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On the equation $-\Delta u + e^u - 1 = 0$ with measures as boundary data

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Abstract If Ω is a bounded domain in $\mathbb{R}^N$, we study conditions on a Radon measure μ on $\partial\Omega$ for solving the equation $-\Delta u + e^u - 1 = 0$ in Ω with $u = \mu$ on $\partial\Omega$. The conditions are expressed in terms of Orlicz capacities.

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1 Introduction

Let Ω be a bounded domain in $\mathbb{R}^N$ with smooth boundary and μ a Radon measure on $\partial\Omega$. In this paper we consider first the problem of finding a function u solution of

$$-\Delta u + e^u - 1 = 0 \quad (1.1)$$

in Ω satisfying $u = \mu$ on $\partial\Omega$. Let $\rho(x) = \text{dist}(x, \partial\Omega)$, then this problem admits a **weak formulation**: find a function $u \in L^1(\Omega)$ such that $e^u \in L^1_\rho(\Omega)$ satisfying

$$\int_{\Omega} (-u\Delta\zeta + (e^u - 1)\zeta) dx = - \int_{\partial\Omega} \frac{\partial\zeta}{\partial\nu} d\mu \quad \forall \zeta \in W_0^{1,\infty}(\Omega) \cap W^{2,\infty}(\Omega). \quad (1.2)$$

This equation has been initiated by Grillo and Véron [16] in 2-dim in the framework of the boundary trace theory. Much works on boundary trace problems for equation of the type

$$-\Delta u + u^q = 0 \quad (1.3)$$

with $q > 1$, have been developed by Le Gall [19], Marcus and Véron [20], [21], Dynkin and Kuznetsov [10], [11], respectively by purely probabilistic methods, by purely analytic methods or by a combination of the preceding aspects. One of the main features of the problem with power nonlinearities is the existence of a critical exponent $q_c = \frac{N+1}{N-1}$ which is linked to the existence of boundary removable sets.

Existence of boundary removable points have been discovered by Gmira and Véron [15]. Let us recall briefly the main results for (1.3):

(i) If $1 < q < q_c$, then for any $\mu \in \mathfrak{M}_+(\partial\Omega)$ there exists a unique function $u \in L^1_+(\Omega) \cap L^q_\rho(\Omega)$ which satisfies (1.3) in Ω and takes the value μ on $\partial\Omega$ in the following weak sense

$$\int_{\Omega} (-u\Delta\zeta + u^q\zeta) dx = - \int_{\partial\Omega} \frac{\partial\zeta}{\partial\nu} d\mu \quad \forall \zeta \in W^{1,\infty}_0(\Omega) \cap W^{2,\infty}(\Omega). \quad (1.4)$$

(ii) If $q \geq q_c$, the above problem can be solved if and only if μ vanishes on boundary Borel subsets with zero $C_{2,q'}^q$ -Bessel capacity. Furthermore a boundary compact set is removable if and only if it has zero $C_{2,q'}^q$ -capacity.

In this article we adapt some of the ideas used for (1.3) to problem

$$\begin{aligned} -\Delta u + e^u - 1 &= 0 & \text{in } \Omega \\ u &= \mu & \text{on } \partial\Omega. \end{aligned} \quad (1.5)$$

Following the terminology of [5] we say that a measure $\mu \in \mathfrak{M}(\partial\Omega)$ is **good** if (3.21) admits a weak solution. Let $P^\Omega(x, y)$ (resp. $G^\Omega(x, y)$) be the Poisson kernel (resp. the Green kernel) in Ω and $\mathbb{P}^\Omega[\mu]$ the Poisson potential of a boundary measure μ (resp. $\mathbb{G}^\Omega[\phi]$ the Green potential of a bounded measure ϕ defined in Ω). A boundary measure μ which satisfies

$$\exp(\mathbb{P}^\Omega[\mu]) \in L^1(\Omega; \rho dx). \quad (1.6)$$

is called **admissible**. Since $\mathbb{P}^\Omega[\mu]$ is a supersolution for (1.1), an admissible measure is good (see [26]). Our first result which extends a previous one obtained in [16] is the following.

Theorem A. *Suppose $\mu \in \mathfrak{M}(\partial\Omega)$ admits Lebesgue decomposition $\mu = \mu_S + \mu_R$ where μ_S and μ_R are mutually singular and μ_R is absolutely continuous with respect to the $(N-1)$ -dim Hausdorff measure dH^{N-1} . If*

$$\exp(\mathbb{P}^\Omega[\mu_S]) \in L^1(\Omega; \rho dx), \quad (1.7)$$

then μ is good.

In order to go further in the study of good measures, it is necessary to introduce an *Orlicz capacity* modeled on the Legendre transform of $r \mapsto p(r) := e^r - 1$. These capacities have been studied by Aissaoui and Benkirane [2] and they inherit most of the properties of the Bessel capacities. The capacity $C_{N^L \ln L}$ associated to

the problem is constructed later and it has strong connexion with Hardy-Littlewood maximal function. In this capacity framework we obtain the following types of results:

Theorem B. *Let $\mu \in \mathfrak{M}_+(\partial\Omega)$ be a good measure, then μ vanishes on boundary Borel subsets E with zero $C_{N^L \ln L}$ -capacity.*

We also give below a result of removability of boundary singularities.

Theorem C. *Let $K \subset \partial\Omega$ be a compact subset with zero $C_{N^L \ln L}$ -capacity. Suppose $u \in C(\overline{\Omega} \setminus K) \cap C^2(\Omega)$ is a positive solution of (1.1) in Ω which vanishes on K , then u is identically zero.*

In the last part of this paper we apply this approach to the problem

$$-\Delta u + e^u - 1 = \mu, \quad (1.8)$$

where μ is a bounded measure, as well as removability questions for internal singularities of solutions of (1.1). In that case the natural capacity associated to the problem is

$$C_{\Delta^L \ln L}(K) = \inf\{\|M[\Delta\eta]\|_{L^1} : \eta \in C_0^2(\Omega) : 0 \leq \eta \leq 1, \eta = 1 \text{ in a neighborhood of } K\} \quad (1.9)$$

where $M[\cdot]$ denotes Hardy-Littlewood's maximal function.

