbb{C})$  and  $d\mu(t) = \frac{i}{4\pi} \Delta u(t) dt \wedge d\bar{t}$  be its Riesz measure. Jensen's formula yields that  $\mu(\mathbb{C}) := \int_{\mathbb{C}} d\mu(t) \leq 1$ . If, in addition,  $u(0) = 0$ , we have

$$u(t) = \int_{\mathbb{C}} \log |1 - \frac{t}{\zeta}| d\mu(\zeta)$$



([15], p. 37). In the notation introduced in this section, Theorem 1.2 yields the following version of a one-variable approximation result:

**THEOREM 2.2.** — *Let  $u \in L^+(\mathbb{C}) \cap C(\mathbb{C})$  with the additional property that*

$$\lim_{|t| \rightarrow \infty} [u(t) - \log |t|]$$

*exists. Given  $\epsilon > 0$ , there exist polynomials  $p_n, q_n$  of degree  $n = n(\epsilon)$  with*

$$(2.4) \quad u(t) - \epsilon \leq \max \left[ \frac{1}{n} \log |p_n(t)|, \frac{1}{n} \log |q_n(t)| \right] \leq u(t), \quad t \in \mathbb{C}.$$

Note that  $u \in L^+(\mathbb{C})$  implies (1.9) and that (2.4) implies that  $p_n$  and  $q_n$  have no common zeros; this latter fact will also follow from the proof of the theorem. This immediately gives an approximation result for the class  $H(\mathbb{C}^2)$  of logarithmically homogeneous psh functions in  $\mathbb{C}^2$ .

**COROLLARY 2.3.** — *Let  $U \in H(\mathbb{C}^2)$  be logarithmically homogeneous with the additional property that  $u(t) := U(1, t)$  satisfies the hypotheses of the previous theorem. Given  $\epsilon > 0$ , there exist homogeneous polynomials  $P_n, Q_n$  of degree  $n = n(\epsilon)$  with no common factors such that*

$$(2.5) \quad U(z, w) - \epsilon \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)| \right] \leq U(z, w),$$

$$(z, w) \in \mathbb{C}^2.$$

*Proof.* — If (2.4) holds, define

$$P_n(z, w) := z^n p_n(w/z) \text{ and } Q_n(z, w) := z^n q_n(w/z).$$

Note that if  $p_n, q_n$  are of degree exactly  $n$ ; i.e., if

$$p_n(t) = a_0 + a_1 t + \dots + a_n t^n \text{ and } q_n(t) = b_0 + b_1 t + \dots + b_n t^n$$

with  $a_n b_n \neq 0$ , then  $P_n(0, w) = a_n w^n$  and  $Q_n(0, w) = b_n w^n$ . Otherwise, we may have  $P_n(0, w) \equiv 0$  and/or  $Q_n(0, w) \equiv 0$ . Then, since  $U(1, w/z) + \log |z| = U(z, w)$  for  $z \neq 0$ , (2.4) implies

$$U(z, w) - \epsilon \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)| \right] \leq U(z, w)$$

for  $z \neq 0$ . But  $U$  is subharmonic on  $z = 0$  so

$$U(0, w) = \limsup_{z \rightarrow 0} U(z, w);$$

together with the previous inequalities, this yields (2.5) for all  $(z, w) \in \mathbb{C}^2$ . □

For a regular compact set  $K \subset \mathbb{C}^N$ , it is known that the Robin function  $\rho_K$  is continuous on  $\mathbb{C}^N \setminus \{0\}$  (cf. [6]). Thus, if  $N = 2$ ,  $\rho_K(1, t) \in L^+(\mathbb{C}) \cap C(\mathbb{C})$  and

$$\lim_{|t| \rightarrow \infty} [\rho_K(1, t) - \log |t|] = \lim_{|t| \rightarrow \infty} \rho_K(1/t, 1) = \rho_K(0, 1).$$

We can apply the corollary to  $\rho_K$  to find homogeneous polynomials  $P_n, Q_n$  with

$$(2.6) \quad \rho_K(z, w) - \epsilon \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)| \right] \leq \rho_K(z, w).$$

To prove the first part of Theorem 1.1, for a regular circled set  $K \subset \mathbb{C}^2$ , using (2.2) from Lemma 2.1 and (2.6), we have

$$(2.7) \quad V_K(z, w) - \epsilon \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)|, 0 \right] \leq V_K(z, w).$$

This gives uniform convergence of

$$\tilde{u}_n(z, w) := \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)|, 0 \right] \rightarrow V_K(z, w)$$

in Theorem 1.1.

For regular circled sets  $K \subset \mathbb{C}^2$ , (2.3) of Lemma 2.1 implies that

$$\text{supp}(dd^c V_K)^2 \subset \{(z, w) : \rho_K(z, w) = 0\}.$$

We now show using (2.6) and (2.7) that

$$(2.8) \quad U_n(z, w) := \max \left[ \frac{1}{n} \log |P_n(z, w) - 1|, \frac{1}{n} \log |Q_n(z, w) - 1| \right] \rightarrow V_K(z, w)$$

locally uniformly on  $\mathbb{C}^2 \setminus \{\rho_K = 0\}$ .

To prove (2.8), we observe from the inequality  $|A - B| \leq 2 \max[|A|, |B|]$  we have

$$(2.9) \quad U_n(z, w) \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)|, 0 \right] + \frac{\log 2}{n}.$$

Now on a compact set  $E \subset \mathbb{C}^2 \setminus \{\rho_K \leq 0\}$ , by (2.7), given  $\epsilon > 0$  with  $2\epsilon < \inf_E V_K$ , for  $n > n_0(\epsilon)$ ,

$$\max[|P_n(z, w)|, |Q_n(z, w)|] > \exp[n(V_K(z, w) - \epsilon)] \text{ on } E.$$

By choosing  $n_0(\epsilon)$  larger, if necessary, we may assume

$$\exp[n(V_K(z, w) - \epsilon)] - 1 > \exp[n(V_K(z, w) - 2\epsilon)] \text{ on } E$$

so that

$$\max[|P_n(z, w) - 1|, |Q_n(z, w) - 1|] > \exp[n(V_K(z, w) - 2\epsilon)] \text{ on } E.$$

Together with (2.7) and (2.9), this proves local uniform convergence outside of  $\{\rho_K \leq 0\}$ . On compact subsets of  $\{\rho_K < 0\}$ , the story is similar due to the logarithmic homogeneity of  $\rho_K$ ,  $\frac{1}{n} \log |P_n(z, w)|$ , and  $\frac{1}{n} \log |Q_n(z, w)|$  and (2.6): for  $r > 0$ , if  $E := \{z \in K : \rho_K(z) < -r\}$ , by (2.6),

$$\max[|P_n(z, w)|, |Q_n(z, w)|] < \exp(-nr) \text{ on } E.$$

Thus,  $|P_n(z, w) - 1|, |Q_n(z, w) - 1| > 1 - \exp(-nr)$  on  $E$ . We conclude that

$$\max\left[\frac{1}{n} \log |P_n(z, w) - 1|, \frac{1}{n} \log |Q_n(z, w) - 1|\right] > \frac{1}{n} \log [1 - \exp(-nr)]$$

on  $E$ .

Hence  $U_n \rightarrow 0$  uniformly on  $E$ .

Note that since we assume that  $K$  is polynomially convex and circled, we have that

$$(2.10) \quad \partial K = \{(z, w) : \rho_K(z, w) = 0\}.$$

Here is an illustrative example of the reduction scheme: let  $K = \{(z, w) \in \mathbb{C}^2 : |z|^2 + |w|^2 \leq 1\}$  be the closed unit ball in  $\mathbb{C}^2$ . Then  $V_K(z, w) = \log^+ (|z|^2 + |w|^2)^{1/2}$  and  $\rho_K(z, w) = \log (|z|^2 + |w|^2)^{1/2}$  so that  $\rho_K(1, t) = \frac{1}{2} \log (1 + |t|^2)$ . Note that the support of  $\Delta\rho_K(1, t)$  is all of  $\mathbb{C}$ , but that

$$\int_{\mathbb{C}} |\log |t|| \Delta\rho_K(1, t) < +\infty.$$

Thus, Theorem 2.2 provides a uniform approximation of the strictly subharmonic function  $\frac{1}{2} \log (1 + |t|^2)$  by a function of the form

$$\max\left[\frac{1}{n} \log |p_n(t)|, \frac{1}{n} \log |q_n(t)|\right].$$

To summarize: using the results of this section, in order to complete the proof of the first part of Theorem 1.1, it remains to prove the one-variable approximation result, Theorem 1.2.

### 3. Main approximation result

In this section, we prove Theorem 1.2. We work exclusively in the complex plane  $\mathbb{C}$  with variable  $z$ . Recall that  $V(z)$  is the logarithmic potential of a probability measure  $\mu$ ;  $V$  is continuous in  $\mathbb{C}$ ;  $\lim_{|t| \rightarrow \infty} [V(t) - \log |t|]$  exists; and  $\int_{\mathbb{C}} |\log |t|| d\mu(t) < \infty$ .

