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POSITIVE SOLUTIONS FOR SLIGHTY SUBCRITICAL ELLIPTIC PROBLEMS VIA ORLICZ SPACES

MABEL CUESTA AND ROSA PARDO

ABSTRACT. This paper concerns semilinear elliptic equations involving sign-changing weight function and a nonlinearity of subcritical nature understood in a generalized sens. Using an Orlicz-Sobolev space setting, we consider superlinear nonlinearities which do not have a polynomial growth, and state sufficient conditions guaranteeing the Palais-Smale condition. We study the existence of a bifurcated branch of classical positive solutions, containing a turning point, and providing multiplicity of solutions.

Positive solutions, subcritical nonlinearity, changing sign weight.
[2020]58E07, 35J20, 35B32, 35J25, 35J61

1. INTRODUCTION

In this paper we study the classical positive solutions to the Dirichlet problem for a class of semilinear elliptic equations whose nonlinear term is of subcritical nature in a generalized sens and involves indefinite nonlinearities. More precisely, given $\Omega \subset \mathbb{R}^N$, $N > 2$, a bounded, connected open subset, with C^2 boundary $\partial\Omega$, we look for positive solutions to:

$$(1.1) \quad -\Delta u = \lambda u + a(x)f(u), \quad \text{in } \Omega, \quad u = 0, \quad \text{on } \partial\Omega,$$

where $\lambda \in \mathbb{R}$ is a real parameter, $a \in C^1(\bar{\Omega})$ changes sign in Ω ,

$$(1.2) \quad f(s) := g(s) + h(s), \quad \text{with } h(s) := \frac{|s|^{2^*-2}s}{[\ln(e + |s|)]^\alpha},$$

$2^* = \frac{2N}{N-2}$ is the critical Sobolev exponent, $\alpha > 0$ is a fixed exponent, and $g \in C^1(\mathbb{R})$ satisfies

$$(H) \quad \begin{cases} (H)_0 & \lim_{s \rightarrow 0} \frac{f(s)}{|s|^{p-2}s} = L_1, & \text{for some } L_1 > 0, \text{ and } p \in \left(2, \frac{2N}{N-2}\right] \\ (H)_\infty & \lim_{s \rightarrow \infty} \frac{g(s)}{|s|^{q-2}s} = L_2, & \text{for some } L_2 \geq 0, \text{ and } q \in \left(2, \frac{2N}{N-2}\right) \\ (H)_{g'} & |g'(s)| \leq C(1 + |s|^{q-2}), & \text{for } s \in \mathbb{R}. \end{cases}$$

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We will say that g (or even f) satisfies hypothesis (H) whenever $(H)_0$, $(H)_\infty$, and $(H)_{g'}$ are satisfied. Since we are interested in positive solutions, we

$$(1.3) \quad \text{redefine } f \text{ to be zero on } (-\infty, 0],$$

note that $f(0) = 0$ and that

$$(1.4) \quad \lim_{s \rightarrow 0^+} \left(\frac{f(s)}{s} - L_1 |s|^{p-2} \right) = 0.$$

When $\lambda = 0$, $a(x) \equiv 1$ and $g(s) \equiv 0$, this kind of nonlinearity has been studied in [5, 6, 7, 16], and in [11] for the case of the p -laplacian operator, with $\alpha > \frac{p}{N-p}$. It is known the existence of uniform L^∞ a priori bounds for any positive classical solution, and as a consequence, the existence of positive solutions. When $\alpha \rightarrow 0$, there is a positive solution blowing up at a non-degenerate point of the Robin function as $\alpha \rightarrow 0$, see [9] for details.

From [10] it is known that $(\lambda_1, 0)$ is a bifurcation point of positive solutions (λ, u_λ) to the equation (1.1).

For f behaving like $|u|^{p-2}u$ at zero with $2 \leq p \leq 2^*$, the influence of the negative part of the weight a is displayed under the sign of $\int_\Omega a(x)\varphi_1(x)^p dx$, where φ_1 is the first positive eigenfunction for $-\Delta$ in $H_0^1(\Omega)$. Specifically, whenever

$$(1.5) \quad \int_\Omega a(x)\varphi_1(x)^p dx < 0$$

the bifurcation of positive solutions from the trivial solution set is 'on the right' of the first eigenvalue, in other words for values of $\lambda > \lambda_1$. And whenever

$$\int_\Omega a(x)\varphi_1(x)^p dx > 0$$

the bifurcation from the trivial solution set is 'on the left' of the first eigenvalue, in other words for values of $\lambda < \lambda_1$.

Inspired by the work of Alama and Tarantello in [1], we will focus our attention to the case $a(x)$ changing sign and (1.5) is satisfied, and, among other things, we will prove the existence of a turning point for a value of the parameter $\Lambda > \lambda_1$, and in particular the existence of solutions when $\lambda = \lambda_1$. We will use local bifurcation and variational techniques.

All throughout the paper, for $v : \Omega \rightarrow \mathbb{R}$, $v = v^+ - v^-$ where

$$v^+(x) := \max\{v(x), 0\} \quad \text{and} \quad v^-(x) := \max\{-v(x), 0\}.$$

Let us also define

$$\Omega^\pm := \{x \in \Omega : \pm a(x) > 0\}, \quad \Omega^0 := \{x \in \Omega : a(x) = 0\},$$

and assume that both Ω^+ , Ω^- are non empty sets.

For this nonlinearity the Palais-Smale condition of the energy functional becomes a delicate issue, needing Orlicz spaces and a Orlicz-Sobolev embedding theorem.

In order to prove (PS) condition, Alama and Tarantello ([1]) assume that the zero set Ω^0 has a non empty interior. This is also a common hypothesis for other authors when dealing with changing sign superlinear nonlinearities [8, 21, 23]. But this is a technical hypothesis. (PS)-condition will be proved in Proposition 3.1 without assuming that hypothesis.

We neither use Ambrosetti-Rabinowitz.

Let us now denote

$$(1.6) \quad C_0 = \inf\{C \geq 0 : f'(s) + C \geq 0 \text{ for all } s \geq 0\},$$

and remark that hypothesis (H) implies that $C_0 < +\infty$. Observe also that

$$(1.7) \quad f(s) + C_0 s \geq 0, \text{ for all } s \geq 0; \quad f(s)s + C_0 s^2 \geq 0, \text{ for all } s \in \mathbb{R}.$$

Let u be a weak solution to (1.1). By a regularity result, see Lemma 2.1, $u \in C^2(\Omega) \cap C^{1,\mu}(\bar{\Omega})$. So by a *solution*, we mean a *classical solution*.