Theorem D. *Let $\mu \in \mathfrak{M}_+^b(\Omega)$ be a bounded good measure, then μ vanishes on boundary Borel subsets E with zero $C_{\Delta^L \ln L}$ -capacity.*

A characterization of positive measures which have the property of vanishing on Borel subsets E with zero $C_{N^L \ln L}$ -capacity is also provided. We also give below a result of removability of boundary singularities.

Theorem E. *Let $K \subset \Omega$ be a compact subset with zero $C_{\Delta^L \ln L}$ -capacity. Suppose $u \in C(\Omega \setminus K) \cap C^2(\Omega)$ is a positive solution of (1.1) in $\Omega \setminus K$ which vanishes on $\partial\Omega$, then u is identically zero.*

This note is essentially derived from the preliminary report [27], written in 2004 and left escheated since this period.

2 Good measures

Proof of Theorem A. For $k > 0$, set $\mu_{R,k} = \inf\{k, \mu_R\}$ and denote by u_k the solution of

$$\begin{aligned} -\Delta u_k + e^{u_k} - 1 &= 0 & \text{in } \Omega \\ u_k &= \mu_S + \mu_{R,k} & \text{on } \partial\Omega. \end{aligned} \quad (2.1)$$

Such a solution exists because

$$\exp(\mathbb{P}^\Omega[\mu_S + \mu_{R,k}]) \leq e^k \exp(\mathbb{P}^\Omega[\mu_S])$$

by the maximum principle, and (1.7) implies that $\exp(\mathbb{P}^\Omega[\mu_S + \mu_{R,k}]) - 1 \in L^1(\Omega; \rho dx)$. The sequence u_k is nondecreasing. Since, for any $\zeta \in C_c^{1,1}(\bar{\Omega})$,

$$\int_{\Omega} (-u_k \Delta \zeta + (e^{u_k} - 1)\zeta) dx = \int_{\partial\Omega} \frac{\partial \zeta}{\partial \nu} d(\mu_S + \mu_{R,k}),$$

if we take in particular for test function ζ the solution ζ_0 of

$$\begin{aligned} -\Delta \zeta_0 &= 1 & \text{in } \Omega \\ \zeta_0 &= 0 & \text{on } \partial\Omega, \end{aligned} \quad (2.2)$$

we get

$$\int_{\Omega} (u_k + (e^{u_k} - 1)\zeta_0) dx = - \int_{\partial\Omega} \frac{\partial \zeta_0}{\partial \nu} d(\mu_S + \mu_{R,k}) \leq c \|\mu\|_{\mathfrak{M}}. \quad (2.3)$$

Thus $u = \lim_{k \rightarrow \infty} u_k$ is integrable,

$$\int_{\Omega} (u + (e^u - 1)\zeta_0) dx \leq c \|\mu\|_{\mathfrak{M}},$$

and the convergence of u_k and e^{u_k} to u and e^u hold respectively in $L^1(\Omega)$ and $L^1(\Omega; \rho dx)$ and u satisfies (1.2). $\square$

The proof of the next result is directly inspired by [5] where nonlinear Poisson equations are treated.

Proposition 2.1 *The following properties hold:*

- (i) *If $\mu \in \mathfrak{M}_+(\partial\Omega)$ is a good measure, then any $\tilde{\mu} \in \mathfrak{M}_+(\partial\Omega)$ smaller than μ is good.*
- (ii) *Let $\{\mu_n\}$ be an increasing sequence of good measures which converges to μ in the weak sense of measures. Then μ is good.*
- (iii) *If $\mu \in \mathfrak{M}_+(\partial\Omega)$ is a good measure and $f \in L^1_+(\partial\Omega)$, then $f + \mu$ is a good measure.*

Proof. (i) Let $u = u_\mu$ be the solution of (3.21) and $w = \inf\{u, \mathbb{P}^\Omega[\tilde{\mu}]\}$. Since $\mathbb{P}^\Omega[\tilde{\mu}]$ is a supersolution for (1.1), w is a supersolution too. Furthermore w is nonnegative and $e^w - 1 \in L^1(\Omega; \rho dx)$. By Doob's theorem w admits a boundary trace $\mu^* \in \mathfrak{M}_+(\partial\Omega)$ and $\mu^* \leq \tilde{\mu} \leq \mu$. Let w^* be the solution of

$$\begin{aligned} -\Delta w^* + e^u - 1 &= 0 & \text{in } \Omega \\ w^* &= \tilde{\mu} & \text{on } \partial\Omega. \end{aligned}$$

then $u \geq w \geq w^*$ and [22],

$$\lim_t \int_{\partial\Omega_t} w^*(t, \cdot) \eta dS_t = \int_{\partial\Omega} \eta d\tilde{\mu} \quad \forall \eta \in C(\partial\Omega),$$

(here we denote by $\partial\Omega_t$ the set of $x \in \Omega$ such that $\rho(x) = t > 0$). This implies that the boundary trace of w^* is $\tilde{\mu}$ and thus $\mu^* = \tilde{\mu}$. Set $\Omega_t = \{x \in \Omega : \rho(x) > t\}$ and let v_t be the solution of

$$\begin{aligned} -\Delta v_t + e^{v_t} - 1 &= 0 & \text{in } \Omega_t \\ v_t &= w & \text{on } \partial\Omega_t. \end{aligned}$$

Then $v_t \leq w$ in Ω_t . Furthermore

$$0 < t' < t \implies v_{t'} \leq v_t \quad \text{in } \Omega_t.$$

Then $\tilde{u} = \lim_{t \rightarrow 0} v_t$ exists, the convergence holds in $L^1(\Omega)$ and $e^{v_t} \rightarrow e^{\tilde{u}}$ in $L^1(\Omega; \rho dx)$ (here we use the fact that $e^w \in L^1(\Omega; \rho dx)$). Because

$$\lim_{t \rightarrow 0} \int_{\partial\Omega_t} \tilde{w}(t, \cdot) \eta dS_t = \int_{\partial\Omega} \eta d\tilde{\mu} \quad \forall \eta \in C(\partial\Omega),$$

and $v_t = \tilde{w}$ on $\partial\Omega_t$, it follows that $\tilde{u}$ admits $\tilde{\mu}$ for boundary trace and thus $\tilde{u} = u_{\tilde{\mu}}$.