In order to prove the theorem we shall prove the following result:

CLAIM 3.1. — For each  $\epsilon > 0$  there exists a number  $N$ , polynomials  $P(z)$  and  $Q(z)$  of degree  $N$ , and sets  $E, F \subset \mathbb{C}$ ,  $E \cap F = \emptyset$  such that

$$\begin{aligned}
 &|V(z) - \frac{1}{N} \log |P(z)|| < \epsilon, \quad z \in \mathbb{C} \setminus E, \\
 (3.1) \quad &V(z) + \epsilon > \frac{1}{N} \log |P(z)|, \quad z \in E,
 \end{aligned}$$

and

$$\begin{aligned}
 &|V(z) - \frac{1}{N} \log |Q(z)|| < \epsilon, \quad z \in \mathbb{C} \setminus F, \\
 (3.2) \quad &V(z) + \epsilon > \frac{1}{N} \log |Q(z)|, \quad z \in F.
 \end{aligned}$$

### 3.1. Pattern of the proof

Step 1: It follows from (1.8) and also from continuity of  $V$  that  $V$  is uniformly continuous in  $\mathbb{C}$ . Convolving if need be with an appropriate bump function one may assume that  $\mu$  has the form

$$(3.3) \quad d\mu(z) = a(z)d\sigma(z),$$

where  $\sigma$  is Lebesgue measure and  $a \geq 0$  is a smooth function in  $\mathbb{C}$ . It follows from (1.9) that

$$a(z) \rightarrow 0 \quad \text{as} \quad |z| \rightarrow \infty.$$

Define

$$(3.4) \quad A := \max_{z \in \mathbb{C}} a(z).$$

Step 2: We reduce the problem to the case when  $\mu$  has compact support. Given a number  $R > 0$  we let  $Q_R$  denote the square

$$Q_R = \{z = x + iy; |x|, |y| < R\}.$$

Given  $\eta > 0$  we find an integer  $M$  and a number  $R$  so that

$$(3.5) \quad \int_{\mathbb{C} \setminus Q_R} |\log |\zeta|| d\mu(\zeta) < \eta,$$

$$(3.6) \quad \mu(\mathbb{C} \setminus Q_R) = 1/M < \eta,$$

and

$$(3.7) \quad \max_{|z| > R/3} a(z) \leq \eta.$$

Denote the logarithmic potential from the portion of  $\mu$  outside  $Q_R$  by

$$V_\infty(z) := \int_{\mathbb{C} \setminus Q_R} \log \left| 1 - \frac{z}{\zeta} \right| d\mu(\zeta).$$

Finally, set

$$(3.8) \quad \frac{1}{M} \log r_\infty := \int_{\mathbb{C} \setminus Q_R} \log |\zeta| d\mu(\zeta).$$

Note that  $r_\infty > R$ .

LEMMA 3.2. — *Let*

$$(3.9) \quad w_\infty \in \mathbb{C}, \quad |w_\infty| = 10r_\infty.$$

Then

$$\left| V_\infty(z) - \frac{1}{M} \log \left| 1 - \frac{z}{w_\infty} \right| \right| \leq C_1 \eta, \quad z \notin E_{w_\infty},$$

and

$$(3.10) \quad \frac{1}{M} \log \left| 1 - \frac{z}{w_\infty} \right| \leq V_\infty(z) + C_2 \eta, \quad z \in E_{w_\infty},$$

where  $C_1, C_2$  are constants independent of  $w_\infty$  and

$$E_{w_\infty} = \left\{ z : |z - w_\infty| < \frac{1}{20} |w_\infty| \right\}.$$

*Remarks.* — **1.** It is clear that  $E_{w_\infty} \cap Q_R = \emptyset$  and also that it is possible to choose two different points  $w'_\infty$  and  $w''_\infty$  satisfying (3.9) so that  $E_{w'_\infty} \cap E_{w''_\infty} = \emptyset$ .

**2.** The values of the constants in this lemma depend upon  $A$ .

**3.** We use the notation  $a \prec b$  to mean  $a \leq Cb$  with  $C$  a constant independent of all parameters except perhaps  $A$  and  $a \asymp b$  to mean  $a \prec b$  and  $b \prec a$ .

*Step 3.* Define

$$V_0(z) := \int_{Q_R} \log |z - \zeta| d\mu(\zeta).$$

Given Lemma 3.2, it remains to approximate  $V_0$  by a function which has the form  $\frac{1}{n} \log |P_N(z)|$ , where  $P_N$  is a polynomial of degree  $N$ . In order to construct this approximation we need a special partition of  $Q_R$ . Existence of the desired partitions is ensured by a lemma due to R. Yulmuhametov [19], see also [10]. We state this result in a form which is adjusted to our situation. Let  $\hat{\mu}$  denote the restriction of  $\mu$  to  $Q_R$ . We have  $\hat{\mu}(Q_R) = (M-1)/M$ . Given an integer  $k$  we split  $Q_R$  into  $k(M-1)$  pieces each of measure  $1/Mk$ .

LEMMA A. — Given an integer  $k > 0$ , there exists a covering of  $Q_R$

$$Q_R = \cup_{l=1}^{(k-1)M} Q^{(l)},$$

and  $\hat{\mu}$ ,

$$\hat{\mu} = \sum_{l=1}^{(k-1)M} \mu^{(l)},$$

with the following properties:

- Each  $Q^{(l)}$  is a rectangle with sides parallel to the coordinate axes such that the ratio of longest to shortest side does not exceed 3;
- each point in  $Q_R$  belongs to at most four distinct rectangles  $Q^{(l)}$ ;
- $\text{supp } \mu^{(l)} \subset Q^{(l)}$ ;
- 

$$(3.11) \quad \mu^{(l)}(Q^{(l)}) = \frac{1}{kM}.$$

Fix such a partition. We look for a polynomial  $P_k$  of degree  $N := k(M-1)$  of the form

$$P_k(z) = \prod_{l=1}^N (z - \zeta^{(l)}),$$

where the choice of the points  $\{\zeta^{(l)}\}_1^{k(M-1)} \subset Q_R$  is related to the partition.

Let  $d(l) := \text{diam}(Q^{(l)})$ . We then have  $\text{Area}(Q^{(l)}) \asymp d(l)^2$ . In choosing the points  $\{\zeta^{(l)}\}_1^{k(M-1)}$ , we first observe that, by (3.3) and (3.4),  $d(l)$  cannot be too small:

$$(3.12) \quad d(l) \geq \frac{1}{3(MA)^{1/2}} \frac{1}{k^{1/2}}.$$

We split the set of indices into two subsets:

$$(3.13) \quad \mathcal{I}_k = \left\{ l : 1 \leq l \leq N, d(l) \leq k^{1/3} \frac{1}{3(MA)^{1/2}} \frac{1}{k^{1/2}} \right\}, \quad \mathcal{J}_k = \{1, 2, \dots, N\} \setminus \mathcal{I}_k.$$

We say that  $Q^{(l)}$  is a *normal* rectangle if  $l \in \mathcal{I}_k$ . For such rectangles we set

$$(3.14) \quad \zeta_0^{(l)} = kM \int_{Q^{(l)}} \zeta d\mu^{(l)}(\zeta),$$

the center of mass of  $\mu^{(l)}$  in  $Q^{(l)}$ , and then take

$$\zeta^{(l)} := \zeta_0^{(l)} + \delta^{(l)} \in Q^{(l)}$$

where  $\delta^{(l)}$  are any complex numbers satisfying

$$(3.15) \quad |\delta^{(l)}| \leq k^{-5}.$$

For  $l \in \mathcal{J}_k$  we let  $\zeta^{(l)} \in Q^{(l)}$  be any points of  $Q_R$  with the property that

$$|\zeta^{(l)} - \zeta^{(m)}| > k^{-5}, \quad l, m \in \mathcal{J}_k, \quad l \neq m.$$

The choice of  $\zeta^{(l)}$ 's is related to the integer  $k$  and to the corresponding partition; hence we write

$$Z_k := \{\zeta^{(l)}\}_1^N, \quad E_k = \{z \in \mathbb{C}; \text{dist}(z, Z_k) < k^{-10}\}.$$

*Step 4:* We approximate the finite potential  $V_0$ .

LEMMA 3.3. — *For each  $\eta > 0$  one can choose  $k$  large enough so that  $|V_0(z) - \frac{1}{kM} \log |P_k(z)|| < \eta, z \notin E_k; V_0(z) + \eta > \frac{1}{kM} \log |P_k(z)|, z \in E_k.$*

Together with Lemma 3.2 this statement immediately yields the Claim since it allows us to choose two polynomials of the form

$$\left(1 - \frac{z}{w'_\infty}\right)^k P_k(z) \text{ and } \left(1 - \frac{z}{w''_\infty}\right)^k Q_k(z)$$

such that the corresponding exceptional sets are disjoint.