Assume that u is a non-negative nontrivial solution. It is easy to see that the solution is strictly positive. Indeed, adding $\pm C_0 a(x)u$ to the r.h.s. of the equation, splitting $a = a^+ - a^-$, taking into account (1.4), and letting in each side the nonnegative terms, we can write

$$(1.8) \quad \left(-\Delta + a^-(x) \left[\frac{f(u)}{u} + C_0 \right] + C_0 a(x)^+ \right) u \\ = \lambda u + a(x)^+ [f(u) + C_0 u] + C_0 a(x)^- u, \quad \text{in } \Omega.$$

Now, the strong Maximum Principle implies that $u > 0$ in Ω , and $\frac{\partial u}{\partial \nu} < 0$ on $\partial\Omega$.

Our main result is the following theorem.

Theorem 1.1. *Assume that $g \in C^1(\mathbb{R})$ satisfies hypothesis (H). Let $C_0 > 0$ be defined by (1.6). If a changes sign in Ω , and (1.5) holds, then there exists a $\Lambda \in \mathbb{R}$,*

$$\lambda_1 < \Lambda < \min \left\{ \lambda_1(\text{int}(\Omega^0)), \quad \lambda_1(\text{int}(\Omega^+ \cup \Omega^0)) + C_0 \sup a^+ \right\}$$

and such that (1.1) has a classical positive solution if and only if $\lambda \leq \Lambda$.

Moreover, there exists a continuum (a closed and connected set) \mathcal{C} of classical positive solutions to (1.1) emanating from the trivial solution set at the bifurcation point $(\lambda, u) = (\lambda_1, 0)$ which is unbounded.

Furthermore,

- (a) For every, $\lambda \in (\lambda_1, \Lambda)$, (1.1) admits at least two classical ordered positive solutions.
- (b) For $\lambda = \Lambda$, problem (1.1) admits at least one classical positive solution.
- (c) For every $\lambda \leq \lambda_1$, problem (1.1) admits at least one classical positive solution.

The paper is organized in the following way. Section 2 contains a regularity result and a non existence result. (PS)-condition and an existence of solutions result for $\lambda < \lambda_1$ based in the Mountain Pass Theorem will be proved in Section 3. A bifurcation result for $\lambda > \lambda_1$ is developed in Section 4. The main result is proved in Section 5. Appendix A contains some useful estimates. Orlicz spaces, a Orlicz-Sobolev embeddings theorems, and variational techniques, also including a (PS) condition in Orlicz-Sobolev spaces setting and the Mountain Pass Theorem, will be treated in Appendix B.

2. A REGULARITY RESULT AND A NON EXISTENCE RESULT

Next, we recall a regularity Lemma stating that any weak solution is in fact a classical solution.

Lemma 2.1. *If $u \in H_0^1(\Omega)$ weakly solves (1.1) with a continuous function f with polynomial critical growth*

$$|f(x, s)| \leq C(1 + |s|^{2^*-1}),$$

then, $u \in C^2(\Omega) \cap C^{1,\mu}(\overline{\Omega})$ and

$$\|u\|_{C^{1,\mu}(\overline{\Omega})} \leq C \left(1 + \|u\|_{L^{(2^*-1)r}(\overline{\Omega})}^{2^*-1} \right),$$

for any $r > N$ and $\mu = 1 - N/r$. Moreover, if $\partial\Omega \in C^{2,\mu}$, then $u \in C^{2,\mu}(\overline{\Omega})$.

Proof. Due to an estimate of Brézis-Kato [3], based on Moser's iteration technique [17], $u \in L^r(\Omega)$ for any $r > 1$; and by elliptic regularity $u \in W^{2,r}(\Omega)$, for any $r > 1$ (see [22, Lemma B.3] and comments below).

Moreover, by Sobolev embeddings for $r > N$ and interior elliptic regularity $u \in C^{1,\alpha}(\overline{\Omega}) \cap C^2(\Omega)$. Furthermore, if $\partial\Omega \in C^{2,\alpha}$, then $u \in C^{2,\alpha}(\overline{\Omega})$. \square

Proposition 2.2. *Let f satisfy hypothesis (H) and let C_0 be defined in (1.6). Assume that a changes sign in Ω .*

- (1) *Problem (1.1) does not admit a positive solution $u \in H_0^1(\Omega)$ for any*

$$\lambda \geq \lambda_1(\text{int}(\Omega^+ \cup \Omega^0)) + C_0 \sup a^+.$$

- (2) *If $\text{int}(\Omega^0) \neq \emptyset$, then $\lambda_1(\text{int}(\Omega^0)) < +\infty$ and (1.1) does not admit a positive solution for any*

$$\lambda \geq \lambda_1(\text{int}(\Omega^0)).$$

Proof. 1. Let $\lambda \geq \lambda_1(\text{int}(\Omega^+ \cup \Omega^0)) + C_0 \sup a^+$, and assume by contradiction that there exists a non-negative non-trivial solution $u \in H_0^1(\Omega)$ to (1.1) for the parameter λ . Since the Maximum Principle $u > 0$ in Ω , see (1.8).

Let $\hat{\varphi}$ be the positive eigenfunction of $(-\Delta, H_0^1(\text{int}(\Omega^+ \cup \Omega^0)))$ of L^2 -norm equal to 1. For simplicity we will denote also by $\hat{\varphi}$ the extension by 0 of $\hat{\varphi}$ in all Ω . By Hopf's maximum principle we have $\frac{\partial \hat{\varphi}}{\partial \nu} < 0$ on $\partial(\text{int}(\Omega^+ \cup \Omega^0))$, where ν is the outward normal.

Again if we multiply the equation (1.1) by $\hat{\varphi}$ and integrate along $\text{int}(\Omega^+ \cup \Omega^0)$ we find, after integrating by parts,

$$\begin{aligned} 0 &> \int_{\partial(\text{int}(\Omega^+ \cup \Omega^0))} u \frac{\partial \hat{\varphi}}{\partial \nu} d\sigma \\ &\quad + \int_{\text{int}(\Omega^+ \cup \Omega^0)} \left[\lambda_1(\text{int}(\Omega^+ \cup \Omega^0)) - \lambda + C_0 a^+(x) \right] u \hat{\varphi} dx \\ &= \int_{\Omega^+} a^+(x) [f(u) + C_0 u] \hat{\varphi} dx > 0, \end{aligned}$$

a contradiction.