(ii) Let $u_n = u_{\mu_n}$ be the solutions of (3.21) with boundary value μ_n . The sequence $\{u_n\}$ is increasing. Since

$$\int_{\Omega} (u_n + (e^{u_n} - 1)\zeta_0) dx = - \int_{\partial\Omega} \frac{\partial \zeta_0}{\partial \nu} d\mu_n \leq - \int_{\partial\Omega} \frac{\partial \zeta_0}{\partial \nu} d\mu, \quad (2.4)$$

we conclude as in the proof of Theorem 1, that u_n increases and converges to a solution $u = u_\mu$ of (3.21) with boundary value μ .

(iii) In the proof of (i) we have actually used the following result : *Let w be a nonnegative supersolution of (1.1) such that $e^w \in L^1(\Omega; \rho dx)$ and let $\mu \in \mathfrak{M}_+(\partial\Omega)$ be the boundary trace of w . Then μ is good.* Let $f \in L^1_+(\partial\Omega)$ and μ be an good measure. We denote by $u = u_\mu$ the solution of (3.21). For $k > 0$, set $f_k = \min\{k, f\}$. The function $w_k = u_\mu + \mathbb{P}^\Omega[f_k]$ is a nonnegative supersolution, and, since $\mathbb{P}^\Omega[f_k] \leq k$, $e^{w_k} \in L^1(\Omega; \rho dx)$. Furthermore the boundary trace of w_k is $\mu + f_k$. Therefore $\mu + f_k$ is good. We conclude by II that $\mu + f$ is good $\square$

Remark. The assertions (i) and (ii) in Theorem 1 are still valid if we replace $r \mapsto e^r - 1$ by any continuous nondecreasing function f vanishing at 0.

3 The Orlicz space framework

3.1 Orlicz capacities

The set of nonnegative measures μ on $\partial\Omega$ such that

$$\exp(\mathbb{P}^\Omega[\mu]) \in L^1(\Omega; \rho dx) \quad (3.1)$$

is not a linear space, but it is a convex subset of $\mathfrak{M}_+(\partial\Omega)$. The role of this set comes from the fact that any measure in $M^{exp}(\partial\Omega)$ is good. Put

$$p(t) = \operatorname{sgn}(s)(e^s - 1), \quad P(t) = e^{|t|} - 1 - |t|,$$

and

$$\bar{p}(s) = \operatorname{sgn}(s) \ln(|s| + 1), \quad P^*(t) = (|t| + 1) \ln(|t| + 1) - |t|.$$

Then P and P^* are complementary functions in the sense of Legendre. Furthermore Young inequality holds

$$xy \leq P(x) + P^*(y) \quad \forall (x, y) \in \mathbb{R} \times \mathbb{R},$$

with equality if and only if $x = \bar{p}(y)$ or $y = p(x)$. It is classical to define

$$M_P(\Omega; \rho dx) = \{\phi \in L^1_{loc}(\Omega) : P(\phi) \in L^1(\Omega; \rho dx)\}, \quad (3.2)$$

$$M_{P^*}(\Omega; \rho dx) = \{\phi \in L^1_{loc}(\Omega) : P^*(\phi) \in L^1(\Omega; \rho dx)\}. \quad (3.3)$$

The Orlicz spaces $L_P(\Omega; \rho dx)$ and $L_{P^*}(\Omega; \rho dx)$ are the vector spaces spanned respectively by $M_P(\Omega; \rho dx)$ and $M_{P^*}(\Omega; \rho dx)$. They are endowed with the Luxemburg norms

$$\|\phi\|_{L_{P_\rho}} = \inf \left\{ k > 0 : \int_{\Omega} P\left(\frac{\phi}{k}\right) \rho dx \leq 1 \right\}. \quad (3.4)$$

and

$$\|\phi\|_{L_{P^*_\rho}} = \inf \left\{ k > 0 : \int_{\Omega} P^*\left(\frac{\phi}{k}\right) \rho dx \leq 1 \right\}. \quad (3.5)$$

Furthermore the Hölder-Young inequality asserts [17]

$$\left| \int_{\Omega} \phi \psi \rho dx \right| \leq \|\phi\|_{L_{P_\rho}} \|\psi\|_{L_{P^*_\rho}} \quad \forall (\phi, \psi) \in L_P(\Omega; \rho dx) \times L_{P^*}(\Omega; \rho dx). \quad (3.6)$$

Since P^* satisfies the Δ_2 -condition, $M_{P^*}(\Omega; \rho dx) = L_{P^*}(\Omega; \rho dx)$ and $L_P(\Omega; \rho dx)$ is the dual space of $L_{P^*}(\Omega; \rho dx)$, (see [13], [2]). Furthermore, since

$$\frac{|a| \ln(1 + |a|)}{2} \leq P^*(a) \leq |a| \ln(1 + |a|) \quad \forall a \in \mathbb{R},$$

the space $L_{P^*}(\Omega; \rho dx)$ is associated with the class $L \ln L(\Omega; \rho dx)$ and to the Hardy-Littlewood maximal function (see [13]). We recall its definition: we consider a cube Q_0 containing Ω , with sides parallel to the axes. If $f \in L^1(\Omega)$ we denote by $\tilde{f}$ its extension by 0 in $Q_0 \setminus \Omega$ and put

$$M_{Q_0}[f](x) = \sup \left\{ \frac{1}{|Q|} \int_Q |f|(y) dy : Q \in \mathcal{Q}_x \right\}$$

where $\mathcal{Q}_x$ denotes the set of all cubes containing x and contained in Q_0 , with sides parallel to the axes. Thus

$$\|f\|_{L \ln L_\rho} := \int_{Q_0} M_{Q_0}[f](x) \rho dx \approx \|f\|_{L_{P^*}_\rho}. \quad (3.7)$$

Definition 3.1 *The space of all measures on $\partial\Omega$ such that $\mathbb{P}^\Omega[\mu] \in L_P(\Omega; \rho dx)$ is denoted by $B^{\exp}(\partial\Omega)$ and endowed with the norm*

$$\|\mu\|_{B^{\exp}} = \|\mathbb{P}^\Omega[\mu]\|_{L_{P_\rho}}. \quad (3.8)$$

The subset of measures such that $\exp(\mathbb{P}^\Omega[\mu]) \in L^1(\Omega; \rho dx)$ is denoted by $\mathfrak{M}^{\exp}(\partial\Omega)$.