We now give the proofs of lemmas 3.2 and 3.3. We begin with the atomization of the external part of the potential,  $V_\infty$ ; i.e., we prove Lemma 3.2.

### 3.2. Proof of Lemma 3.2

The quantity to be estimated

$$D_\infty(z) = V_\infty(z) - \frac{1}{M} \log \left|1 - \frac{z}{w_\infty}\right|,$$

admits two representations:

$$(3.16) \quad D_\infty(z) = \int_{\mathbb{C} \setminus Q_R} \left( \log \left|1 - \frac{z}{\zeta}\right| - \log \left|1 - \frac{z}{w_\infty}\right| \right) d\mu(\zeta);$$

and also

$$(3.17) \quad \begin{aligned} D_\infty(z) &= \int_{\mathbb{C} \setminus Q_R} (\log |z - \zeta| - \log |z - w_\infty|) d\mu(\zeta) + \frac{\log 10}{M} \\ &= \int_{\mathbb{C} \setminus Q_R} \log \left|1 + \frac{w_\infty - \zeta}{z - w_\infty}\right| d\mu(\zeta) + \frac{\log 10}{M}. \end{aligned}$$

The term  $\frac{\log 10}{M}$  does not exceed  $\eta \log 10$  and does not influence our estimates. We consider the following cases:

**Case 1:**  $|z| \leq R/2$ .

In this case it suffices to use the representation (3.16) and note that for  $\zeta \notin Q_R$ ,

$$\log 1/2 \leq \log \left| 1 - \frac{z}{\zeta} \right|, \log \left| 1 - \frac{z}{w_\infty} \right| \leq \log 3/2.$$

**Case 2:**  $R/2 \leq |z| \leq 3|w_\infty|$ .

Note that the set  $E_{w_\infty}$  is contained in this annulus. We still use the representation (3.16) and estimate each summand independently. We have

$$\begin{aligned} & \int_{\mathbb{C} \setminus Q_R} \log \left| 1 - \frac{z}{\zeta} \right| d\mu(\zeta) \\ &= \left( \int_{\zeta \in \mathbb{C} \setminus Q_R, |\zeta| < 4|w_\infty|} + \int_{|\zeta| > 4|w_\infty|} \right) \log \left| 1 - \frac{z}{\zeta} \right| d\mu(\zeta) = S_1(z) + S_2(z). \end{aligned}$$

We then have

$$\begin{aligned} S_1(z) &= \int_{\zeta \in \mathbb{C} \setminus Q_R, |\zeta| < 4|w_\infty|} \log |z - \zeta| d\mu(\zeta) - \int_{\zeta \in \mathbb{C} \setminus Q_R, |\zeta| < 4|w_\infty|} \log |\zeta| d\mu(\zeta) \\ &= S_{11}(z) + S_{12}. \end{aligned}$$

Note that  $S_{12}$  is independent of  $z$ ; from (3.5),  $|S_{12}| \prec \eta$ . In order to estimate  $S_{11}(z)$  we mention that according to (3.3) and (3.5)

$$\int_{|z-\zeta| < 1} \log |z - \zeta| d\mu(\zeta) \asymp \eta;$$

this is used for (3.10). In the rest of the set  $\{\zeta \in \mathbb{C} \setminus Q_R, |\zeta| < 4|w_\infty|\}$  we have

$$0 < \log |z - \zeta| < 10 \log r_\infty.$$

Using (3.8) and (3.6) we have  $|S_{11}| \asymp \eta$ .

When estimating  $S_2(z)$  it suffices to observe that, since  $|z|/|\zeta| \leq 3/4$ , the integrand is bounded and then apply (3.6).

**Case 3:**  $|z| \geq 3|w_\infty|$ .

We now use (3.17). We have

$$\begin{aligned} D_\infty(z) &= \left( \int_{\zeta \notin Q_R, |\zeta| < 2|w_\infty|} + \int_{2|w_\infty| < |\zeta| < 4|z|} + \int_{4|z| < |\zeta|} \right) \\ & \quad \log \left| 1 + \frac{w_\infty - \zeta}{z - w_\infty} \right| d\mu(\zeta) + \frac{\log 10}{M} \\ &= T_1(z) + T_2(z) + T_3(z) + \frac{\log 10}{M}. \end{aligned}$$

We have  $|T_1| \asymp 1/M$  since the integrand is bounded. When estimating  $T_2$  we observe that the integrand is bounded from above throughout the whole



region of integration thus it suffices to estimate the integral over the region  $|z - \zeta| < |z|/5$ , say, in which the integrand is not bounded from below. In this domain we have

$$\int_{|z-\zeta|<|z|/5} \log \left| 1 + \frac{w_\infty - \zeta}{z - w_\infty} \right| d\mu(\zeta) = \int_{|z-\zeta|<|z|/5} \log |z - \zeta| d\mu(\zeta) - \int_{|z-\zeta|<|z|/5} \log |z - w_\infty| d\mu(\zeta).$$

The estimate of the right hand side is similar to that of  $S_1(z)$ . Precisely, to get an *upper bound* on  $\int_{|z-\zeta|<|z|/5} \log |z - w_\infty| d\mu(\zeta)$ , since  $|z| \geq 3|w_\infty|$  and  $|z - \zeta| < |z|/5$ , we have  $|z - w_\infty| \leq 4|z|/3$  and  $4|z|/5 \leq |\zeta| \leq 6|z|/5$ . Hence

$$\int_{|z-\zeta|<|z|/5} \log |z - w_\infty| d\mu(\zeta) \leq \int_{|z-\zeta|<|z|/5} \log(4|z|/3) d\mu(\zeta) \leq \int_{|z-\zeta|<|z|/5} \log(5|\zeta|/3) d\mu(\zeta).$$

From (3.5) and (3.6),  $\int_{|z-\zeta|<|z|/5} \log(5|\zeta|/3) d\mu(\zeta) \asymp \eta$ . For the other integral,

$$\left| \int_{|z-\zeta|<|z|/5} \log |z - \zeta| d\mu(\zeta) \right| \prec \eta$$

from (3.3) and (3.7).

The estimate of  $T_3$  is also straightforward; we use  $|z - w_\infty| > \sqrt{2}|w_\infty|$  and  $|\zeta| > 12|w_\infty|$  to obtain

$$0 \leq T_3(z) = \int_{|\zeta|>4|z|} \log \left| \frac{z - \zeta}{z - w_\infty} \right| d\mu(\zeta) \leq \int_{|\zeta|>4|z|} \log \frac{5}{8} \frac{|\zeta|}{|w_\infty|} d\mu(\zeta),$$

and apply (3.5).

### 3.3. Proof of Lemma 3.3

We turn to the atomization of the potential  $V_0$ .

We split the proof into several steps.

a. Write

$$D_0(z) := V_0(z) - \frac{1}{kM} \log |P_k(z)| = \sum_{l=1}^N \underbrace{\int_{Q^{(l)}} (\log |z - \zeta| - \log |z - \zeta^{(l)}|) d\mu^{(l)}(\zeta)}_{j_l(z)}.$$

We will estimate the contributions from  $j_l$ 's for  $l \in \mathcal{I}_k$  and  $l \in \mathcal{J}_k$  separately. The general estimate in **b.** will be used in **c.**

**b.** *Estimation of  $j_l(z)$ : Assume  $z \notin Q^{(l)}$ .*

Then

$$j_l(z) = \Re \int_{Q^{(l)}} (L(\zeta) - L(\zeta^{(l)})) d\mu^{(l)}(\zeta)$$

with

$$L(\zeta) = \log(z - \zeta).$$

Using the Taylor expansion

$$\begin{aligned} L(\zeta) - L(\zeta^{(l)}) &= L'(\zeta^{(l)})(\zeta - \zeta^{(l)}) + \int_{\zeta^{(l)}}^{\zeta} L''(s)(\zeta - s) ds \\ &= L'(\zeta^{(l)})(\zeta - \zeta_0^{(l)}) - L'(\zeta^{(l)})\delta^{(l)} + \int_{\zeta^{(l)}}^{\zeta} L''(s)(\zeta - s) ds \end{aligned}$$

as well as (3.14) and (3.11) we obtain

$$j_l(z) = \Re \left( \frac{\delta^{(l)}}{Mk} \frac{1}{z - \zeta^{(l)}} + \int_{Q^{(l)}} \int_{\zeta^{(l)}}^{\zeta} \frac{\zeta - s}{(z - s)^2} ds d\mu^{(l)}(\zeta) \right).$$

Taking (3.15) into account we obtain

$$(3.18) \quad |j_l(z)| \leq \frac{1}{Mk^6} \frac{1}{\text{dist}(z, Q^{(l)})} + \frac{1}{kM} \frac{d(l)^2}{\text{dist}(z, Q^{(l)})^2}.$$

