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Samy Skander Bahoura

► **To cite this version:**

| Samy Skander Bahoura. About Brezis-Merle Problem in dimension 2.. 2016. hal-00149613v5

**HAL Id: hal-00149613**

**<https://hal.science/hal-00149613v5>**

Preprint submitted on 12 Jan 2016 (v5), last revised 3 Aug 2020 (v9)

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# ABOUT BREZIS-MERLE PROBLEM WITH LIPSCHITZ CONDITION.

SAMY SKANDER BAHOURA

ABSTRACT. We give a blow-up analysis for Brezis-Merle problem with Dirichlet condition. As an application, we have another proof for Brezis-Merle Problem with Lipschitz condition.

**Mathematics Subject Classification:** 35J60 35B45 35B50

Keywords: blow-up, boundary, Dirichlet condition, a priori estimate, Lipschitz condition.

## 1. INTRODUCTION AND MAIN RESULTS

We set  $\Delta = -(\partial_{11} + \partial_{22})$  on open set  $\Omega$  of  $\mathbb{R}^2$  with a smooth boundary.

We consider the following equation:

$$(P) \begin{cases} \Delta u = V e^u & \text{in } \Omega \subset \mathbb{R}^2, \\ u = 0 & \text{in } \partial\Omega. \end{cases}$$

Here, we assume that:

$$0 \leq V \leq b < +\infty, \quad e^u \in L^1(\Omega) \text{ and } u \in W_0^{1,1}(\Omega).$$

We can see in [6] a nice formulation to this problem  $(P)$  in the sens of the distributions. This Problem arises in geometrical and physical problems, see for example [1, 2, 16, 17]. The above equation was studied by many authors, with or without the boundary condition, also for Riemannian surfaces, see [1-18], where one can find some existence and compactness results. In [5] we have the following important Theorem,

**Theorem A**(Brezis-Merle [5]).*For  $(u_i)_i$  and  $(V_i)_i$  two sequences of functions relative to  $(P)$  with,*

$$0 < a \leq V_i \leq b < +\infty$$

*then it holds,*

$$\sup_K u_i \leq c,$$

*with  $c$  depending on  $a, b, K$  and  $\Omega$ .*

One can find in [5] an interior estimate if we assume  $a = 0$ , but we need an assumption on the integral of  $e^{u_i}$ , namely, we have:

**Theorem B**(Brezis-Merle [5]).*For  $(u_i)_i$  and  $(V_i)_i$  two sequences of functions relative to the problem (P) with,*

$$0 \leq V_i \leq b < +\infty \text{ and } \int_{\Omega} e^{u_i} dy \leq C,$$

*then it holds;*

$$\sup_K u_i \leq c,$$

*with  $c$  depending on  $b, C, K$  and  $\Omega$ .*

When  $a = 0$ , the boundedness of  $\int_{\Omega} e^{u_i}$  is a necessary condition to work on the problem (P) as showed in [5] by the following counterexample.

**Theorem C**(Brezis-Merle [5]).*There are two sequences  $(u_i)_i$  and  $(V_i)_i$  of the problem (P) with,*

$$0 \leq V_i \leq b < +\infty \text{ and } \int_{\Omega} e^{u_i} dy \leq C,$$

*such that,*

$$\sup_{\Omega} u_i \rightarrow +\infty.$$

Note that for the problem (P), by using the Pohozaev identity, we can prove that  $\int_{\Omega} e^{u_i}$  is uniformly bounded when  $0 < a \leq V_i \leq b < +\infty$  and  $\|\nabla V_i\|_{L^{\infty}} \leq A$  and  $\Omega$  starshaped, when  $a = 0$  and  $\nabla \log V_i$  is uniformly bounded, we can bound uniformly  $\int_{\Omega} V_i e^{u_i}$ . In [14], Ma-Wei have proved that those results stay true for all open sets not necessarily starshaped.

In [8], Chen-Li have proved that if  $a = 0$  and  $\nabla \log V_i$  is uniformly bounded, then the functions are uniformly bounded near the boundary.

In [8], Chen-Li have proved that if  $a = 0$  and  $\int_{\Omega} e^{u_i}$  is uniformly bounded and  $\nabla \log V_i$  is uniformly bounded, then we have the compactness result directly. Ma-Wei in [14], extend this result in the case where  $a > 0$ .