The following result follows immediately from the definition of the Luxemburg norm.

Proposition 3.2 *If $\mu \in B^{\exp}(\partial\Omega)$ there exists $a_0 > 0$ such that $a\mu \in \mathfrak{M}^{\exp}(\partial\Omega)$ for all $0 \leq a < a_0$. Conversely, if $\mu \in \mathfrak{M}^{\exp}(\partial\Omega)$, then $a\mu \in B^{\exp}(\partial\Omega)$ for all $a > 0$.*

The analytic characterization of $B^{\exp}(\partial\Omega)$ can be done in introducing the space of normal derivatives of Green potentials of $L \ln L$ functions:

$$N^{L \ln L}(\partial\Omega) = \{\eta : \rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta]) \in L \ln L(\Omega; \rho dx)\}. \quad (3.9)$$

where ρ^* is a smooth positive function with value ρ in a neighborhood of $\partial\Omega$. Then

$$\left| \int_{\partial\Omega} \eta d\mu \right| = \left| \int_{\Omega} \mathbb{P}^\Omega[\mu] \Delta(\rho^* \mathbb{P}^\Omega[\eta]) dx \right| \leq \|\mathbb{P}^\Omega[\mu]\|_{L_{P_\rho}} \|\rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta])\|_{L_{P^*}_\rho}. \quad (3.10)$$

We take for norm on $N^{L \ln L}(\partial\Omega)$

$$\|\eta\|_{N^{L \ln L}} = \|\rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta])\|_{L_{P^*}_\rho}, \quad (3.11)$$

and define the $C_{N^{L \ln L}}$ -capacity of a compact subset K of $\partial\Omega$ by

$$C_{N^{L \ln L}}(K) = \inf \{ \|\eta\|_{N^{L \ln L}} : \eta \in C^2(\partial\Omega), 0 \leq \eta \leq 1, \eta \geq 1 \text{ in a neighborhood of } K \}. \quad (3.12)$$

Considering the bilinear form $\mathcal{H}$ on $L_{P_\rho^*}(\partial\Omega) \times L_{P_\rho}(\partial\Omega)$

$$\mathcal{H}(\eta, \mu) := - \int_{\Omega} \mathbb{P}^\Omega[\mu] \Delta(\rho^* \mathbb{P}^\Omega[\eta]) dx \quad (3.13)$$

then

$$\begin{aligned} \mathcal{H}(\eta, \mu) &= - \int_{\Omega} \int_{\partial\Omega} P^\Omega(x, y) d\mu(y) \Delta(\rho^* \mathbb{P}^\Omega[\eta])(x) dx \\ &= - \int_{\partial\Omega} \int_{\Omega} \Delta(\rho^* \mathbb{P}^\Omega[\eta])(x) P^\Omega(x, y) dx d\mu(y). \end{aligned} \quad (3.14)$$

It is classical to define

$$C_{N^L \ln L}^*(K) = \sup\{\mu(K) : \mu \in \mathfrak{M}_+(\partial\Omega), \mu(K^c) = 0, \|\mathbb{P}^\Omega[\mu]\|_{L_{P_\rho}} \leq 1\}. \quad (3.15)$$

The following result due to Fuglede [14] (and to Aissaoui-Benkirane in the Orlicz space framework [2]) is a consequence of the Kneser-Fan min-max theorem.

Proposition 3.3 *For any compact set $K \subset \partial\Omega$, there holds*

$$C_{N^L \ln L}^*(K) = C_{N^L \ln L}(K). \quad (3.16)$$

As a direct consequence of (3.10), we have the following

Proposition 3.4 *If $\mu \in B_+^{\text{exp}}(\partial\Omega)$, it does not charge Borel subsets with $C_{N^L \ln L}$ -capacity zero.*

3.2 Good measures and removable sets

Proof of Theorem B. Let K be a compact subset with $C_{N^L \ln L}$ -capacity zero. There exist a sequence $\{\eta_n\} \subset C^2(\partial\Omega)$ such that $0 \leq \eta_n \leq 1$, $\eta_n = 1$ in a neighborhood of K and

$$\lim_{n \rightarrow \infty} \|\eta_n\|_{N^L \ln L} = \|\rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta_n])\|_{L_{P_\rho^*}} = 0. \quad (3.17)$$

Take $\rho^* \mathbb{P}^\Omega[\eta_n]$ as a test function, then

$$\int_{\Omega} (-u \Delta(\rho^* \mathbb{P}^\Omega[\eta_n]) + (e^u - 1) \rho^* \mathbb{P}^\Omega[\eta_n]) dx = - \int_{\partial\Omega} \frac{\partial(\rho^* \mathbb{P}^\Omega[\eta_n])}{\partial\nu} d\mu$$

Since $\frac{\partial(\rho^* \mathbb{P}^\Omega[\eta_n])}{\partial\nu} = \eta_n$ and $\mu > 0$, there holds $-\int_{\partial\Omega} \frac{\partial(\rho^* \mathbb{P}^\Omega[\eta_n])}{\partial\nu} d\mu \geq \mu(K)$.