2. Let $\lambda \geq \lambda_1(\text{int}(\Omega^0))$ and assume by contradiction that there exists a positive solution $u \in H_0^1(\Omega)$ of problem (1.1) for the parameter λ . Let $\tilde{\varphi}$ be a positive eigenfunction associated to $\lambda_1(\text{int}(\Omega^0)) < +\infty$. For simplicity we will also denote by $\tilde{\varphi}$ the extension by 0 in all Ω . If we multiply equation (1.1) by $\tilde{\varphi}$ and integrate along Ω^0 we find, after integrating by parts,

$$\int_{\text{int}(\Omega^0)} \nabla u \cdot \nabla \tilde{\varphi} dx = \lambda \int_{\text{int}(\Omega^0)} u \tilde{\varphi} dx.$$

On the other hand

$$\int_{\text{int}(\Omega^0)} \nabla u \cdot \nabla \tilde{\varphi} dx = \lambda_1(\text{int}(\Omega^0)) \int_{\text{int}(\Omega^0)} \tilde{\varphi} u dx + \int_{\partial(\text{int}(\Omega^0))} u \frac{\partial \tilde{\varphi}}{\partial \nu} d\sigma.$$

Hence

$$0 > \int_{\partial(\text{int}(\Omega^0))} u \frac{\partial \tilde{\varphi}}{\partial \nu} d\sigma = \left(\lambda - \lambda_1(\text{int}(\Omega^0)) \right) \int_{\text{int}(\Omega^0)} u \tilde{\varphi} dx \geq 0,$$

a contradiction. \square

3. AN EXISTENCE RESULT FOR $\lambda < \lambda_1$

In this section we prove the existence of a nontrivial solution to equation (1.1) for $\lambda < \lambda_1$, through the Mountain Pass Theorem.

3.1. On Palais-Smale sequences. In this subsection, we define the framework for the functional J_λ associated to the problem (1.1) $_\lambda$. Hereafter we denote by $\|\cdot\|$ the usual norm of $H_0^1(\Omega)$:

$$\|u\| = \left(\int_{\Omega} |\nabla u|^2 dx \right)^{1/2}.$$

Given $f(s) = h(s) + g(s)$ defined by (1.2), let us denote by $F(s) := \int_0^s f(t) dt$. Observe that (1.7) implies the following

$$(3.1) \quad F(s) + \frac{1}{2}C_0s^2 \geq 0, \text{ for all } s \geq 0.$$

Consider the functional $J_\lambda : H_0^1(\Omega) \rightarrow \mathbb{R}$ given by

$$J_\lambda[v] := \frac{1}{2} \int_{\Omega} |\nabla v|^2 dx - \frac{\lambda}{2} \int_{\Omega} (v^+)^2 dx - \int_{\Omega} a(x)F(v^+) dx.$$

Observe that for all $v \in H_0^1(\Omega)$, $J_\lambda[v^+] \leq J_\lambda[v]$.

The functional J_λ is well defined and belongs to the class C^1 with

$$J'_\lambda[v] \psi = \int_{\Omega} \nabla v \nabla \psi dx - \lambda \int_{\Omega} v^+ \psi dx - \int_{\Omega} a(x)f(v^+) \psi dx,$$

for all $\psi \in H_0^1(\Omega)$. Consequently, non-negative critical points of the functional J_λ correspond to non-negative weak solutions to (1.1).

The next Proposition proves that *Palais-Smale sequences* are bounded whenever $\lambda < \lambda_1(\text{int} \Omega^0)$, where $\lambda_1(\text{int} \Omega^0)$ may be infinite.

Proposition 3.1. *Assume that $g \in C^1(\mathbb{R})$ satisfies hypothesis (H) and assume also that $\lambda < \lambda_1(\text{int} \Omega^0) \leq +\infty$.*

Then any (PS) sequence, that is, a sequence satisfying

$$(J_1) \quad J_\lambda[u_n] \leq C,$$

$$(J_2) \quad |J'_\lambda[u_n] \psi| \leq \varepsilon_n \|\psi\|, \text{ where } \varepsilon_n \rightarrow 0 \text{ as } n \rightarrow +\infty$$

is a bounded sequence.

Proof. 1. Let $\{u_n\}_{n \in \mathbb{N}}$ be a (PS) sequence in $H_0^1(\Omega)$ and assume by contradiction that $\|u_n\| \rightarrow +\infty$. Let us first prove the following claim:

Claim. Let $v \in H_0^1(\Omega)$ be the weak limit of $v_n = \frac{u_n}{\|u_n\|}$ and assume that $v_n \rightarrow v$, strongly in $L^{2^*-1}(\Omega)$ and a.e. Then $v = 0$ a.e. in Ω .

Assume that $v \neq 0$ and denote $\gamma_n = \|u_n\|$. Let $\omega_n := \{x \in \Omega : v_n^+(x) > 1\}$, then for any $\psi \in C_0^1(\Omega)$,

$$\left| \frac{\ln(e + \gamma_n)^\alpha}{\gamma_n^{2^*-1}} \frac{(u_n^+(x))^{2^*-1}}{[\ln(e + \gamma_n v_n^+(x))]^\alpha} |\psi| \right| \leq |v_n^+(x)|^{2^*-1} \|\psi\|_\infty, \quad \forall x \in \omega_n.$$

Let $x \in \Omega \setminus \omega_n$, using the estimates (A.1),

$$\left| \frac{\ln(e + \gamma_n)^\alpha}{\gamma_n^{2^*-1}} \frac{(u_n^+)^{2^*-1}}{[\ln(e + \gamma_n v_n^+)]^\alpha} |\psi| \right| \leq (|v_n^+|^{2^*-2}) \|\psi\|_\infty \leq \|\psi\|_\infty$$

Besides, by the reverse of the Lebesgue dominated convergence theorem, see for instance [2, Theorem 4.9, p. 94], there exists $h_i \in L^1(\Omega)$, $1 \leq i \leq 3$ such that, up to a subsequence,

$$|v_n^+|^{2^*-1} \leq h_1, |v_n^+|^{p-1} \leq h_2 |v_n^+|^{2^*-2} \leq h_3, \quad , \quad a.e. \quad x \in \Omega,$$

for all $n \in \mathbb{N}$, and therefore

$$\left| \frac{\ln(e + \gamma_n)^\alpha}{\gamma_n^{2^*-1}} f(u_n^+) \psi \right| \leq C (h_1 + h_2 + h_3 + 1) \|\psi\|_\infty \in L^1(\Omega).$$

By Lebesgue dominated convergent theorem we have

$$\frac{\ln(e + \gamma_n)^\alpha}{\gamma_n^{2^*-1}} a(\cdot) f(u_n^+) \psi \rightarrow a(\cdot) (v^+)^{2^*-1} \psi \quad \text{strongly in } L^1(\Omega).$$

We have used here that if $v^+(x) \neq 0$, then

$$\lim_{n \rightarrow +\infty} \frac{\ln(e + \gamma_n)}{\ln(e + \gamma_n v_n^+(x))} = 1,$$

and if $v^+(x) = 0$, then

$$\lim_{n \rightarrow +\infty} \left(\frac{\ln(e + \gamma_n)}{\ln(e + \gamma_n v_n^+(x))} \right)^\alpha |v_n^+(x)|^{2^*-1} \leq \lim_{n \rightarrow +\infty} |v_n^+(x)|^{2^*-2} = 0.$$

On the other hand

$$\frac{\ln(e + \gamma_n)^\alpha}{\gamma_n^{2^*-1}} \int_{\Omega} \nabla u_n \cdot \nabla \psi \, dx \rightarrow 0.$$

Hence, using (J_2) for an arbitrary test function ψ , multiplying by $\frac{\ln(e+\gamma_n)^\alpha}{\gamma_n^{2^*-1}}$ and passing to the limit we find

$$\int_{\Omega} a(x)(v^+)^{2^*-1}\psi \, dx = 0 \quad \forall \psi \in C_0^1(\Omega).$$

In particular $v^+ = 0$ a.e. in $\Omega \setminus \Omega^0$.