**c.** *Contribution from remote normal rectangles.*

Consider

$$(3.19) \quad l \in \mathcal{I}_k \quad \text{with} \quad \text{dist}(z, Q^{(l)}) > 3k^{-1/2}.$$

It follows from the definition of normal rectangle in (3.13) and  $l \in \mathcal{I}_k$  that

$$|s - z| \prec k^{1/3} \text{dist}(z, Q^{(l)})$$

for all  $s \in Q^{(l)}$ . Combining this with (3.18), integrating with respect to Lebesgue measure  $\sigma$  over  $Q^{(l)}$ , and recalling that  $\text{Area}(Q^{(l)}) \asymp d(l)^2$ , we obtain

$$|j_l(z)| \prec \frac{k^{1/3}}{k^5} \int_{Q^{(l)}} \frac{d\sigma(s)}{|s - z|} + \frac{k^{2/3}}{k} \int_{Q^{(l)}} \frac{d\sigma(s)}{|s - z|^2}.$$

Therefore

$$\begin{aligned} \sum_{l \in \mathcal{I}_k, \text{dist}(z, Q^{(l)}) > 3k^{-1/2}} |j_l(z)| &\prec k^{-14/3} \int_{|s-z| > 3k^{-1/2}, |s| < 2R} \frac{d\sigma(s)}{|s - z|} \\ &\quad + \frac{k^{2/3}}{k} \int_{|s-z| > 3k^{-1/2}, |s| < 2R} \frac{d\sigma(s)}{|s - z|^2}. \end{aligned}$$

We have, uniformly with respect to  $z \in \mathbb{C}$ :

$$\int_{|s-z|>3k^{-1/2}, |s|<R} \frac{d\sigma(z)}{|s-z|^2} < \int_{1>|s-z|>3k^{-1/2}} \frac{d\sigma(z)}{|s-z|^2} + 4\pi R^2 = O(\log k),$$

$k \rightarrow \infty,$

and similarly

$$\int_{|s-z|>3k^{-1/2}, |s|<R} \frac{d\sigma(z)}{|s-z|} = O(1), \quad k \rightarrow \infty.$$

Therefore

$$\sum_{l \in \mathcal{I}_k, \text{dist}(z, Q^{(l)}) > 3k^{-1/2}} |j_l(z)| \prec k^{-1/3} \log k \rightarrow 0 \text{ as } k \rightarrow \infty.$$

Thus choosing  $k$  large enough we can make the contribution from the remote normal rectangles; *i.e.*, those satisfying (3.19), arbitrarily small.

**d. Contribution from normal rectangles which are close to  $z$ .**

Set

$$\mathcal{B}_k(z) := \{l \in \mathcal{I}_k : \text{dist}(z, Q^{(l)}) < 3k^{-1/2}\}.$$

In this section we estimate

$$\sum_{l \in \mathcal{B}_k(z)} j_l(z).$$

It follows from the construction that the total number of indices in  $\mathcal{B}_k(z)$  is bounded by some constant independent of  $z$  and  $k$  and also, from the definition of normal rectangle, that all the rectangles  $Q^{(l)}$ ,  $l \in \mathcal{B}_k(z)$  are contained in the disk  $\{|\zeta - z| \leq Ck^{-1/6}\}$ ,  $C$  being independent of  $z$  and  $k$ . Let  $\zeta^{(m)}$  be the point nearest to  $z$  among all  $\{\zeta^{(l)}\}_{l \in \mathcal{B}_k(z)}$ . We then have, using (3.3) and (3.4),

$$\sum_{l \in \mathcal{B}_k(z)} |j_l(z)| \prec \int_{\{|\zeta-z| \leq Ck^{-1/6}\}} |\log |z - \zeta|| d\sigma(\zeta) + |\log |z - \zeta^{(m)}|| \int_{\{|\zeta-z| \leq Ck^{-1/6}\}} d\sigma(\zeta).$$

Assuming now that  $z \notin E_k$  (*i.e.*,  $|z - \zeta^{(m)}| > k^{-10}$ ) we obtain

$$\sum_{l \in \mathcal{B}_k(z)} |j_l(z)| \prec k^{-1/3} \log k.$$

Clearly if  $z \in E_k$ , we get a lower bound:

$$\sum_{l \in \mathcal{B}_k(z)} j_l(z) \geq -Ck^{-1/3} \log k.$$

e. *Contribution of non-normal rectangles.*

Define

$$D_n(z) := \sum_{l \in \mathcal{J}_k} j_l(z).$$

Let

$$E = \bigcup_{l \in \mathcal{J}_k} Q^{(l)}; \quad \tilde{\mu} = \sum_{l \in \mathcal{J}_k} \mu^{(l)}.$$

From (3.13), the area of each non-normal rectangle is at least  $(10MA)^{-1} k^{-1/3}$  and the total area they cover does not exceed  $16R^2$  (since the multiplicity of the covering is at most 4). Hence we have

$$(3.20) \quad \#\mathcal{J}_k \prec k^{1/3}.$$

Therefore

$$\tilde{\mu}(Q_R) \prec k^{-2/3}.$$

We first assume that  $|z| < 2R$ . Letting  $\zeta_m$  denote the point which is the nearest to  $z$  among all  $\zeta^{(l)}$ ,  $l \in \mathcal{J}_k$ , we have

$$|D_n(z)| \prec \int_{Q_R} |\log |z - \zeta|| d\tilde{\mu}(\zeta) + |\log |z - \zeta_m|| \int_{Q_R} d\tilde{\mu}(\zeta) = A_1(z) + A_2(z).$$

Now by (3.3) and (3.4),

$$\begin{aligned} |A_1(z)| &\prec A \int_{|\zeta - z| < k^{-5}} |\log |z - \zeta|| d\sigma(\zeta) \\ &\quad + \log k \int_{|\zeta - z| > k^{-5}, \zeta \in Q_R} d\tilde{\mu}(\zeta) \prec k^{-2/3} \log k. \end{aligned}$$

Assuming  $z \notin E_k$  (i.e.,  $|z - \zeta_m| > k^{-10}$ ) we have

$$|A_2(z)| \prec \log k \tilde{\mu}(Q_R) \prec k^{-2/3} \log k.$$

Otherwise we get a one-sided bound. These inequalities complete the estimate of  $D_n$  in the case  $|z| < 2R$ .

If  $|z| > 2R$  we simply have

$$D_n(z) = \sum_{l \in \mathcal{J}_k} \int_{Q^{(l)}} \left( \log \left| 1 - \frac{\zeta}{z} \right| - \log \left| 1 - \frac{\zeta^{(l)}}{z} \right| \right) d\mu^l(\zeta),$$

and since the integrands are bounded we obtain

$$|D_n(z)| \prec k^{-2/3}, \quad |z| > 2R.$$

This inequality completes our estimates.

### 4. Convergence of the Monge-Ampère measures

We return to  $\mathbb{C}^2$  with variables  $(z, w)$ . We use the notation  $d = \partial + \bar{\partial}$  and  $d^c = i(\bar{\partial} - \partial)$  where, for a  $C^1$  function  $u$ ,

$$\partial u := \frac{\partial u}{\partial z} dz + \frac{\partial u}{\partial w} dw, \quad \bar{\partial} u := \frac{\partial u}{\partial \bar{z}} d\bar{z} + \frac{\partial u}{\partial \bar{w}} d\bar{w}$$

so that  $dd^c = 2i\partial\bar{\partial}$ . For a  $C^2$  function  $u$ ,

$$(dd^c u)^2 = 16 \left[ \frac{\partial^2 u}{\partial z \partial \bar{z}} \frac{\partial^2 u}{\partial w \partial \bar{w}} - \frac{\partial^2 u}{\partial z \partial \bar{w}} \frac{\partial^2 u}{\partial w \partial \bar{z}} \right] \frac{i}{2} dz \wedge d\bar{z} \wedge \frac{i}{2} dw \wedge d\bar{w}$$

is, up to a positive constant, the determinant of the complex Hessian of  $u$  times the volume form on  $\mathbb{C}^2$ . Thus if  $u$  is also psh,  $(dd^c u)^2$  is a positive measure which is absolutely continuous with respect to Lebesgue measure. If  $u$  is psh in an open set  $D$  and locally bounded there, or, more generally, if the unbounded locus of  $u$  is compactly contained in  $D$ , then  $(dd^c u)^2$  is a positive measure in  $D$  (cf. [2], [9]). We discuss aspects of this last statement that we need.