If we assume  $V$  more regular, we can have another type of estimates, a sup + inf type inequalities. It was proved by Shafrir see [15], that, if  $(u_i)_i, (V_i)_i$  are two sequences of functions solutions of the previous equation without assumption on the boundary and,  $0 < a \leq V_i \leq b < +\infty$ , then we have the following interior estimate:

$$C\left(\frac{a}{b}\right) \sup_K u_i + \inf_{\Omega} u_i \leq c = c(a, b, K, \Omega).$$

One can see in [9] an explicit value of  $C\left(\frac{a}{b}\right) = \sqrt{\frac{a}{b}}$ . In his proof, Shafrir has used a blow-up function, the Stokes formula and an isoperimetric inequality, see [2]. For Chen-Lin, they have used the blow-up analysis combined with some geometric type inequality for the integral curvature.

Now, if we suppose  $(V_i)_i$  uniformly Lipschitzian with  $A$  the Lipschitz constant, then,  $C(a/b) = 1$  and  $c = c(a, b, A, K, \Omega)$ , see Brezis-Li-Shafrir [4]. This result was extended for Hölderian sequences  $(V_i)_i$  by Chen-Lin, see [9]. Also, one can see in [12], an extension of the Brezis-Li-Shafrir result to compact Riemannian surfaces without boundary. One can see in [13] explicit form,  $(8\pi m, m \in \mathbb{N}^*$  exactly), for the numbers in front of the Dirac masses when the solutions blow-up. Here, the notion of isolated blow-up point is used. Also, in [18], we have refined estimates near the isolated blow-up points and the bubbling behavior of the blow-up sequences.

In [7], we have some a priori estimates on the 2 and 3-spheres  $\mathbb{S}_2, \mathbb{S}_3$ .

Here we give the behavior of the blow-up points on the boundary and a proof of Brezis-Merle Problem with Lipschitz condition.

The Brezis-Merle Problem (see [5]) is:

**Problem.** Suppose that  $V_i \rightarrow V$  in  $C^0(\bar{\Omega})$  with  $0 \leq V_i \leq b$  for some positive constant  $b$ . Also, we consider a sequence of solutions  $(u_i)$  of  $(P)$  relative to  $(V_i)$  such that,

$$\int_{\Omega} e^{u_i} dx \leq C,$$

is it possible to have:

$$\|u_i\|_{L^\infty} \leq C = C(b, C, V, \Omega)?$$

Here, we give a characterization of the behavior of the blow-up points on the boundary and also, in particular we extend Chen-Li theorem ( $\nabla \log V_i$  uniformly bounded). Also, we give a new proof of Chen-Li result (when  $\nabla V_i$  is uniformly bounded, the method of Chen-Li use some local estimates). For the behavior of the blow-up points on the boundary, the following condition is enough,

$$0 \leq V_i \leq b,$$

The condition  $V_i \rightarrow V$  in  $C^0(\bar{\Omega})$  is not necessary, but for the proof of the compactness for the Brezis-Merle problem we assume that:

$$\|\nabla V_i\|_{L^\infty} \leq A.$$

We have the following characterization of the behavior of the blow-up points on the boundary.

**Theorem 1.1.** *Assume that  $\max_{\Omega} u_i \rightarrow +\infty$ , where  $(u_i)$  are solutions of the problem (P) with:*

$$0 \leq V_i \leq b \text{ and } \int_{\Omega} e^{u_i} dx \leq C, \quad \forall i,$$

*then, after passing to a subsequence, there is a function  $u$ , there is a number  $N \in \mathbb{N}$  and  $N$  points  $x_1, \dots, x_N \in \partial\Omega$ , such that,*

$$\partial_{\nu} u_i \rightarrow \partial_{\nu} u + \sum_{j=1}^N \alpha_j \delta_{x_j}, \quad \alpha_j \geq 4\pi, \text{ weakly in the sense of measure } L^1(\partial\Omega).$$

$$u_i \rightarrow u \text{ in } C_{loc}^1(\bar{\Omega} - \{x_1, \dots, x_N\}).$$

In the following theorem, we have a proof of the global a priori estimate which concern the problem (P). The proof of Chen-Li and Ma-Wei [8,14], use the moving-plane method.