Assume that $\text{int } \Omega^0 \neq \emptyset$, and that $\lambda < \lambda_1(\text{int } \Omega^0)$. Thus, for any $\psi \in C_0^1(\text{int } \Omega^0)$ we have from (J_2)

$$\int_{\text{int } \Omega^0} \nabla u_n \cdot \nabla \psi \, dx - \lambda \int_{\text{int } \Omega^0} u_n^+ \psi \, dx = o(1).$$

Dividing by $\|u_n\|$ and passing to the limit we have

$$\int_{\text{int } \Omega^0} \nabla v \cdot \nabla \psi \, dx = \lambda \int_{\text{int } \Omega^0} v^+ \psi \, dx.$$

From the Maximum Principle, $v \geq 0$ in $\text{int } \Omega^0$. Since $\lambda < \lambda_1(\text{int } \Omega^0)$ then it must be $v^+ \equiv 0$ in $\text{int } \Omega^0$. Hence $v^+ \equiv 0$ in Ω .

On the other hand, taking u_n^- as a test function in the condition (J_2) ,

$$\left| - \int_{\Omega} |\nabla u_n^-|^2 \, dx - \int_{\Omega} a(x)f(u_n^+)u_n^- \, dx \right| = \int_{\Omega} |\nabla u_n^-|^2 \, dx \leq \epsilon_n \|u_n^-\|$$

so $\|u_n^-\| \rightarrow 0$ and then $v^- \equiv 0$, and we conclude the proof of the claim.

2. In order to achieve a contradiction, we use a Hölder inequality, and properties on convergence into an Orlicz space, cf. Appendix B.

To this end, the analysis of Lemma A.2 give us the existence of $\alpha^* > 0$ such that the function $s \rightarrow \frac{s^{2^*-1}}{[\ln(e+s)]^\alpha}$ is increasing along $[0, +\infty[$ if $\alpha \leq \alpha^*$. In this case we will denote

$$(3.2) \quad m(s) = \frac{s^{2^*-1}}{[\ln(e+s)]^\alpha}$$

If $\alpha > \alpha^*$ the function $s \rightarrow \frac{s^{2^*-1}}{[\ln(e+s)]^\alpha}$ possesses a local maximum s_1 in $[0, +\infty[$. Let us denote by \bar{s}_1 the unique solution $s > s_1$ such that

$$\frac{s_1^{2^*-1}}{[\ln(e+s_1)]^\alpha} = \frac{\bar{s}_1^{2^*-1}}{[\ln(e+\bar{s}_1)]^\alpha}$$

and define the non-decreasing function

$$(3.3) \quad m(s) := \begin{cases} \frac{s^{2^*-1}}{[\ln(e+s)]^\alpha} & \text{if } s \notin [s_1, \bar{s}_1], \\ \frac{s_1^{2^*-1}}{[\ln(e+s_1)]^\alpha} & \text{if } s \in [s_1, \bar{s}_1]. \end{cases}$$

It follows that

$$(3.4) \quad s \rightarrow M(s) = \int_0^s m(t) dt \quad \text{is a } N\text{-function in } [0, +\infty[.$$

By using

$$\lim_{s \rightarrow +\infty} \frac{\ln(e+s)}{\ln(e+2s)} = 1 \quad \text{and} \quad \lim_{s \rightarrow 0} \frac{\ln(e+s)}{\ln(e+2s)} = 1,$$

we get that

$$\lim_{s \rightarrow +\infty} \frac{m(2s)}{m(s)} < +\infty \quad \text{and} \quad \lim_{s \rightarrow 0^+} \frac{m(2s)}{m(s)} < +\infty,$$

which implies that there exists $K > 0$ such that $m(2s) \leq Km(s)$ for all $s \geq 0$ and consequently M satisfies the Δ_2 -condition (B.1).

Since $v_n \rightharpoonup 0$ in $H_0^1(\Omega)$ and strongly in $L^2(\Omega)$, it follows from (J_2) applied to $\psi = u_n$ that

$$(3.5) \quad \lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n^+) u_n}{\|u_n\|^2} dx = \lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n^+)}{\|u_n\|} v_n^+ dx = 1.$$

Since the Hölder inequality into Orlicz spaces, see Proposition B.11.(ii),

$$(3.6) \quad \int_{\Omega} \left| a(x) \frac{f(u_n^+)}{\|u_n\|} v_n^+ \right| dx \leq \frac{\|a\|_{\infty}}{\|u_n\|} \|f(u_n^+)\|_{M^*} \|v_n^+\|_M$$

By Theorem B.3 and Theorem B.12 we have

$$(3.7) \quad \|v_n - v\|_M \rightarrow 0.$$

Moreover, since there exists $C > 0$ such that $m(s) \leq Cs^{2^*-1}$ and $M(s) \leq Cs^{2^*}$ for all $s \geq 0$, and the sequence $\{u_n\}_{n \in \mathbb{N}} \subset H_0^1(\Omega)$, then, for each $n \in \mathbb{N}$, there exists a C_n such that

$$|u_n m(u_n)| \leq C_n, \quad |M(|u_n|)| \leq C_n.$$

By using definition B.8 of M^* and identities of Proposition B.9 we have

$$M^*(|m(u_n)|) = |u_n m(u_n)| - M(|u_n|)$$

then, for each $n \in \mathbb{N}$,

$$\int_{\Omega} M^*(|m(u_n)|) dx \leq 2C_n.$$

Observe that $f(s) \leq C(1+m(s))$, that $M^*(f(s)) \leq M^*(C(1+m(s)))$, see Proposition B.11.(iii), and by convexity of M^* , that

$$\|f(u_n^+)\|_{M^*} \leq \int_{\Omega} M^*(C(1+m(u_n^+))) dx + 1 \leq C'_n,$$

see Proposition B.11.(i), and the r.h.s. is bounded for each n . Consequently, $a(x)\frac{f(u_n^+)}{\|u_n\|} \in L_{M^*}(\Omega)$, which is the dual of $L_M(\Omega)$ (see [15], Theorem 14.2).