Furthermore

$$\left| \int_{\Omega} u \Delta(\rho^* \mathbb{P}^\Omega[\eta_n]) dx \right| \leq \|u\|_{L_{P_\rho}} \|\rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta_n])\|_{L_{P_\rho^*}}. \quad (3.18)$$

Then

$$\mu(E) \leq \int_{\Omega} (e^u - 1) \rho^* \mathbb{P}^{\Omega}[\eta_n] dx + \|u\|_{L_{F\rho}} \|\rho^{-1} \Delta(\rho^* \mathbb{P}^{\Omega}[\eta_n])\|_{L_{P\rho}^*}.$$

By the same argument as in [5], $\lim_{n \rightarrow \infty} \rho^* \mathbb{P}^{\Omega}[\eta_n] = 0$, a.e. in Ω , and there exists a nonnegative L_{ρ}^1 -function Φ such that $0 \leq \rho^* \mathbb{P}^{\Omega}[\eta_n] \leq \Phi$. By (3.17), (3.18) and Lebesgue's theorem, $\mu(E) = 0$. $\square$

Definition 3.5 *A subset $E \subset \partial\Omega$ is said removable for equation (1.1), if and only if any positive solution $u \in C^2(\Omega)$ of (1.1) in Ω , which is continuous in $\bar{\Omega} \setminus E$ and vanishes on $\partial\Omega \setminus E$, is identically zero.*

Proof of Theorem C. Let $u \in C(\bar{\Omega} \setminus K)$ be a solution of (1.1) which is zero on $\partial\Omega \setminus K$. Let $\{\eta_n\} \subset C^2(\partial\Omega)$ such that $0 \leq \eta_n \leq 1$, $\eta_n = 1$ in a neighborhood $\mathcal{V}$ of K and (3.17) holds. Put $\theta_n = 1 - \eta_n$. Put $\rho_K(x) = \text{dist}(x, K)$. Then, as a consequence of Keller-Osserman estimate and the fact that u vanishes on K^c , there holds

$$u(x) \leq C \frac{\rho(x) \ln(2/\rho_K(x))}{\rho_K(x)} + D.$$

Thus the function $\zeta_n = \rho^* \mathbb{P}^{\Omega}[\theta_n]$ is an admissible test function for u , and

$$\int_{\Omega} (-u \Delta \zeta_n + (e^u - 1) \zeta_n) dx = 0.$$

Clearly $\mathbb{P}^{\Omega}[\theta_n] = 1 - \mathbb{P}^{\Omega}[\eta_n]$ and

$$\Delta \zeta_n = \Delta \rho^* - \Delta(\rho^* \mathbb{P}^{\Omega}[\eta_n])$$

Inasmuch we can modify ρ^* in order to have $-\Delta \rho^* \geq 0$, in which case $\rho^* = \rho$ near $\partial\Omega$ is replaced by $\rho^* \approx \rho$, we derive

$$\begin{aligned} - \int_{\Omega} u \Delta \zeta_n dx &= - \int_{\Omega} \zeta_n^{-1} \Delta \zeta_n u \zeta_n dx \\ &\geq -2^{-1} \int_{\Omega} (e^u - 1 - u) \zeta_n dx - \int_{\Omega} Q(\zeta_n^{-1} \Delta(\rho^* \mathbb{P}^{\Omega}[\eta_n])) \zeta_n dx, \end{aligned}$$

where

$$Q(r) = (|r| + 2^{-1}) \ln(2|r| + 1) - |r| \leq C|r| \ln(|r| + 1) \quad \forall r \in \mathbb{R}.$$

Therefore

$$\int_{\Omega} (e^u - 1 - u) \zeta_n dx \leq 2C \int_{\Omega} |\Delta(\rho^* \mathbb{P}^{\Omega}[\eta_n])| \ln(1 + \rho^{-2} |\Delta(\rho^* \mathbb{P}^{\Omega}[\eta_n])|) dx, \quad (3.19)$$

since $\zeta_n^{-1} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \leq \rho^{-2} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|$. Furthermore

$$\begin{aligned} \ln(1 + \rho^{-2} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) &= -\ln \rho + \ln(\rho + \rho^{-1} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) \\ &\leq -\ln \rho + \ln(1 + \rho^{-1} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) \end{aligned}$$

But (we can assume $\rho \leq 1$)

$$\begin{aligned} &\int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln(1 + \rho^{-2} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) dx \\ &\leq -\int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln \rho dx + \int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln(1 + \rho^{-1} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) dx, \end{aligned}$$

and

$$\begin{aligned} &\int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln \rho^{-1} dx \\ &= \int_{\{|\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \leq 1\}} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln \rho^{-1} dx + \int_{\{|\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| > 1\}} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln \rho^{-1} dx \\ &\leq \int_{\{|\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \leq 1\}} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln \rho^{-1} dx + \int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln(1 + \rho^{-1} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) dx \end{aligned}$$

But

$$\lim_{n \rightarrow \infty} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| = 0 \quad \text{a. e. in } \Omega,$$

at least up to some subsequence. Thus

$$\lim_{n \rightarrow \infty} \int_{\Omega} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])| \ln(1 + \rho^{-2} |\Delta(\rho^* \mathbb{P}^\Omega[\eta_n])|) dx = 0 \quad (3.20)$$

Using (4.12), we derive $u = 0$.

Conversely, assume that $C_{N^L \ln L}(K) > 0$. By Proposition 3.3 there exists a non negative non-zero measure $\mu \in \mathfrak{M}_+(\partial\Omega)$ such that $\mu(K^c) = 0$ in the space $B_+^{exp}(\partial\Omega)$. This means that $\theta\mu \in M_+^{exp}(\partial\Omega)$ for some $\theta > 0$. Thus problem (3.21) admits a solution. $\square$

Several questions can be addressed

- 1- If a measure μ is good does there exist an increasing sequence of measures $\{\mu_n\}$ which converges to μ such that $\theta_n \mu_n$ is admissible for some $\theta_n > 0$?
- 2- If a measure μ , singular with respect to $\mathcal{H}^{N-1}$ is good does it exist an increasing sequence of admissible measures $\{\mu_n\}$ converging to μ ?
- 3- If a measure μ does not charge Borel sets with $C^{L \ln L}$ -capacity zero, does it exist $\theta > 0$ such that $\theta\mu$ is admissible?
- 4- If a singular measure μ is good, then $(1 - \delta)\mu$ is admissible for any $\delta \in (0, 1)$?