**Theorem 1.2.** *Assume that  $(u_i)$  are solutions of (P) relative to  $(V_i)$  with the following conditions:*

$$\|\nabla V_i\|_{L^{\infty}} \leq A \text{ and } \int_{\Omega} e^{u_i} \leq C,$$

*we have,*

$$\|u_i\|_{L^{\infty}} \leq c(b, A, C, \Omega),$$

## 2. PROOF OF THE THEOREMS

Proof of theorem 1.1:

We have,

$$\int_{\partial\Omega} \partial_{\nu} u_i d\sigma \leq C,$$

Without loss of generality, we can assume that  $\partial_{\nu} u_i > 0$ . Thus, (using the weak convergence in the space of Radon measures), we have the existence of a positive Radon measure  $\mu$  such that,

$$\int_{\partial\Omega} \partial_{\nu} u_i \varphi d\sigma \rightarrow \mu(\varphi), \quad \forall \varphi \in C^0(\partial\Omega).$$

We take an  $x_0 \in \partial\Omega$  such that,  $\mu(x_0) < 4\pi$ . Without loss of generality, we can assume that the following curve,  $B(x_0, \epsilon) \cap \partial\Omega := I_\epsilon$  is an interval. (In this case, it is more simple to construct the following test function  $\eta_\epsilon$ ). We choose a function  $\eta_\epsilon$  such that,

$$\begin{cases} \eta_\epsilon \equiv 1, & \text{on } I_\epsilon, \quad 0 < \epsilon < \delta/2, \\ \eta_\epsilon \equiv 0, & \text{outside } I_{2\epsilon}, \\ 0 \leq \eta_\epsilon \leq 1, \\ \|\nabla\eta_\epsilon\|_{L^\infty(I_{2\epsilon})} \leq \frac{C_0(\Omega, x_0)}{\epsilon}. \end{cases}$$

We take a  $\tilde{\eta}_\epsilon$  such that,

$$\begin{cases} \Delta\tilde{\eta}_\epsilon = 0 & \text{in } \Omega \subset \mathbb{R}^2, \\ \tilde{\eta}_\epsilon = \eta_\epsilon & \text{in } \partial\Omega. \end{cases}$$

We use the following estimate, see [3, 6, 17],

$$\|\nabla u_i\|_{L^q} \leq C_q, \quad \forall i \text{ and } 1 < q < 2.$$

We deduce from the last estimate that,  $(u_i)$  converge weakly in  $W_0^{1,q}(\Omega)$ , almost everywhere to a function  $u \geq 0$  and  $\int_\Omega e^u < +\infty$  (by Fatou lemma). Also,  $V_i$  weakly converge to a nonnegative function  $V$  in  $L^\infty$ . The function  $u$  is in  $W_0^{1,q}(\Omega)$  solution of :

$$\begin{cases} \Delta u = Ve^u \in L^1(\Omega) & \text{in } \Omega \subset \mathbb{R}^2, \\ u = 0 & \text{in } \partial\Omega. \end{cases}$$

According to the corollary 1 of Brezis-Merle result, see [5], we have  $e^{ku} \in L^1(\Omega)$ ,  $k > 1$ . By the elliptic estimates, we have  $u \in C^1(\bar{\Omega})$ .

We can write,

$$\Delta((u_i - u)\tilde{\eta}_\epsilon) = (V_i e^{u_i} - V e^u)\tilde{\eta}_\epsilon - 2 \langle \nabla(u_i - u), \nabla\tilde{\eta}_\epsilon \rangle. \quad (1)$$

We use the interior estimate of Brezis-Merle, see [5],

*Step 1:* Estimate of the integral of the first term of the right hand side of (1).

We use the Green formula between  $\tilde{\eta}_\epsilon$  and  $u$ , we obtain,

$$\int_\Omega V e^u \tilde{\eta}_\epsilon dx = \int_{\partial\Omega} \partial_\nu u \eta_\epsilon \leq 4\epsilon \|\partial_\nu u\|_{L^\infty} = C\epsilon \quad (2)$$

We have,

$$\begin{cases} \Delta u_i = V_i e^{u_i} & \text{in } \Omega \subset \mathbb{R}^2, \\ u_i = 0 & \text{in } \partial\Omega. \end{cases}$$

We use the Green formula between  $u_i$  and  $\tilde{\eta}_\epsilon$  to have:

$$\int_{\Omega} V_i e^{u_i} \tilde{\eta}_\epsilon dx = \int_{\partial\Omega} \partial_\nu u_i \tilde{\eta}_\epsilon d\sigma \rightarrow \mu(\eta_\epsilon) \leq \mu(I_{2\epsilon}) \leq 4\pi - \epsilon_0, \quad \epsilon_0 > 0 \quad (3)$$

From (2) and (3) we have for all  $\epsilon > 0$  there is  $i_0 = i_0(\epsilon)$  such that, for  $i \geq i_0$ ,

$$\int_{\Omega} |(V_i e^{u_i} - V e^u) \tilde{\eta}_\epsilon| dx \leq 4\pi - \epsilon_0 + C\epsilon \quad (4)$$

Step 2: Estimate of integral of the second term of the right hand side of (1).