A psh function  $u$  in  $D$  is an usc function  $u$  in  $D$  which is subharmonic (or identically  $-\infty$ ) on components of  $D \cap L$  for complex affine lines  $L$ . In particular,  $u$  is a locally integrable function in  $D$  such that

(4.1)

$$dd^c u = 2i \left[ \frac{\partial^2 u}{\partial z \partial \bar{z}} dz \wedge d\bar{z} + \frac{\partial^2 u}{\partial w \partial \bar{w}} dw \wedge d\bar{w} + \frac{\partial^2 u}{\partial z \partial \bar{w}} dz \wedge d\bar{w} + \frac{\partial^2 u}{\partial \bar{z} \partial w} d\bar{z} \wedge dw \right]$$

is a positive  $(1, 1)$  current (dual to  $(1, 1)$  forms); i.e., a  $(1, 1)$  form with distribution coefficients. Thus the derivatives in (4.1) are to be interpreted in the distribution sense. Here, a  $(1, 1)$  current  $T$  on a domain  $D$  in  $\mathbb{C}^2$  is positive if  $T \wedge (i\beta \wedge \bar{\beta})$  is a positive distribution for all  $(1, 0)$  forms  $\beta = adz + bdw$  with  $a, b \in C_0^\infty(D)$  (smooth functions having compact support in  $D$ ). Writing the action of a current  $T$  on a test form  $\psi$  as  $\langle T, \psi \rangle$ , this means that

$$\langle T, \phi(i\beta \wedge \bar{\beta}) \rangle \geq 0 \text{ for all } \phi \in C_0^\infty(D) \text{ with } \phi \geq 0.$$

For a discussion of currents and the general definition of positivity, we refer the reader to Klimek [13], section 3.3.

Following [2], we now define  $(dd^c v)^2$  for a psh  $v$  in  $D$  if  $v \in L_{loc}^\infty(D)$  using the fact that  $dd^c v$  is a positive  $(1, 1)$  current with measure coefficients. First

note that if  $v$  were of class  $C^2$ , given  $\phi \in C_0^\infty(D)$ , we have

$$\begin{aligned} \int_D \phi(dd^c v)^2 &= - \int_D d\phi \wedge d^c v \wedge dd^c v \\ &= - \int_D dv \wedge d^c \phi \wedge dd^c v = \int_D v dd^c \phi \wedge dd^c v \end{aligned}$$

since all boundary integrals vanish. The applications of Stokes' theorem are justified if  $v$  is smooth; for arbitrary psh  $v$  in  $D$  with  $v \in L_{loc}^\infty(D)$ , these formal calculations serve as motivation to *define*  $(dd^c v)^2$  as a positive measure (precisely, a positive current of bidegree  $(2, 2)$  and hence a positive measure) via

$$\langle (dd^c v)^2, \phi \rangle := \int_D v dd^c \phi \wedge dd^c v.$$

This defines  $(dd^c v)^2$  as a  $(2, 2)$  current (acting on  $(0, 0)$  forms; i.e., test functions) since  $v dd^c v$  has measure coefficients. We refer the reader to [2] or [13] (p. 113) for the verification of positivity of  $(dd^c v)^2$ . Also, the use of Stokes' theorem is valid and hence, for simplicity, we will write  $\langle (dd^c v)^2, \phi \rangle$  as  $\int_D \phi(dd^c v)^2$ .

Despite the fact that  $L_{loc}^1(D)$  might appear to be the natural topology in which to study psh functions, work of Cegrell and Lelong (cf. [13] section 3.8) yields that on, e.g., a ball  $D$ , for any psh function  $v \in L_{loc}^\infty(D)$ , there always exists a sequence of continuous psh functions  $\{v_j\}$  with  $v_j \rightarrow v$  in  $L_{loc}^1(D)$  but  $(dd^c v_j)^2 = 0$  for all  $j$ . In the locally bounded category, however, the complex Monge-Ampère operator is continuous under (a.e.) monotone limits (cf. Bedford-Taylor [3] or Sadullaev [16]). A simpler argument shows that local uniform convergence of a sequence of locally bounded psh functions  $\{v_j\}$  to  $v$  implies weak- $*$  convergence  $(dd^c v_j)^2 \rightarrow (dd^c v)^2$ : in case  $v_j, v$  are smooth, given  $\phi \in C_0^\infty(D)$ ,

$$\begin{aligned} \int_D \phi(dd^c v_j)^2 &= \int_D v_j dd^c v_j \wedge dd^c \phi \\ &= \int_D v dd^c v_j \wedge dd^c \phi + \int_D (v_j - v) dd^c v_j \wedge dd^c \phi. \end{aligned}$$

The first term tends to  $\int_D v dd^c v \wedge dd^c \phi = \int_D \phi(dd^c v)^2$  since  $dd^c v_j \rightarrow dd^c v$  as positive  $(1, 1)$  currents; from the uniform convergence  $v_j \rightarrow v$ , the family  $\{dd^c v_j\}$  is locally uniformly bounded (cf. [16]) so that the second term goes to zero. In particular, we obtain the following result.

**PROPOSITION 4.1.** — *Let  $K \subset \mathbb{C}^2$  be a regular, polynomially convex compact set. Suppose  $\{u_n\} \subset L^+(\mathbb{C}^2)$  converges uniformly to  $V_K$  on  $\mathbb{C}^2$ .*

Then

$$(dd^c u_n)^2 \rightarrow (dd^c V_K)^2$$

weak- $^*$  as measures in  $\mathbb{C}^2$ . Thus with  $K, \{\tilde{u}_n\}$  as in Theorem 1.1,

$$(dd^c \tilde{u}_n)^2 \rightarrow (dd^c V_K)^2.$$

The functions  $\{U_n\}$  of Theorem 1.1 are *not* locally bounded, but they are in the classical Sobolev space  $W_{\text{loc}}^{1,2}(\mathbb{C}^2)$ . Following [2] as before – but altering the final application of Stokes’ theorem – we note that if  $v \in W_{\text{loc}}^{1,2}(D)$  for some domain  $D$ , and  $\phi \in C_0^\infty(D)$ , we can formally write

$$\begin{aligned} \int_D \phi (dd^c v)^2 &= - \int_D d\phi \wedge d^c v \wedge dd^c v \\ &= - \int_D dv \wedge d^c \phi \wedge dd^c v = - \int_D dv \wedge d^c v \wedge dd^c \phi \end{aligned}$$

since all boundary integrals vanish. In this case, these calculations serve as motivation to define  $(dd^c v)^2$  as a positive measure for a psh function  $v$  in  $W_{\text{loc}}^{1,2}(D)$  via

$$\int_D \phi (dd^c v)^2 := - \int_D dv \wedge d^c v \wedge dd^c \phi.$$

The functions  $u(z, w) := \frac{1}{2} \log(|z|^2 + |w|^2)$  and  $\tilde{u}(z, w) = \max[\log|z|, \log|w|]$  are canonical examples of such functions with

$$(4.2) \quad (dd^c u)^2 = (dd^c \tilde{u})^2 = (2\pi)^2 \delta_{(0,0)}$$

([9], Corollary 6.4). More generally, if  $f$  and  $g$  are holomorphic functions near  $(0, 0)$ , an elementary calculation (cf. [2], p. 15) shows that

$$(4.3) \quad \left( dd^c \frac{1}{2} \log(|f|^2 + |g|^2) \right)^2 = 0 \text{ on } \{|f|^2 + |g|^2 > 0\}.$$

Thus if  $f(0, 0) = g(0, 0) = 0$  and  $(0, 0)$  is an isolated zero of  $\{f = g = 0\}$ , in a neighborhood of the origin, the Monge-Ampère measures

$$(dd^c \max(\log|f|, \log|g|))^2, \left( dd^c \frac{1}{2} \log(|f|^2 + |g|^2) \right)^2$$

are supported at  $(0, 0)$ . Indeed, we have

$$(4.4) \quad (dd^c \max(\log|f|, \log|g|))^2 = \left( dd^c \frac{1}{2} \log(|f|^2 + |g|^2) \right)^2 = m(2\pi)^2 \delta_{(0,0)}$$

near  $(0, 0)$  where  $m$  is the degree of the mapping  $(z, w) \rightarrow (f(z, w), g(z, w))$  at  $(0, 0)$ . For example, taking  $(z, w) \rightarrow (z, w^2)$ ,

$$\left( dd^c \frac{1}{2} \log(|z|^2 + |w|^4) \right)^2 = 2(2\pi)^2 \delta_{(0,0)}.$$

To see how (4.2) implies (4.4), following [2], p. 16, we observe that with  $u(z, w) := \frac{1}{2} \log(|z|^2 + |w|^2)$ , the form

$$\omega := d^c u \wedge dd^c u$$

restricted to a sphere  $S_\epsilon := \{(z, w) : |z|^2 + |w|^2 = \epsilon^2\}$  equals  $2\epsilon^{-3}d\sigma_\epsilon$  where  $d\sigma_\epsilon$  is the volume form on  $S_\epsilon$ . If we write  $F(z, w) := (f(z, w), g(z, w))$  and  $v(z, w) := \frac{1}{2} \log(|f|^2 + |g|^2)$ , then

$$d^c v \wedge dd^c v = F^* \omega = F^*(d^c u \wedge dd^c u).$$

Moreover,

$$\int F^*(\epsilon^{-3}d\sigma_\epsilon) = 2\pi^2 m.$$

Hence

$$\int_{S_\epsilon} d^c v \wedge dd^c v = \int F^*(2\epsilon^{-3}d\sigma_\epsilon) = 4\pi^2 m.$$

From (4.3),  $(dd^c v)^2$  is supported at  $(0, 0)$  and the second equality in (4.4) follows. The first follows from Corollary 6.4 of [9].