3.3 More general nonlinearities

$$\begin{aligned} -\Delta u + P(u) &= 0 && \text{in } \Omega \\ u &= \mu && \text{on } \partial\Omega, \end{aligned} \quad (3.21)$$

where P is a convex increasing function vanishing at 0 and such that $\lim_{r \rightarrow \infty} P(r)/r = \infty$: In Theorem A- P , (1.7) should be replaced by

$$P(\mathbb{P}^\Omega[\mu_S]) \in L^1(\Omega; \rho \, dx). \quad (3.22)$$

In Proposition 2.1- P , (i), (ii) and (iii) still hold. For simplicity we assume that P is a N -function in the sense of Orlicz spaces i.e.

$$P(r) = \int_0^r p(s) \, ds$$

where p is increasing, vanishes at 0 and tends to infinity at infinity. Let P^* be the conjugate N -function, $L_P(\Omega; \rho \, dx)$ and $L_{P^*}(\Omega; \rho \, dx)$ the corresponding Orlicz spaces endowed with the Luxemburg norms. Then Proposition 3.4- P is valid, provided the space

$$B^P(\partial\Omega) := \{\mu \in \mathfrak{M}(\partial\Omega) : \mathbb{P}^\Omega[\mu] \in L_P(\Omega; \rho \, dx)\}$$

endowed with its natural norm replaces $B^{\exp}(\partial\Omega)$ with the norm (4.10). We set

$$N^{P^*}(\partial\Omega) = \{\eta : \rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta]) \in L_{P^*}(\Omega; \rho \, dx)\}$$

with corresponding norm

$$\|\eta\|_{N^{P^*}} = \|\rho^{-1} \Delta(\rho^* \mathbb{P}^\Omega[\eta])\|_{L_{P^*}}$$

and the corresponding capacity $C_{N^{P^*}}$. The proof of Proposition 3.4- P , consequence of Young inequality between Orlicz space is valid with modification. **However**, it appears that the full characterization of removable sets cannot be adapted without further properties of the function P^* like the Δ_2 -condition. Some results in this directions have been obtained in [18] where a necessary and sufficient condition for removability of boundary set is given, under a very restrictive growth condition on P which reduces the nonlinearity to power-like with limited exponent.

4 Internal measures

Several above techniques can be extended to the following types of problem in which $\mu \in \mathfrak{M}_+^b(\Omega)$:

$$\begin{aligned} -\Delta u + e^u - 1 &= \mu && \text{in } \Omega \\ u &= 0 && \text{on } \partial\Omega. \end{aligned} \quad (4.1)$$

For this specific problem many interesting results can be found in [3] where the analysis of μ is made by comparison with the Hausdorff measure in dimension $(N-2)$, $\mathcal{H}^{N-2}$. It is proved in particular that if a measure μ satisfies $\mu \leq 4\pi\mathcal{H}^{N-2}$, then problem (3.21) admits a solution, while if μ charges some Borel set A with Hausdorff dimension less than $N - 2$, no solution exists. The results we provide are different and in the Orlicz capacities framework.

We define the classes $M_P(\Omega)$ and $M_{P^*}(\Omega)$ similarly to $M_P(\Omega; \rho dx)$ and $M_{P^*}(\Omega; \rho dx)$ except that the measure ρdx is replaced by the Lebesgue measure dx . The Orlicz spaces $L_P(\Omega)$ and $L_{P^*}(\Omega)$ are defined from $M_P(\Omega)$ and $M_{P^*}(\Omega)$ and endowed with the respective Luxemburg norms $\|\cdot\|_P$ and $\|\cdot\|_{P^*}$. We put

$$\Delta^{L \ln L}(\Omega) := \{\eta \in W_0^{1,1}(\Omega) : \Delta\eta \in L_{P^*}(\Omega)\}, \quad (4.2)$$

with natural norm

$$\|\eta\|_{\Delta^{L \ln L}} := \|\eta\|_{L^1} + \|\Delta\eta\|_{L_{P^*}}. \quad (4.3)$$

The norm in $M_{P^*}(\Omega)$ can be characterized using the Hardy-Littlewood maximal function $f \mapsto M_{Q_0}[f]$ since

$$\|f\|_{L \ln L} := \int_{Q_0} M_{Q_0}[f](x) dx \approx \|f\|_{L_{P^*}}. \quad (4.4)$$

Since P^* satisfies the Δ_2 -condition, $C_0^\infty(\Omega)$ is dense in $\Delta^{L \ln L}(\Omega)$. Inequality (3.10) becomes

$$\left| \int_{\Omega} \eta d\mu \right| = \left| \int_{\Omega} \eta \Delta \mathbb{G}^\Omega[\mu] dx \right| = \left| \int_{\Omega} \mathbb{G}^\Omega[\mu] \Delta \eta dx \right| \leq \|\mathbb{G}^\Omega[\mu]\|_{L_P} \|\Delta\eta\|_{L_{P^*}}, \quad (4.5)$$

for $\eta \in C_c^{1,1}(\bar{\Omega})$. We define the $C_{\Delta^{L \ln L}}$ -capacity of a compact subset K of $\partial\Omega$ by

$$C_{\Delta^{L \ln L}}(K) = \inf\{\|\Delta\eta\|_{L_{P^*}} : \eta \in C_c^2(\Omega), \eta \geq 0, \eta \geq 1 \text{ in a neighborhood of } K\}, \quad (4.6)$$

By the min-max theorem there holds

$$C_{\Delta^{L \ln L}}(K) = \sup\{\mu(K) : \mu \in \mathfrak{M}_+^b(\Omega), \mu(K^c) = 0, \|\mathbb{G}^\Omega[\mu]\| \leq 1\}. \quad (4.7)$$

Remark. The characterization of the $C_{\Delta^{L \ln L}}$ -capacity is not simple, however, by a result of [7, Th1], there holds

$$\|D^2\eta\|_{L^{1,\infty}} \leq C \|\Delta\eta\|_{L \ln L} \quad \forall \eta \in C_c^{1,1}(\bar{\Omega}) \quad (4.8)$$

where $L^{1,\infty}(\Omega)$ denotes the weak L^1 -space, that is the space of all measurable functions f defined in Ω satisfying

$$meas(\{x \in \Omega : |f(x)| > t\}) \leq \frac{c}{t}, \quad \forall t > 0 \quad (4.9)$$

and $\|f\|_{L^{1,\infty}}$ is the smallest constant such that (4.9) holds.