On the other hand, from J_2 , for all $\psi \in C_c^\infty(\Omega)$,

$$(3.8) \quad \left| \int_{\Omega} \nabla v_n \nabla \psi \, dx - \lambda_n \int_{\Omega} v_n \psi \, dx - \int_{\Omega} a(x) \frac{f(u_n^+)}{\|u_n\|} \psi \, dx \right| \leq \frac{\varepsilon_n}{\|u_n\|} \|\psi\|.$$

Taking the limit, and since $C_c^\infty(\Omega)$ is dense in $L_M(\Omega)$ (see [12]),

$$(3.9) \quad \lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n^+)}{\|u_n\|} \psi \, dx = 0, \quad \text{for all } \psi \in L_M(\Omega).$$

Moreover, since (3.7), $v_n \rightarrow v = 0$ in $L_M(\Omega)$. Hence [2, Proposition 3.13 (iv)], and (3.9) imply

$$\lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n^+)}{\|u_n\|} v_n \, dx = 0,$$

which contradicts (3.5), ending the proof. \square

Theorem 3.2. *Assume the hypothesis of Proposition 3.1 and let $\{u_n\}_{n \in \mathbb{N}}$ be a (PS) sequence in $H_0^1(\Omega)$.*

Then, there exists a subsequence, denoted by $\{u_n\}_{n \in \mathbb{N}}$, such that

$$u_n \rightarrow u \quad \text{in } H_0^1(\Omega).$$

Proof. From Proposition 3.1 we know that the sequence is bounded. Consequently, there exists a subsequence, denoted by $\{u_n\}_{n \in \mathbb{N}}$, and some $u \in H_0^1(\Omega)$ such that

$$(3.10) \quad u_n \rightharpoonup u \quad \text{weakly in } H_0^1(\Omega),$$

$$(3.11) \quad \int_{\Omega} a(x) g(u_n) |u_n - u| \, dx \rightarrow 0,$$

$$(3.12) \quad u_n \rightarrow u \quad \text{a.e.}$$

By testing (J_2) against $\psi = u_n - u$ and using (3.10), and (3.11) we get

$$\begin{aligned} \|u_n - u\|^2 &= \int_{\Omega} \nabla u_n \cdot \nabla (u_n - u) \, dx + o(1) \\ &\leq \|a\|_{\infty} \int_{\Omega} \frac{|u_n|^{2^*-1}}{[\ln(e + |u_n|)]^\alpha} |u_n - u| \, dx + o(1). \end{aligned}$$

Claim.

$$\int_{\Omega} \frac{|u_n|^{2^*-1}}{[\ln(e + |u_n|)]^\alpha} |u_n - u| \, dx = o(1),$$

In order to prove this claim, we use as in the above proposition, a Hölder inequality and a compact embedding into an Orlicz space, c.f. Appendix B.

By Theorem B.3 and Theorem B.12 we have

$$(3.13) \quad \|u_n - u\|_M \rightarrow 0,$$

where m , and M are defined by (3.2)-(3.4), as in the above proposition. On the other hand, since there exists $C > 0$ such that $m(s) \leq Cs^{2^*-1}$ and $M(s) \leq Cs^{2^*}$ for all $s \geq 0$, and the sequence $\{u_n\}_{n \in \mathbb{N}}$ is bounded in $H_0^1(\Omega)$, then

$$|u_n m(u_n)| \leq C, \quad |M(|u_n|)| \leq C \quad \text{for all } n \in \mathbb{N}$$

By using definition B.8 of M^* and identities of Proposition B.9 we have

$$M^*(|m(u_n)|) = |u_n m(u_n)| - M(|u_n|)$$

then

$$\int_{\Omega} M^*(|m(u_n)|) dx \leq C$$

for all $n \in \mathbb{N}$. Finally, by inequality (B.5) of Proposition B.12 we get

$$\sup \left\{ \|m(|u_n|)\|_{M^*}, n \in \mathbb{N} \right\} \leq C + 1.$$

Now, using Holder's inequality (B.6) and that $\frac{s^{2^*-1}}{[\ln(e+s)]^\alpha} \leq m(s)$ for all $s \geq 0$, we get

$$\int_{\Omega} \frac{|u_n|^{2^*-1}}{[\ln(e+|u_n|)]^\alpha} |u_n - u| dx \leq \|u_n - u\|_M \|m(u_n)\|_{M^*} \leq (C+1) \|u_n - u\|_M$$

and it follows from (3.13) that $\|u_n - u\| \rightarrow 0$. \square

3.2. An existence result for $\lambda < \lambda_1$. The next Theorem provides a solution to (1.1) for $\lambda < \lambda_1$ based on the Mountain Pass Theorem.

Theorem 3.3. *Assume that $\Omega \subset \mathbb{R}^N$ is a bounded domain with C^2 boundary. Assume that the nonlinearity f defined by (1.2) satisfies (H), and that the weight $a \in C^1(\overline{\Omega})$. Then, the boundary value problem (1.1) $_\lambda$ has at least one classical positive solution for any $\lambda < \lambda_1$.*

Proof. We verify the hypothesis of the Mountain Pass Theorem, see [13, Theorem 2, §8.5]. Observe that the derivative of the functional $J'_\lambda : H_0^1(\Omega) \rightarrow H_0^1(\Omega)$ is Lipschitz continuous on bounded sets of $H_0^1(\Omega)$; also the (PS) condition is satisfied, see Proposition 3.1. Clearly $J_\lambda[0] = 0$.

1. Let now $u \in H_0^1(\Omega)$ with $\|u\| = r$, for $r > 0$ to be selected below. Then,

$$(3.14) \quad J_\lambda[u] = \frac{r^2}{2} - \frac{\lambda}{2} \int_\Omega (u^+)^2 dx - \int_\Omega a(x)F(u^+) dx.$$

From hypothesis (H) we have

$$\left| \int_\Omega a(x)G(u^+) dx \right| \leq C \int_\Omega (|u|^p + |u|^q) dx \leq C(r^p + r^q).$$

where $G(s) := \int_0^s g(t) dt$. Now, definition (1.2) implies that

$$\left| \int_\Omega a(x)F(u^+) dx \right| \leq C(r^p + r^q + r^{2^*}).$$

In view of (3.14), and thanks to the Poincaré inequality we get

$$J_\lambda[u] \geq \frac{1}{2} \left(1 - \frac{|\lambda|}{\lambda_1}\right) r^2 - C(r^p + r^q + r^{2^*}) \geq C_1 r^2,$$

taking $|\lambda| < \lambda_1$, $r > 0$ small enough, and using that $p, q, 2^* > 2$.

2. Now, fix some element $0 \leq u_0 \in H_0^1(\Omega)$, $u_0 > 0$ in Ω^+ , $u_0 \equiv 0$ in Ω^- . Let $v = tu_0$ for a certain $t = t_0 > 0$ to be selected a posteriori. Since

$$(3.15) \quad f(tu_0) = |t|^{2^*-2} t f(u_0) \left(\frac{\ln(e + |u_0|)}{\ln(e + |tu_0|)} \right)^\alpha + g(tu_0),$$

then $f(tu_0)/t \rightarrow +\infty$ as $t \rightarrow +\infty$ in Ω^+ .