Thus for our functions

$$U_n(z, w) = \max\left[\frac{1}{n} \log |P_n(z, w) - 1|, \frac{1}{n} \log |Q_n(z, w) - 1|\right],$$

the Monge-Ampère measures  $(dd^c U_n)^2$  are supported on the finite point sets  $K_n := \{(z, w) : P_n(z, w) = Q_n(z, w) = 1\}$ , and by the local uniform convergence of  $U_n \rightarrow V_K$  off of  $\partial K = \{\rho_K = 0\}$  (see (2.10)), given  $\epsilon > 0$ , for  $n > n_0(\epsilon)$ ,

$$(4.5) \quad K_n \subset (\partial K)^\epsilon := \{(z, w) : |\rho_K(z, w)| \leq \epsilon\}.$$

From Proposition 3.2 of [5], in  $\mathbb{C}^2$ , convergence of a sequence  $\{v_j\}$  of psh functions in the Sobolev space  $W_{\text{loc}}^{1,2}(\mathbb{C}^2)$  implies weak-\* convergence of the Monge-Ampère measures  $\{(dd^c v_j)^2\}$ ; we will apply this result to prove Theorem 4.3.

A simple example motivated from the one-variable example in the introduction illustrates the distinction between approximation by  $\{\tilde{u}_n\}$  and by  $\{U_n\}$ .

*Example 4.2.* — Let  $K = \{(z, w) : |z|, |w| \leq 1\}$  be the closed unit bidisk. Then

$$V_K(z, w) = \max[\log |z|, \log |w|, 0] = \max[\rho_K(z, w), 0]$$

so we can trivially take  $P_n(z, w) = z^n$  and  $Q_n(z, w) = w^n$  in Theorem 1.1. Then  $\tilde{u}_n = V_K$  for all  $n$  while

$$U_n(z, w) = \max\left[\frac{1}{n} \log |z^n - 1|, \frac{1}{n} \log |w^n - 1|\right].$$



Thus  $K_n$  consists of ordered pairs  $\zeta_{jk}^{(n)} := (\omega_n^j, \omega_n^k)$ ,  $j, k = 1, \dots, n$  where  $\omega_n = \exp(2\pi i/n)$  is a primitive  $n$ -th root of unity. It is standard that

- $t \rightarrow t^n - 1$  is a Fekete polynomial of degree  $n$  for the closed unit disk in  $\mathbb{C}$ ;
- $(dd^c V_K)^2 = d\theta_z \times d\theta_w$ , the standard measure on the torus  $T := \{|z| = 1\} \times \{|w| = 1\}$  (of mass  $(2\pi)^2$ );
- $U_n \rightarrow V_K$  locally uniformly in  $\mathbb{C}^2 \setminus K$  and  $U_n \rightarrow 0$  locally uniformly in  $K^o = \{\rho_k < 0\}$ , but  $\{U_n\}$  does not converge pointwise on  $T$ ; however,
- $(dd^c U_n)^2 = \frac{(2\pi)^2}{n^2} \sum_{j,k=1}^n \delta_{\zeta_{jk}^{(n)}} \rightarrow (dd^c V_K)^2$ .

The assumption in Theorem 1.1 that  $K$  is circled, regular and polynomially convex implies that  $K$  is *balanced*; i.e.,  $(z, w) \in K$  and  $\lambda \in \mathbb{C}$  with  $|\lambda| \leq 1$  imply  $(\lambda z, \lambda w) \in K$ ; moreover  $K = \bar{D}$  where  $D = \{(z, w) : \phi(z, w) < 1\}$  is a balanced, pseudoconvex domain determined by  $\phi(z, w) := \exp \rho_K(z, w)$ , the *Minkowski functional* of  $D$ .

THEOREM 4.3. — *If  $K = \bar{D}$  with  $D$  strictly pseudoconvex, then*

$$(dd^c U_n)^2 \rightarrow (dd^c V_K)^2$$

*weak-\* as measures in  $\mathbb{C}^2$ .*

*Proof.* — We first note that all of the functions  $U_n$  and  $V_K$  have the same total Monge-Ampère mass:

$$(4.6) \quad \int_{\mathbb{C}^2} (dd^c U_n)^2 = \int_{\mathbb{C}^2} (dd^c V_K)^2 = (2\pi)^2.$$

This is a standard fact about psh functions  $u \in L^+(\mathbb{C}^2)$ ; cf. [18].

Using [12], Theorem 4.1.8, we can find a subsequence  $\{U_{n_j}\}$  of  $\{U_n\}$  with  $U_{n_j} \rightarrow U$  in  $L^p_{\text{loc}}(\mathbb{C}^2)$  for some psh  $U$  for all  $p \in [1, \infty)$ . Since  $U_n \rightarrow V_K$  locally uniformly on  $\mathbb{C}^2 \setminus \{\rho_K = 0\}$ , estimates (2.6), (2.7) and (2.9) imply conditions i)-iii) in Theorem 2.2 of [7]; and we conclude that  $U_n \rightarrow V_K$  in  $L^1_{\text{loc}}(\mathbb{C}^2)$ . Hence  $U = V_K$  and the full sequence  $\{U_n\}$  converges; i.e., we have, in particular, that  $U_n \rightarrow V_K$  in both  $L^2_{\text{loc}}(\mathbb{C}^2)$  and  $L^1_{\text{loc}}(\mathbb{C}^2)$ . From this latter convergence,  $\nabla U_n$  converges weakly (as distributions) to  $\nabla V_K$ . Using Blocki's result, to show that  $(dd^c U_n)^2 \rightarrow (dd^c V_K)^2$  weak-\* as measures, it thus suffices to show that  $\nabla U_n \rightarrow \nabla V_K$  in  $L^2_{\text{loc}}(\mathbb{C}^2)$ . Note that  $U_n, V_K \in W^{1,2}_{\text{loc}}(\mathbb{C}^2)$  (e.g., from [5], Theorem 1.1).

Fix a strictly pseudoconvex domain  $B = \{(z, w) : \psi(z, w) < 0\}$  containing  $K$  where  $\psi$  is strictly psh. We want to show that  $\nabla U_n \rightarrow \nabla V_K$  in

$L^2(B)$ . It suffices to show that the norms converge; *i.e.*,

$$\|\nabla U_n\|^2 := \int_B |\nabla U_n|^2 \rightarrow \int_B |\nabla V_K|^2 = \|\nabla V_K\|^2.$$

That is, by standard Hilbert space theory, weak convergence plus convergence of the norms imply convergence in the norm. Note that by the weak convergence of  $\nabla U_n$  to  $\nabla V_K$  (or simply Fatou's lemma) we have

$$(4.7) \quad \liminf_{n \rightarrow \infty} \|\nabla U_n\| \geq \|\nabla V_K\|;$$

we want to show the limit exists and equals  $\|\nabla V_K\|$ .

Let  $V_n := \max[U_n, 0]$ . From the proof of the first part of Theorem 1.1 in section 2,  $V_n \rightarrow V_K$  uniformly on  $\mathbb{C}^2$  and hence, from Proposition 4.1,  $(dd^c V_n)^2 \rightarrow (dd^c V_K)^2$  weak- $*$  as measures on  $\mathbb{C}^2$ . By an observation of Cegrell,  $V_n \rightarrow V_K$  in  $W_{loc}^{1,2}(\mathbb{C}^2)$ . Precisely, if  $\{u_j\}$ ,  $u$  are subharmonic functions in  $W_{loc}^{1,2}(\mathbb{R}^m)$  and  $u_j \rightarrow u$  locally uniformly, then  $u_j \rightarrow u$  in  $W_{loc}^{1,2}(\mathbb{R}^m)$ . To see this, we may assume that  $u_j, u$  are of class  $C^2$  and we use the identity

$$\frac{1}{2} \Delta(v^2) = v \Delta v + |\nabla v|^2$$

for such functions. Take  $\Omega' \subset\subset \Omega \subset\subset \mathbb{R}^m$  and  $\eta \in C_0^\infty(\Omega)$  with  $0 \leq \eta \leq 1$  and  $\eta = 1$  on  $\Omega'$ . Then

$$\begin{aligned} \int_{\Omega'} |\nabla(u_j - u)|^2 &\leq \int_{\Omega} \eta |\nabla(u_j - u)|^2 = \frac{1}{2} \int_{\Omega} \eta \Delta[(u_j - u)^2] \\ &\quad - \int_{\Omega} \eta(u_j - u) \Delta(u_j - u) \\ &\leq \left| \frac{1}{2} \int_{\Omega} (u_j - u)^2 \Delta \eta \right| + \left| \int_{\Omega} \eta(u_j - u) \Delta(u_j - u) \right| \\ &\leq C \int_{\Omega} (u_j - u)^2 + \left| \int_{\Omega} \eta(u_j - u) \Delta(u_j - u) \right| \end{aligned}$$

(here  $C$  depends on  $\eta$ ) which tends to zero as  $j \rightarrow \infty$  since  $u_j \rightarrow u$  uniformly on  $\bar{\Omega}$  and  $\Delta u_j \rightarrow \Delta u$  as measures.