Definition 4.1 *The space of all bounded measures in Ω such that $\mathbb{G}^\Omega[\mu] \in L_P(\Omega)$ is denoted by $B^{\text{exp}}(\Omega)$, with norm*

$$\|\mu\|_{B^{\text{exp}}} = \|\mathbb{G}^\Omega[\mu]\|_{L_P}. \quad (4.10)$$

The subset of measures such that $\exp(\mathbb{G}^\Omega[\mu]) \in L^1(\Omega)$ is denoted by $\mathfrak{M}^{\text{exp}}(\Omega)$.

Thus Proposition 3.4 and Theorem B are valid under the form

Proposition 4.2 *If $\mu \in B_+^{\text{exp}}(\Omega)$, it does not charge Borel subsets with $C_{\Delta L \ln L}$ -capacity zero.*

Theorem 4.3 *Let $\mu \in \mathfrak{M}_+(\Omega)$ be a good measure, then μ vanishes on Borel subset E with zero $C_{\Delta L \ln L}$ -capacity.*

Theorem C has the following counter part

Theorem 4.4 *Let $K \subset \Omega$ be compact. Any solution of*

$$\begin{aligned} -\Delta u + e^u - 1 &= 0 && \text{in } \Omega \setminus K \\ u &= 0 && \text{on } \partial\Omega, \end{aligned} \quad (4.11)$$

vanishes identically in Ω if and only if $C_{\Delta L \ln L}(K) = 0$.

Proof. Let $u \in C(\Omega \setminus K)$ be a solution of (1.1) which is zero on $\partial\Omega$. Let $\{\eta_n\} \subset C^2(\Omega)$ such that $0 \leq \eta_n \leq 1$, $\eta_n = 1$ in a neighborhood $\mathcal{V}$ of K and (3.17) holds. Put $\rho_K(x) = \text{dist}(x, K)$. Then, as a consequence of Keller-Osserman estimate for this type of nonlinearity (see [25]), there holds

$$u(x) \leq C \ln(2/\rho_K(x)) + D.$$

Put $\theta_n = 1 - \eta_n$. Then the function $\zeta_n = \phi_1 \theta_n$ (ϕ_1 being the first eigenfunction of $-\Delta$) is an admissible test function for u , and

$$\int_{\Omega} (-u \Delta \zeta_n + (e^u - 1) \zeta_n) dx = 0.$$

We derive

$$\begin{aligned} - \int_{\Omega} u \Delta \zeta_n dx &= - \int_{\Omega} \zeta_n^{-1} \Delta \zeta_n u dx \\ &\geq -2^{-1} \int_{\Omega} (e^u - 1 - u) dx - \int_{\Omega} Q(\Delta(\zeta_n)) dx. \end{aligned}$$

Therefore

$$\int_{\Omega} (e^u - 1 - u) \zeta_n dx \leq 2C \int_{\Omega} |\Delta \zeta_n| \ln(1 + |\Delta \zeta_n|) dx, \quad (4.12)$$

Since the right-hand side goes to zero when $n \rightarrow \infty$, the conclusion follows. $\square$

4.1 More on good measures

The main characterization of good measures is the following

Theorem 4.5 *Assume μ is a positive good measure, then there exists an increasing sequence $\{\mu_n\} \subset B_+^{exp}(\Omega)$ which converges weakly to μ .*

The proof will necessitate several intermediate results which are classical in the framework of Lebesgue measure or Bessel capacities, but appear to be new for Orlicz capacities.

Lemma 4.6 *Let $K \subset \Omega$, then $C_{\Delta^{L \ln L}}(K) = 0$ if and only if there exists $\eta \in \Delta^{L \ln L}(\Omega)$ such that $\eta \geq 0$ and $K \subset \{y \in \Omega : \eta(y) = \infty\}$.*

Proof. By the definition of the capacity, for any $\lambda > 0$ and $\eta \in \Delta^{L \ln L}(\Omega)$, $\eta \geq 0$,

$$C_{\Delta^{L \ln L}}(\{y \in \Omega : \eta(y) \geq \lambda\}) \leq \frac{1}{\lambda} \|\eta\|_{\Delta^{L \ln L}}. \quad (4.13)$$

This implies

$$C_{\Delta^{L \ln L}}(\{y \in \Omega : \eta(y) = \infty\}) = 0.$$

□

Lemma 4.7 *Suppose $\{\eta_j\}$ is a Cauchy sequence in $\Delta^{L \ln L}(\Omega)$. Then there exist a subsequence $\{\eta_{j_\ell}\}$ and $\eta \in \Delta^{L \ln L}(\Omega)$ such that*

$$\lim_{j_\ell \rightarrow \infty} \eta_{j_\ell} = \eta,$$

uniformly outside an open subset of arbitrary small $C_{\Delta^{L \ln L}}$ -capacity.