From definition, and integrating by parts,

$$\begin{aligned} F(s) &= \int_0^s \left(\frac{t^{2^*-1}}{\ln(e+t)^\alpha} + g(t) \right) dt \\ &= \frac{1}{2^*} sh(s) + G(s) + \frac{\alpha}{2^*} \int_0^s \left(\frac{1}{\ln(e+t)} \right)^{\alpha+1} \frac{t^{2^*}}{e+t} dt. \end{aligned}$$

It can be easily seen that $\lim_{s \rightarrow +\infty} \frac{G(s)}{sf(s)} = 0$.

Therefore, using l'Hôpital's rule we can write

$$(3.16) \quad \lim_{s \rightarrow +\infty} \frac{F(s)}{sf(s)} = \frac{1}{2^*} \in \left(0, \frac{1}{2}\right),$$

hence

$$(3.17) \quad \lim_{t \rightarrow +\infty} \frac{F(tu_0)}{tu_0 f(tu_0)} = \frac{1}{2^*} \in \left(0, \frac{1}{2}\right) \quad \text{in } \Omega^+.$$

Let $C_0 \geq 0$ be such that $F(s) + \frac{1}{2}C_0s^2 \geq 0$ for all $s \geq 0$ (see (1.7)), and let

$$(3.18) \quad \tilde{\Omega}_\delta^+ := \{x \in \Omega^+ : a(x) = a^+(x) > \delta\}.$$

By definition, $u_0 \equiv 0$ in Ω^- , so, introducing $\pm \frac{1}{2}C_0(tu_0)^2$, splitting the integral, and using (3.17)-(3.18) we obtain

$$\begin{aligned} - \int_{\Omega} a(x)F(tu_0) dx &= - \int_{\Omega^+} a^+(x)F(tu_0) dx \\ &\leq \frac{C_0t^2}{2} \int_{\Omega^+} a^+(x)u_0^2 dx - \int_{\tilde{\Omega}_\delta^+} a^+(x) \left[\frac{1}{2}C_0(tu_0)^2 + F(tu_0) \right] dx \\ &\leq C + \frac{C_0t^2}{2} \int_{\Omega^+} a^+(x)u_0^2 dx - \frac{\delta t^2}{2} \int_{\tilde{\Omega}_\delta^+} \left[C_0u_0^2 + \frac{u_0f(tu_0)}{2^*t} \right] dx. \end{aligned}$$

Hence, there exists a positive constant $C > 0$ such that

$$\begin{aligned} J_\lambda[tu_0] &= \frac{t^2}{2}\|u_0\|^2 - t^2\frac{\lambda}{2}\|u_0\|_{L^2(\Omega)}^2 - \int_{\Omega^+} a^+(x)F(tu_0) \\ &\leq C(1+t^2) - \frac{\delta t^2}{2} \int_{\tilde{\Omega}_\delta^+} \left[C_0(u_0)^2 + \frac{u_0f(tu_0)}{2^*t} \right] dx < 0 \end{aligned}$$

for $t = t_0 > 0$ big enough.

Step 3. We have at last checked that all the hypothesis of the Mountain Pass Theorem are accomplished. Let

$$\Gamma := \{\mathbf{g} \in C([0, 1]; H_0^1(\Omega)) : \mathbf{g}(0) = 0, \mathbf{g}(1) = t_0u_0\},$$

then, there exists $c \geq C_1 r^2 > 0$ such that

$$c := \inf_{\mathbf{g} \in \Gamma} \max_{0 \leq t \leq 1} J_\lambda[\mathbf{g}(t)]$$

is a critical value of J_λ , that is, the set $\mathcal{H}_c := \{v \in H_0^1(\Omega) : J_\lambda[v] = c, J'_\lambda[v] = 0\} \neq \emptyset$. Thus there exists $u \in H_0^1(\Omega)$, $u \geq 0$, $u \neq 0$ such that for each $\psi \in H_0^1(\Omega)$, we have

$$(3.19) \quad \int_{\Omega} \nabla u \cdot \nabla \psi dx = \int_{\Omega} [\lambda u^+ + a(x)f(u^+)]\psi dx.$$

and thereby u is a nontrivial weak solution to (3.19). By Lemma 2.1, u is a classical solution, and by (1.8), $u > 0$ in Ω . \square

4. A BIFURCATION RESULT FOR $\lambda > \lambda_1$

Next Proposition uses Crandall - Rabinowitz's local bifurcation theory, see [10], and Rabinowitz's global bifurcation theory, see [19].

Proposition 4.1. *Let us define*

$$\Lambda := \sup\{\lambda > 0 : (1.1) \text{ admits a positive solution}\}.$$

If (1.5) holds then,

$$\lambda_1 < \Lambda < \min \left\{ \lambda_1(\text{int}(\Omega^0)), \quad \lambda_1(\text{int}(\Omega^+ \cup \Omega^0)) + C_0 \sup a^+ \right\}$$

where $C_0 > 0$ is such that $f(s) + C_0 s \geq 0$ for all $s \geq 0$, (see definition (1.6)).

Moreover, there exists an unbounded continuum (a closed and connected set) \mathcal{C} of classical positive solutions to (1.1) emanating from the trivial solution set at the bifurcation point $(\lambda, u) = (\lambda_1, 0)$.

Proof. Proposition 2.2 proves the upper bounds for Λ . Next we concentrate our attention in proving that $\Lambda > \lambda_1$. Choosing λ as the bifurcation parameter, we check that the conditions of Crandall - Rabinowitz's Theorem [10] are satisfied. For $r > N$, we define the set $W_+^{2,r} := \{u \in W^{2,r}(\Omega) : u > 0 \text{ in } \Omega\}$, and consider $W_+^{2,r}(\Omega) \cap W_0^{1,r}(\Omega)$ endowed with the topology of $W^{2,r}(\Omega)$. If $r > N$, we have that $W_+^{2,r}(\Omega) \cap W_0^{1,r}(\Omega) \hookrightarrow C_0^{1,\mu}(\Omega)$ for $\mu = 1 - \frac{N}{r} \in (0, 1)$. Moreover, from Hopf's lemma, we know that if \tilde{u} is a positive solution to (1.1) then \tilde{u} lies in the interior of $W_+^{2,r}(\Omega) \cap W_0^{1,r}(\Omega)$.

We consider the map $\mathcal{F} : \mathbb{R} \times W_+^{2,r}(\Omega) \cap W_0^{1,r}(\Omega) \rightarrow L^r(\Omega)$ for $r > N$,

$$\mathcal{F} : (\lambda, u) \rightarrow -\Delta u - \lambda u - a(x)f(u)$$

The map \mathcal{F} is a continuously differentiable map. Since hypothesis (i), $g(0) = 0$, and so $a(x)F(0) = 0$, $\mathcal{F}(\lambda, 0) = 0$ for all $\lambda \in \mathbb{R}$, and since $F_u(x, 0) = 0$,

$$D_u \mathcal{F}(\lambda_1, 0)w := -\Delta w - \lambda_1 w,$$

$$D_{\lambda, u} \mathcal{F}(\lambda_1, 0)w := -w.$$

Observe that

$$N(D_u \mathcal{F}(\lambda_1, 0)) = \text{span}[\varphi_1], \quad \text{codim } R(D_u \mathcal{F}(\lambda_1, 0)) = 1,$$

$$D_{\lambda, u} \mathcal{F}(\lambda_1, 0)\varphi_1 = -\varphi_1 \notin R(D_u \mathcal{F}(\lambda_1, 0)),$$

where $N(\cdot)$ is the kernel, and $R(\cdot)$ denotes the range of a linear operator.