We will work in an equivalent  $L^2$ -norm using a weight function. To construct this function, we are assuming that  $K = \bar{D}$  with  $D = \{(z, w) : \rho_K(z, w) < 0\}$  strictly pseudoconvex; hence  $\exp \rho_K$  is strictly psh and we work on the sub-level sets  $B = B_R := \{(z, w) : \exp \rho_K(z, w) < e^R\}$  for  $R > 0$ . For each set  $B$  we define

$$\psi(z, w) := \exp \rho_K(z, w) - e^R.$$

The (semi-) norm in our new  $L^2$ -space is

$$\|\nabla u\|_{\psi}^2 := \int_B dd^c \psi \wedge d^c u \wedge du.$$

If  $\psi(z) = A_1|z|^2 + A_2$  then  $\|\nabla u\|_\psi^2 = 4A_1\|\nabla u\|^2$ ; in general, due to strict plurisubharmonicity and smoothness of  $\psi$ , we have

$$c_1\|\nabla u\| \leq \|\nabla u\|_\psi \leq c_2\|\nabla u\|$$

for constants  $c_1, c_2$  depending only on  $\psi$ . The same argument as before gives a version of (4.7) in our new norm:

$$(4.8) \quad \liminf_{n \rightarrow \infty} \|\nabla U_n\|_\psi \geq \|\nabla V_K\|_\psi.$$

Now via integration by parts, we get

$$\int_B dd^c\psi \wedge dU_n \wedge d^cU_n = \int_B (-\psi)(dd^cU_n)^2$$

modulo boundary integrals  $\pm \int_{\partial B} dU_n \wedge d^cU_n \wedge d^c\psi \pm \int_{\partial B} \psi d^cU_n \wedge dd^cU_n$ . Since  $\psi = 0$  on  $\partial B$ , this last term vanishes. Similarly,

$$\int_B dd^c\psi \wedge dV_K \wedge d^cV_K = \int_B (-\psi)(dd^cV_K)^2$$

modulo boundary integrals  $\pm \int_{\partial B} dV_K \wedge d^cV_K \wedge d^c\psi \pm \int_{\partial B} \psi d^cV_K \wedge dd^cV_K$ ; again, this latter term vanishes. Thus we must show that

$$(4.9) \quad \int_{\partial B} dU_n \wedge d^cU_n \wedge d^c\psi \rightarrow \int_{\partial B} dV_K \wedge d^cV_K \wedge d^c\psi$$

and

$$(4.10) \quad \int_B (-\psi)(dd^cU_n)^2 \rightarrow \int_B (-\psi)(dd^cV_K)^2.$$

Using (4.5), given  $\epsilon > 0$ , for  $n > n_0(\epsilon)$  we have  $(dd^cU_n)^2$  is supported in  $(\partial K)^\epsilon$ , and

$$1 - 2\epsilon - e^R \leq \psi(z, w) \leq 1 + 2\epsilon - e^R$$

on this set so that

$$(2\pi)^2(1 - 2\epsilon - e^R) \leq \int_B \psi(dd^cU_n)^2 \leq (2\pi)^2(1 + 2\epsilon - e^R).$$

Since  $(dd^cV_K)^2$  is supported on  $\partial K$  and, from (4.6), the total Monge-Ampère mass of  $V_K$  is  $(2\pi)^2$ , we have  $\int_B (-\psi)(dd^cV_K)^2 = (2\pi)^2(e^R - 1)$  so that

$$\left| \int_B (-\psi)(dd^cU_n)^2 - \int_B (-\psi)(dd^cV_K)^2 \right| \leq (2\pi)^2 2\epsilon$$

for  $n > n_0(\epsilon)$ . This gives (4.10).

To prove (4.9), we observe that for any fixed  $R > 0$ , for  $n$  sufficiently large,  $U_n = V_n$  on  $\partial B = \partial B_R$ . Thus we may replace  $U_n$  by  $V_n$  in (4.9). Now

$(dd^c V_n)^2 \rightarrow (dd^c V_K)^2$  weak- $*$  and the support of  $(dd^c V_n)^2$  is compactly contained in  $B$  for  $n$  large so

$$\int_B (-\psi)(dd^c V_n)^2 \rightarrow \int_B (-\psi)(dd^c V_K)^2.$$

Since  $V_n \rightarrow V_K$  in  $W_{loc}^{1,2}(\mathbb{C}^2)$ ,

$$\int_B dd^c \psi \wedge dV_n \wedge d^c V_n \rightarrow \int_B dd^c \psi \wedge dV_K \wedge d^c V_K.$$

Via the previously described integration by parts, (4.9) follows. □

*Remark 4.4.* — If  $K$  is not strictly pseudoconvex, if we can find  $\tilde{K} = \bar{\bar{D}}$  balanced with  $\tilde{D}$  strictly pseudoconvex and with  $\text{supp}(dd^c V_K)^2 \subset \tilde{K}$ , the same argument works using the function  $\tilde{\psi}(z, w) = \exp \rho_{\tilde{K}}(z, w) - e^R$ . For example, for the bidisk  $K$ ,  $\text{supp}(dd^c V_K)^2$  is the unit torus which is contained in the ball  $\tilde{K} = \{(z, w) : |z|^2 + |w|^2 \leq 2\}$ .

*Remark 4.5.* — Let  $\Omega$  be a bounded hyperconvex domain in  $\mathbb{C}^N$ ; i.e., there exists a negative psh function  $\psi$  in  $\Omega$  with  $\{z \in \Omega : \psi(z) \leq -c\} \subset\subset \Omega$  for all  $c > 0$ . A bounded psh function  $v$  belongs to the class  $\mathcal{E}_0(\Omega)$  if  $\lim_{z' \rightarrow z} v(z') = 0$  for all  $z \in \partial\Omega$  and  $\int_{\Omega} (dd^c v)^N < +\infty$ . Finally, a psh function  $v$  in  $\Omega$  belongs to the class  $\mathcal{F}(\Omega)$  if there exists a sequence of functions  $v_j \in \mathcal{E}_0(\Omega)$  with  $\sup_j \int_{\Omega} (dd^c v_j)^N < +\infty$  which decreases to  $v$  on  $\Omega$ . A recent result of Cegrell [8] states the following: for a sequence  $\{u_n\} \subset \mathcal{F}(\Omega)$ , if  $u_n \rightarrow u \in \mathcal{F}(\Omega)$  in  $L^1_{loc}(\Omega)$  and if there exists a strictly psh function  $v \in \mathcal{E}_0(\Omega)$  such that  $\lim_{n \rightarrow \infty} \int_{\Omega} v(dd^c u_n)^N = \int_{\Omega} v(dd^c u)^N$ , then  $(dd^c u_n)^N$  converges weak- $*$  to  $(dd^c u)^N$ . The sequence  $\{u_n\}$  must lie in  $\mathcal{F}(\Omega)$  in order that certain integration by parts formulae are valid. Note that functions in  $\mathcal{E}_0(\Omega)$  have zero boundary values; moreover, if  $u_n \in \mathcal{F}(\Omega)$  then  $\limsup_{z' \rightarrow z} u_n(z') = 0$  for all  $z \in \partial\Omega$  (cf. [1]). It might appear that (4.10) would suffice (without (4.9)) to prove Theorem 4.3. However, the functions  $U_n$  do not lie in the class  $\mathcal{F}(B)$  since  $\limsup_{z' \rightarrow z} U_n(z') \neq 0$  for all  $z \in \partial B$ .

As mentioned in the introduction, from Bishop’s construction, one obtains the following result.

**PROPOSITION 4.6.** — *Let  $K \subset \mathbb{C}^N$  be a regular, polynomially convex compact set. Then there exists a sequence of special polynomial polyhedra  $\{\kappa_n\}$  where  $\kappa_n$  is the closure of a union of a finite number of connected components of*

$$\mathcal{K}_n := \{(z_1, \dots, z_N) : |P_{n,1}(z_1, \dots, z_N)| < 1, |P_{n,N}(z_1, \dots, z_N)| < 1\}$$

with  $\{P_{n,1}, \dots, P_{n,N}\}$  polynomials having degree  $n$ , such that the extremal functions  $\{V_{\kappa_n}\}$  converge uniformly to  $V_K$  and  $(dd^c V_{\kappa_n})^N \rightarrow (dd^c V_K)^N$  weak- $*$ .