Let  $\Sigma_\epsilon = \{x \in \Omega, d(x, \partial\Omega) = \epsilon^3\}$  and  $\Omega_{\epsilon^3} = \{x \in \Omega, d(x, \partial\Omega) \geq \epsilon^3\}$ ,  $\epsilon > 0$ . Then, for  $\epsilon$  small enough,  $\Sigma_\epsilon$  is hypersurface.

The measure of  $\Omega - \Omega_{\epsilon^3}$  is  $k_2 \epsilon^3 \leq \mu_L(\Omega - \Omega_{\epsilon^3}) \leq k_1 \epsilon^3$ .

**Remark:** for the unit ball  $\bar{B}(0, 1)$ , our new manifold is  $\bar{B}(0, 1 - \epsilon^3)$ .

We write,

$$\int_{\Omega} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx = \int_{\Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx + \int_{\Omega - \Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx. \quad (5)$$

Step 2.1: Estimate of  $\int_{\Omega - \Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx$ .

First, we know from the elliptic estimates that  $\|\nabla \tilde{\eta}_\epsilon\|_{L^\infty} \leq C_1/\epsilon^2$ ,  $C_1$  depends on  $\Omega$

We know that  $(|\nabla u_i|)_i$  is bounded in  $L^q$ ,  $1 < q < 2$ , we can extract from this sequence a subsequence which converge weakly to  $h \in L^q$ . But, we know that we have locally the uniform convergence to  $|\nabla u|$  (by Brezis-Merle theorem), then,  $h = |\nabla u|$  a.e. Let  $q'$  be the conjugate of  $q$ .

We have,  $\forall f \in L^{q'}(\Omega)$

$$\int_{\Omega} |\nabla u_i| f dx \rightarrow \int_{\Omega} |\nabla u| f dx$$

If we take  $f = 1_{\Omega - \Omega_{\epsilon^3}}$ , we have:

$$\text{for } \epsilon > 0 \exists i_1 = i_1(\epsilon) \in \mathbb{N}, \quad i \geq i_1, \quad \int_{\Omega - \Omega_{\epsilon^3}} |\nabla u_i| \leq \int_{\Omega - \Omega_{\epsilon^3}} |\nabla u| + \epsilon^3.$$

Then, for  $i \geq i_1(\epsilon)$ ,

$$\int_{\Omega - \Omega_{\epsilon^3}} |\nabla u_i| \leq \text{mes}(\Omega - \Omega_{\epsilon^3}) \|\nabla u\|_{L^\infty} + \epsilon^3 = \epsilon^3(k_1 \|\nabla u\|_{L^\infty} + 1).$$

Thus, we obtain,

$$\int_{\Omega - \Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx \leq \epsilon C_1 (2k_1 \|\nabla u\|_{L^\infty} + 1) \quad (6)$$

The constant  $C_1$  does not depend on  $\epsilon$  but on  $\Omega$ .

Step 2.2: Estimate of  $\int_{\Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx$ .

We know that,  $\Omega_\epsilon \subset\subset \Omega$ , and ( because of Brezis-Merle's interior estimates)  $u_i \rightarrow u$  in  $C^1(\Omega_{\epsilon^3})$ . We have,

$$\|\nabla(u_i - u)\|_{L^\infty(\Omega_{\epsilon^3})} \leq \epsilon^3, \text{ for } i \geq i_3 = i_3(\epsilon).$$

We write,

$$\int_{\Omega_{\epsilon^3}} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx \leq \|\nabla(u_i - u)\|_{L^\infty(\Omega_{\epsilon^3})} \|\nabla \tilde{\eta}_\epsilon\|_{L^\infty} \leq C_1 \epsilon \text{ for } i \geq i_3,$$

For  $\epsilon > 0$ , we have for  $i \in \mathbb{N}$ ,  $i \geq \max\{i_1, i_2, i_3\}$ ,

$$\int_{\Omega} | \langle \nabla(u_i - u) | \nabla \tilde{\eta}_\epsilon \rangle | dx \leq \epsilon C_1 (2k_1 \|\nabla u\|_{L^\infty} + 2) \quad (7)$$