Hence, the hypotheses of Crandall-Rabinowitz theorem are satisfied and $(\lambda_1, 0)$ is a bifurcation point. Thus, decomposing

$$C_0^{1,\mu}(\overline{\Omega}) = \text{span}[\varphi_1] \oplus Z,$$

where $Z = \text{span}[\varphi_1]^\perp$, there exists a neighbourhood \mathcal{U} of $(\lambda_1, 0)$ in $\mathbb{R} \times C_0^{1,\mu}(\overline{\Omega})$, and continuous functions $\lambda(s), \tilde{w}(s)$, $s \in (-\varepsilon, \varepsilon)$, $\lambda : (-\varepsilon, \varepsilon) \rightarrow$

\mathbb{R} , $\tilde{w} : (-\varepsilon, \varepsilon) \rightarrow Z$ such that $\lambda(0) = \lambda_1$, $\tilde{w}(0) = 0$, with $\int_{\Omega} \tilde{w} \varphi_1 dx = 0$, and the only nontrivial solutions to (1.1) in \mathcal{U} , are

$$(4.1) \quad \{(\lambda(s), s\varphi_1 + s\tilde{w}(s)) : s \in (-\varepsilon, \varepsilon)\}.$$

Set $u = u(s) = s\varphi_1 + s\tilde{w}(s)$. Note that by continuity $\tilde{w}(s) \rightarrow 0$ as $s \rightarrow 0$, which guarantees that $u(s) > 0$ in Ω for all $s \in (0, \varepsilon)$ small enough.

Next, we show that $\lambda(s) > \lambda_1$ for all s small enough. Since (3.15), and hypothesis $(H)_0$ on f , note that $\frac{a(x)f(su)}{s^{p-1}u^{p-1}} \rightarrow L_1 a(x)$ as $s \rightarrow 0$. In fact, as $\tilde{w}(s) \rightarrow 0$ uniformly as $s \rightarrow 0$, hypothesis $(H)_0$ yields

$$\frac{a(x)f(s\varphi_1 + s\tilde{w}(s))}{s^{p-1}(\varphi_1 + \tilde{w}(s))^{p-1}} \rightarrow L_1 a(x) \text{ uniformly in } \Omega \quad \text{as } s \rightarrow 0.$$

Hence, multiplying and dividing by $(\varphi_1 + \tilde{w}(s))^{p-1}$, we deduce

$$\frac{1}{s^{p-1}} \int_{\Omega} a(x)f(u(s))\varphi_1 \xrightarrow{s \rightarrow 0} L_1 \int_{\Omega} a(x)\varphi_1^p.$$

Now we prove that $\lambda(s) > \lambda_1$ arguing by contradiction. Assume that there is a sequence $(\lambda_n, u_n) = (\lambda(s_n), u(s_n))$ of bifurcated solutions to (1.1) in \mathcal{U} , with $\lambda(s_n) \leq \lambda_1$. Multiplying (1.1) $_{\lambda_n}$ by φ_1 and integrating by parts

$$0 \leq \frac{(\lambda_1 - \lambda(s_n))}{s_n^{p-1}} \int_{\Omega} u(s_n)\varphi_1 = \frac{1}{s_n^{p-1}} \int_{\Omega} a(x)f(u(s_n))\varphi_1 \rightarrow L_1 \int_{\Omega} a(x)\varphi_1^p < 0$$

which yields a contradiction, and consequently, $\Lambda > \lambda_1$. Finally, Rabinowitz's global bifurcation Theorem [19] states that in fact, the set \mathcal{C} of positive solutions to (1.1) emanating from $(\lambda_1, 0)$ is a continuum (a closed and connected set) which is either unbounded, or contains another bifurcation point, or contains a pair of points (λ, u) , $(\lambda, -u)$ with $u \neq 0$. Since (1.8), any non-negative non-trivial solution is strictly positive, moreover $(\lambda_1, 0)$ is the only bifurcation point to positive solutions, so \mathcal{C} can not reach another bifurcation point. Since (1.3), neither \mathcal{C} contains a pair of points (λ, u) , $(\lambda, -u)$ with $u \neq 0$, which state that \mathcal{C} is unbounded, ending the proof. \square

5. PROOF OF THEOREM 1.1

First we prove an auxiliary result.

Proposition 5.1. *For each $\lambda \in (\lambda_1, \Lambda)$, the following holds:*

- (i) *Problem (1.1) $_{\lambda}$ admits a positive solution*

$$u_{\lambda} = \inf \{u(x) : u > 0 \text{ solving } (1.1)_{\lambda}\},$$

in other words u_λ is minimal.

- (ii) Moreover, the map $\lambda \rightarrow u_\lambda$ is strictly monotone increasing, that is, if $\lambda < \mu < \Lambda$, then $u_\lambda(x) < u_\mu(x)$ for all $x \in \Omega$, and $\frac{\partial u_\lambda}{\partial \nu}(x) > \frac{\partial u_\mu}{\partial \nu}(x)$ for all $x \in \partial\Omega$.
- (iii) Furthermore, u_λ is a local minimum of the functional J_λ .

Proof. (i.a) Step 1. Existence of positive solutions for any $\lambda \in (\lambda_1, \Lambda)$.

Let $\lambda \in (\lambda_1, \Lambda)$ be fixed. By definition of Λ , there exists a $\lambda_0 \in (\lambda, \Lambda)$ such that the problem $(1.1)_{\lambda_0}$ admits a positive solution u_0 . It is easy to verify that $u_0 > 0$ is a supersolution to $(1.1)_\lambda$. Indeed, for any $\psi \in H_0^1(\Omega)$ with $\psi \geq 0$ in Ω

$$\int_{\Omega} \nabla u_0 \nabla \psi \, dx - \lambda \int_{\Omega} u_0 \psi \, dx - \int_{\Omega} a(x) f(u_0) \psi \, dx = (\lambda_0 - \lambda) \int_{\Omega} u_0 \psi \, dx \geq 0.$$