However, it is not known how one can construct full component sets of the form  $\mathcal{K}_n$  approximating  $K$  as we have in Theorem 1.1 using (1.5) nor how to construct functions  $u_n$  of the form

$$u_n(z_1, \dots, z_N) := \max \left[ \frac{1}{n} \log |\tilde{P}_{n,1}(z_1, \dots, z_N)|, \dots, \frac{1}{n} \log |\tilde{P}_{n,N}(z_1, \dots, z_N)| \right]$$

for some polynomials  $\tilde{P}_{n,1}, \dots, \tilde{P}_{n,N}$  so that, with

$$K_n := \{(z_1, \dots, z_N) : u_n(z_1, \dots, z_N) = -\infty\}$$

we have  $(dd^c u_n)^N$  is supported in  $K_n$  as in (1.6) and

- $u_n \rightarrow V_K$  locally uniformly in  $\mathbb{C}^N \setminus K$ ;
- $u_n \rightarrow V_K$  in  $L^1_{\text{loc}}(\mathbb{C}^N)$ ; and
- $(dd^c u_n)^N \rightarrow (dd^c V_K)^N$  weak- $*$ .

As a step in this direction, we can achieve a partial result in  $\mathbb{C}^2$ .

PROPOSITION 4.7. — *Let  $K \subset \mathbb{C}^2$  be a regular, polynomially convex compact set. Then there exists a sequence of pairs of polynomials  $\{\tilde{P}_n, \tilde{Q}_n\}$  with  $\deg \tilde{P}_n = \deg \tilde{Q}_n = n$  such that the functions*

$$v_n(z, w) := \max \left[ \frac{1}{n} \log |\tilde{P}_n(z, w)|, \frac{1}{n} \log |\tilde{Q}_n(z, w)| \right]$$

converge to  $V_K$  in  $L^1_{\text{loc}}(\mathbb{C}^2 \setminus K)$  and  $\rho_{v_n} \rightarrow \rho_K$  uniformly on  $\mathbb{C}^2$ . In particular, if  $K$  has empty interior (e.g., if  $K \subset \mathbb{R}^2$ ), then  $v_n \rightarrow V_K$  in  $L^1_{\text{loc}}(\mathbb{C}^2)$ .

*Proof.* — Form the Robin function  $\rho_K$  of  $V_K$  (see section 2) and construct the regular, polynomially convex, circled set

$$K_\rho := \{(z, w) \in \mathbb{C}^2 : \rho_K(z, w) \leq 0\}.$$

Apply Theorem 1.1 to obtain a sequence of pairs  $\{P_n, Q_n\}$  of homogeneous polynomials such that if  $\epsilon > 0$  is given, then

$$\rho_K(z, w) - \epsilon \leq \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)| \right] \leq \rho_K(z, w)$$

for all  $(z, w) \in \mathbb{C}^2$  if  $n > n(\epsilon)$ . Construct

$$\tilde{P}_n = \text{Tch}_K P_n, \quad \tilde{Q}_n = \text{Tch}_K Q_n$$

where, for a homogeneous polynomial  $H_n$  of degree  $n$ ,

$$\text{Tch}_K H_n := H_n + H_{n-1}$$

with  $\deg H_{n-1} \leq n - 1$  and  $\|\text{Tch}_K H_n\|_K \leq \|H_n + R_{n-1}\|_K$  for all polynomials  $R_{n-1}$  of degree at most  $n - 1$ . By Theorem 3.2 of [6],

$$\limsup_{n \rightarrow \infty} \|\tilde{P}_n\|_K^{1/n} \leq 1, \quad \limsup_{n \rightarrow \infty} \|\tilde{Q}_n\|_K^{1/n} \leq 1.$$

Thus, given  $\epsilon > 0$ , for  $n > n(\epsilon)$  we have

$$\max[\|\tilde{P}_n\|_K, \|\tilde{Q}_n\|_K] \leq (1 + \epsilon)^n$$

so that the the functions

$$v_n(z, w) := \max \left[ \frac{1}{n} \log |\tilde{P}_n(z, w)|, \frac{1}{n} \log |\tilde{Q}_n(z, w)| \right]$$

satisfy

- $v_n \in L(\mathbb{C}^2)$ ;
- given  $\epsilon > 0$ , there exist  $N = N(\epsilon)$  with  $v_n \leq \epsilon$  on  $K$  for  $n > N(\epsilon)$ ;
- $\rho_{v_n} \rightarrow \rho_K$  uniformly on  $\mathbb{C}^2$ .

This last item follows since

$$\rho_{v_n} = \max \left[ \frac{1}{n} \log |P_n(z, w)|, \frac{1}{n} \log |Q_n(z, w)| \right].$$

By Theorem 2.2 of [7], we conclude that  $v_n \rightarrow V_K$  in  $L^1_{\text{loc}}(\mathbb{C}^2 \setminus K)$ . □

### BIBLIOGRAPHY

- [1] P. AHAG, “A Dirichlet problem for the complex Monge-Ampère operator in  $\mathcal{F}(f)$ ”, *Michigan Math. J.* **55** (2007), no. 1, p. 123-138.
- [2] E. BEDFORD & B. A. TAYLOR, “The Dirichlet problem for a complex Monge-Ampère equation”, *Inv. Math.* **37** (1976), p. 1-44.
- [3] ———, “A new capacity for plurisubharmonic functions”, *Acta Math.* **149** (1982), p. 1-40.
- [4] E. BISHOP, “Mappings of partially analytic spaces”, *Amer. J. Math.* **83** (1961), p. 209-242.
- [5] Z. BLOCKI, “On the definition of the Monge-Ampère operator in  $\mathbb{C}^2$ ”, *Math. Ann.* **328** (2004), no. 3, p. 415-423.
- [6] T. BLOOM, “Some applications of the Robin function to multivariable approximation theory”, *J. Approx. Th.* **92** (1998), p. 1-21.
- [7] ———, “Random polynomials and Green functions”, *International Math. Res. Notices* **28** (2005), p. 1689-1708.
- [8] U. CEGRELL, “Weak-\* convergence of Monge-Ampère measures”, *Math. Z.* **254** (2006), no. 3, p. 505-508.
- [9] J.-P. DEMAILLY, “Monge-Ampère operators, Lelong numbers and intersection theory”, *Complex analysis and geometry* (1993), p. 115-193, Univ. Ser. Math., Plenum, New York.
- [10] D. DRASIN, “Approximation of subharmonic functions with applications”, in *Approximation, complex analysis, and potential theory*, NATO Sci. Ser. II Math. Phys. Chem., vol. 37, Kluwer Acad. Publ., Dordrecht, 2001, Montreal, QC, 2000, p. 163-189.

- [11] L. HÖRMANDER, *An Introduction to Complex Analysis in Several Variables*, Van Nostrand, 1966.
- [12] ———, *Notions of Convexity*, Birkhäuser, 1994.
- [13] M. KLIMEK, *Pluripotential Theory*, Clarendon Press, Oxford, 1991.
- [14] Y. LYUBARSKII & E. MALINNIKOVA, “On approximation of subharmonic functions”, *Journal d’Analyse Math.* **83** (2001), p. 121-149.
- [15] L. I. RONKIN, *Introduction to the Theory of Entire Functions of Several Variables*, Amer. Math. Soc., Providence, 1974.
- [16] A. SADULLAEV, “Rational approximation and pluripolar sets”, *Math USSR Sbornik* **47** (1984), p. 91-113.
- [17] H. STAHL, “The convergence of Padé approximants to functions with branch points”, *J. Approx. Th.* **91** (1997), p. 139-204.
- [18] B. A. TAYLOR, “An estimate for an extremal plurisubharmonic function on  $\mathbb{C}^n$ ”, Sémin. d’Analyse P. Lelong - P. Dolbeault - H. Skoda, *Années 1981/83*, Lect. Notes Math. 1028, 318-328, 1983.
- [19] R. YULMUKHAMETOV, “Approximation of subharmonic functions”, *Anal. Math.* **11** (1985), no. 3, p. 257-282, Russian.

Manuscrit reçu le 6 juillet 2006,  
accepté le 15 mars 2007.

Thomas BLOOM  
University of Toronto  
Toronto (Canada)  
bloom@math.toronto.edu

Norman LEVENBERG  
Indiana University  
Bloomington, IN 47405 (USA)  
nlevenbe@indiana.edu

Yu. LYUBARSKII  
Norwegian University of Science and Technology  
Trondheim, 7491 (Norway)  
yura@math.ntnu.no