From (4) and (7), we have, for  $\epsilon > 0$ , there is  $i_3 = i_3(\epsilon) \in \mathbb{N}$ ,  $i_3 = \max\{i_0, i_1, i_2\}$  such that,

$$\int_{\Omega} |\Delta[(u_i - u)\tilde{\eta}_\epsilon]| dx \leq 4\pi - \epsilon_0 + \epsilon 2C_1 (2k_1 \|\nabla u\|_{L^\infty} + 2 + C) \quad (8)$$

We choose  $\epsilon > 0$  small enough to have a good estimate of (1).

Indeed, we have:

$$\begin{cases} \Delta[(u_i - u)\tilde{\eta}_\epsilon] = g_{i,\epsilon} & \text{in } \Omega \subset \mathbb{R}^2, \\ (u_i - u)\tilde{\eta}_\epsilon = 0 & \text{in } \partial\Omega. \end{cases}$$

with  $\|g_{i,\epsilon}\|_{L^1(\Omega)} \leq 4\pi - \epsilon_0$ .



We can use Theorem 1 of [5] to conclude that there is  $q > 1$  such that:

$$\int_{V_\epsilon(x_0)} e^{q(u_i-u)} dx \leq \int_{\Omega} e^{q(u_i-u)\tilde{\eta}_\epsilon} dx \leq C(\epsilon, \Omega).$$

where,  $V_\epsilon(x_0)$  is a neighborhood of  $x_0$  in  $\bar{\Omega}$ .

Thus, for each  $x_0 \in \partial\Omega - \{\bar{x}_1, \dots, \bar{x}_m\}$  there is  $\epsilon_{x_0} > 0, q_{x_0} > 1$  such that:

$$\int_{B(x_0, \epsilon_{x_0})} e^{q_{x_0} u_i} dx \leq C, \quad \forall i. \quad (9)$$

By the elliptic estimates,  $(u_i \eta)_i$  is uniformly bounded in  $W^{2, q_1}(\Omega)$  and also, in  $C^1(\bar{\Omega})$ . (Here,  $\eta$  is a cut-off function.)

Finally, we have, for some  $\epsilon > 0$  small enough,

$$\|u_i\|_{C^{1, \theta}[B(x_0, \epsilon)]} \leq c_3 \quad \forall i.$$

We have proved that, there is a finite number of points  $\bar{x}_1, \dots, \bar{x}_m$  such that the sequence  $(u_i)_i$  is locally uniformly bounded in  $\bar{\Omega} - \{\bar{x}_1, \dots, \bar{x}_m\}$ .

*Proof of theorem 1.2:*

The first Pohozaev identity applied around each blow-up point, see for example [14], gives :

$$\int_{\partial\Omega_{x_k}} [(\partial_\nu u_i) \nabla u_i - \frac{1}{2} |\nabla u_i|^2 \nu] dx = \int_{\Omega_{x_k}} \nabla V_i e^{u_i} - \int_{\partial\Omega_{x_k}} V_i e^{u_i} \nu, \quad (10)$$

We use the boundary condition on  $\Omega$  and the boundedness of  $u_i$  and  $\partial_j u_i$  outside the  $x_k$ , to have:

$$\int_{\partial\Omega} (\partial_\nu u_i)^2 dx \leq c_0(b, A, C, \Omega). \quad (11)$$

Thus we can use the weak convergence in  $L^2(\partial\Omega)$  to have a subsequence  $\partial_\nu u_i$ , such that:

$$\int_{\partial\Omega} \partial_\nu u_i \varphi dx \rightarrow \int_{\partial\Omega} \partial_\nu u \varphi dx, \quad \forall \varphi \in L^2(\partial\Omega), \quad (12)$$

Thus,  $\alpha_j = 0, j = 1, \dots, N$  and  $(u_i)$  is uniformly bounded.

**ACKNOWLEDGEMENT.**

The work is supported by YY. Li's Grant. The author would like to thank Pr. YY.Li for his support.

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DEPARTEMENT DE MATHÉMATIQUES, UNIVERSITÉ PIERRE ET MARIE CURIE, 2 PLACE JUSSIEU, 75005, PARIS, FRANCE.

*E-mail address:* samybahoura@yahoo.fr