Proof. By Lemma 4.6, η_j and η are finite outside a set F with zero $C_{\Delta^{L \ln L}}$ -capacity. There exists a subsequence $\{\eta_{j_\ell}\}$ such that

$$\|\eta_{j_\ell} - \eta\|_{\Delta^{L \ln L}} \leq 2^{-2^\ell}.$$

Put $E_\ell = \{y \in \Omega : \eta_{j_\ell} - \eta(y) \geq 2^{-\ell}\}$. By (4.13) $C_{\Delta^{L \ln L}}(E_\ell) \leq 2^{-\ell}$, and if $G_m = \cup_{\ell \geq m} E_\ell$, there holds $C_{\Delta^{L \ln L}}(G_m) \leq 2^{1-m}$. Therefore

$$C_{\Delta^{L \ln L}}(\cap_{m \geq 1} G_m) = 0.$$

Since for any $y \notin G_m \cup F$, there holds

$$|(\eta_{j_\ell} - \eta)(y)| \leq 2^{-\ell},$$

the claim follows. □

Lemma 4.8 *If $\eta \in \Delta^{L \ln L}(\partial\Omega)$ it has a unique quasi-continuous representative with respect to the capacity $C_{\Delta^{L \ln L}}$.*

Proof. Uniqueness is clear as in the Bessel capacity case [1, Chap 6]. Let $\{\eta_j\} \subset C_0^2(\Omega)$ be a sequence which converges to η in $\Delta^{L \ln L}(\Omega)$. Then there exists a subsequence $\{\eta_{j_\ell}\}$ such that η_{j_ℓ} converges to η uniformly on the complement of an open set of arbitrarily small $C_{\Delta^{L \ln L}}$ -capacity. This is the claim. $\square$

Proof of Theorem 4.5. The method is adapted from [12, Th 8], [4, Lemma 4.2]. By Lemma 4.8 we can define the functional h on $\Delta^{L \ln L}(\Omega)$ by

$$h(\eta) = \int_{\Omega} \bar{\eta}_+ d\mu \quad \forall \eta \in \Delta^{L \ln L}(\Omega),$$

where $\bar{\eta}$ stands for the $C_{\Delta^{L \ln L}}$ -quasi-continuous representative of η . Notice that we can write

$$h(\eta) = - \int_{\Omega} \Delta \mathbb{G}^{\Omega}[\mu] \eta dx = - \int_{\Omega} \mathbb{G}^{\Omega}[\mu] \Delta \eta dx$$

The following steps are similar to the previous proofs:

Step 1- The functional h is convex, positively homogeneous and l.s.c. The convexity and the homogeneity are clear. If $\eta_n \rightarrow \eta$ in $\Delta^{L \ln L}(\partial\Omega)$, then by Lemma 4.8 we can extract a subsequence which is converging everywhere except for a set with zero capacity. The conclusion follows from Fatou's lemma.

Step 2- Since $L_P(\Omega)$ is the dual space of $L_{P^*}(\Omega)$, for any continuous linear form α on $\Delta^{L \ln L}(\Omega)$ there exists $\beta \in L_P(\Omega)$ such that

$$\alpha(\eta) = - \int_{\Omega} \beta \Delta \eta dx \quad \forall \eta \in \Delta^{L \ln L}(\Omega).$$

Therefore, in the sense of distributions there holds

$$\alpha(\eta) = - \langle \Delta \beta, \eta \rangle \quad \forall \eta \in C_0^{\infty}(\Omega).$$

Step 3- By the geometric Hahn-Banch theorem, h is the upper convex hull of the continuous linear functionals on $\Delta^{L \ln L}(\partial\Omega)$ it dominates. Fix a function $\eta_0 \in C_0^{\infty}(\Omega)$ and $\epsilon > 0$, there exists a continuous linear form α on $\Delta^{L \ln L}(\Omega)$ and constants a, b such that

$$a + bt + \alpha(\eta) \leq 0 \quad \forall (\eta, t) \in \mathcal{E} := \{(\eta, t) \in \Delta^{L \ln L}(\Omega) \times \mathbb{R} : h(\eta) \leq t\},$$

and

$$a + b(h(\eta_0) - \epsilon) + \alpha(\eta_0) > 0.$$

The same ideas as in [4, Lemma 4.2] yields successively to $a = 0$ and $b < 0$. If we put $\sigma(\eta) = -b^{-1}\alpha(\eta)$ we derive $\sigma(\eta) \leq h(\eta)$ for all $\eta \in \Delta^{L \ln L}(\Omega)$. This implies in particular that $\sigma(\eta) \leq 0$ if $\eta \leq 0$, thus σ is a positive linear form on $\Delta^{L \ln L}(\Omega)$. Therefore there exists a Radon measure ν on Ω and $\beta \in L_P(\Omega)$ such that $-\Delta\beta = \nu$, $0 \leq \nu \leq \mu$ and

$$\int_{\Omega} \eta_0 d\mu \leq \epsilon + \int_{\Omega} \eta_0 d\nu.$$

Step 4- Considering an increasing sequence of compact sets K_j such that $K_j \subset \overset{\circ}{K}_{j+1}$ and $\cup_j K_j = \Omega$, we construct for each $j \in \mathbb{N}^*$ a Radon measure ν_j and $\beta_j \in L_P(\Omega)$ such that $-\Delta\beta_j = \nu_j$, $0 \leq \nu_j \leq \mu$ and

$$\int_{K_j} d\mu \leq j^{-1} + \int_{K_j} d\nu_j.$$

At last we can assume that the sequence $\{\nu_j\}$ is increasing since if $-\Delta\beta_j = \nu_j$ for $j = 1, 2$, then

$$-\Delta\beta_{1,2} = \sup\{\nu_1, \nu_2\} \leq \nu_1 + \nu_2 = -\Delta\beta_1 - \Delta\beta_2$$

thus $\beta_{1,2} \in L_P(\Omega)$. Iterating this process, we can replace the sequence $\{\nu_j\}$ by $\{\nu'_j\} := \{\nu_1, \sup\{\nu_1, \nu_2\}, \sup\{\nu_3, \sup\{\nu_1, \nu_2\}\} \dots\}$. The sequence $\{\nu'_j\}$ is increasing, converges to μ and since $\beta_j = \mathbb{G}^{\Omega}[\nu'_j]$ with $\beta_j \in L_P(\Omega)$, ν'_j belongs to $B^{exp}(\Omega)$. $\square$

As a consequence of this result and the characterization of linear functionals over $L \ln L(\Omega)$, the following result holds.

Corollary 4.9 *Assume μ is a bounded positive good measure in Ω , then there exists an increasing sequence of positive measures ν_j in Ω and positive real numbers θ_j such that ν_j to μ in the weak sense of measures and $\exp(\theta_j \mathbb{G}^{\Omega}[\nu_j]) \in L^1(\Omega)$.*

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