Moreover, for every $\delta > 0$ satisfying

$$(5.1) \quad 0 < \delta < \left(\frac{\lambda - \lambda_1}{2L_1 \|a^-\|_\infty} \right)^{\frac{1}{p-2}} \frac{1}{\|\varphi_1\|_\infty}$$

the function $\underline{u} = \delta\varphi_1$ is a subsolution for $(1.1)_\lambda$ whenever $\lambda > \lambda_1$. Let $\delta > 0$ satisfying (5.1) and such that $g(s) \geq 0$ for any $s \in [0, \delta\|\varphi_1\|_{L^\infty(\Omega)}]$. For any $\psi \in H_0^1(\Omega)$, $\psi > 0$ with in Ω we deduce

$$\begin{aligned} & \delta \int_{\Omega} \nabla \varphi_1 \nabla \psi \, dx - \lambda \delta \int_{\Omega} \varphi_1 \psi \, dx - \int_{\Omega} a(x) f(\delta\varphi_1) \psi \, dx \\ &= -(\lambda - \lambda_1) \delta \int_{\Omega} \varphi_1 \psi \, dx - \int_{\Omega} a(x) f(\delta\varphi_1) \psi \, dx \\ &= -(\lambda - \lambda_1) \delta \int_{\Omega} \varphi_1 \psi \, dx \\ &\quad - \int_{\Omega} a(x) \left[\frac{(\delta\varphi_1)^{2^*-1}}{[\ln(e + \delta\varphi_1)]^\alpha} + g(\delta\varphi_1) \right] \psi \, dx \\ &\leq -(\lambda - \lambda_1) \delta \int_{\Omega} \varphi_1 \psi \, dx \\ &\quad + \|a^-\|_\infty \int_{\Omega} [h(\delta\varphi_1) + g(\delta\varphi_1)] \psi \, dx < 0. \end{aligned}$$

This allow us to take $\underline{u} = \delta\varphi_1$ as a subsolution for $(1.1)_\lambda$ with $\underline{u} < u_0$. The sub- and supersolution method now guarantees a positive solution u to $(1.1)_\lambda$, with $\underline{u} \leq u \leq u_0$.

(i.b) Step 2. Existence of a minimal positive solution u_λ for any $\lambda \in (\lambda_1, \Lambda)$.

To show that there is in fact a minimal solution, for each $x \in \Omega$ we define

$$\underline{u}_\lambda(x) := \inf \{u(x) : u > 0 \text{ solving } (1.1)_\lambda\}.$$

Firstly, we claim that $\underline{u}_\lambda \geq 0$, $\underline{u}_\lambda \not\equiv 0$. Assume by contradiction that $\underline{u}_\lambda \equiv 0$. This would yield a sequence u_n of positive solutions to $(1.1)_\lambda$ such that $\|u_n\|_{C(\overline{\Omega})} \rightarrow 0$ as $n \rightarrow \infty$, or in other words, $(\lambda, 0)$ is a bifurcation point from the trivial solution set to positive solutions. Set $v_n := \frac{u_n}{\|u_n\|_{C(\overline{\Omega})}}$. Observe that v_n is a weak solution to the problem

$$(5.2) \quad -\Delta v_n = \lambda v_n + a(x)f(u_n)/\|u_n\|_{C(\overline{\Omega})} \text{ in } \Omega; \quad v_n = 0 \text{ on } \partial\Omega.$$

It follows from $(H)_0$ that $\frac{a(x)f(u_n)}{\|u_n\|_{C(\overline{\Omega})}} \rightarrow 0$ in $C(\overline{\Omega})$ as $n \rightarrow \infty$. Therefore, the right-hand side of (5.2) is bounded in $C(\overline{\Omega})$. Hence, by the elliptic regularity, $v_n \in W^{2,r}(\Omega)$ for any $r > 1$, in particular for $r > N$. Then, the Sobolev embedding theorem implies that $\|v_n\|_{C^{1,\alpha}(\overline{\Omega})}$ is bounded by a constant C that is independent of n . Then, the compact embedding of $C^{1,\mu}(\overline{\Omega})$ into $C^{1,\beta}(\overline{\Omega})$ for $0 < \beta < \mu$ yields, up to a subsequence, $v_n \rightarrow \Phi \geq 0$ in $C^{1,\beta}(\overline{\Omega})$. Since $\|v_n\|_{C(\overline{\Omega})} = 1$, we have that $\|\Phi\|_{C(\overline{\Omega})} = 1$. Hence, $\Phi \geq 0$, $\Phi \not\equiv 0$.

Using the weak formulation of equation (5.2), passing to the limit, and taking into account that λ is fixed and $v_n \rightarrow \Phi$, we obtain that $\Phi \geq 0$, $\Phi \not\equiv 0$, is a weak solution to the equation

$$-\Delta\Phi = \lambda\Phi \text{ in } \Omega, \quad \Phi = 0 \text{ on } \partial\Omega.$$

Then, by the maximum principle it follows that $\Phi = \varphi_1 > 0$, the first eigenfunction, and $\lambda = \lambda_1$ is its corresponding eigenvalue, which contradicts that $\lambda > \lambda_1$.

Secondly, we show that \underline{u}_λ solves $(1.1)_\lambda$. We argue on the contrary. Observe that the minimum of any two positive solutions to $(1.1)_\lambda$ furnishes a supersolution to $(1.1)_\lambda$. Assume that there are a finite number of solutions to $(1.1)_\lambda$, then $\underline{u}_\lambda(x) := \min \{u(x) : u > 0 \text{ solves } (1.1)_\lambda\}$ and \underline{u}_λ is a supersolution. Choosing ε_0 small enough so that $\varepsilon_0\varphi_1 < \underline{u}_\lambda$, the sub-supersolution method provides a solution $\varepsilon_0\varphi_1 \leq v \leq \underline{u}_\lambda$. Since v is a solution and \underline{u}_λ is not, then $v \not\leq \underline{u}_\lambda$, contradicting the definition of \underline{u}_λ , and achieving this part of the proof.

Assume now that there is a sequence u_n of positive solutions to $(1.1)_\lambda$ such that, for each $x \in \Omega$, $\inf u_n(x) = \underline{u}_\lambda(x) \geq 0$, $\underline{u}_\lambda \not\equiv 0$. Let $\underline{u}_1 := \min\{u_1, u_2\}$. Choosing ε_1 small enough so that $\varepsilon_1\varphi_1 < \underline{u}_1$, the sub-supersolution method provides a solution $\varepsilon_1\varphi_1 \leq v_1 \leq \underline{u}_1$. We reason by induction.

Let $\underline{u}_n := \min\{v_{n-1}, u_{n+1}\}$. Choosing ε_n small enough so that $\varepsilon_n \varphi_1 < \underline{u}_n$, the sub- supersolution method provides a solution $\varepsilon_n \varphi_1 \leq v_n \leq \underline{u}_n \leq v_{n-1}$. With this induction procedure, we build a monotone sequence of solutions v_n , such that

$$(5.3) \quad 0 < v_n \leq \underline{u}_n \leq v_{n-1} \leq \underline{u}_{n-1} \leq \cdots \leq v_1.$$

Since monotonicity and Lemma 2.1, $\|v_n\|_{C(\overline{\Omega})} \leq \|v_1\|_{C(\overline{\Omega})}$, by elliptic regularity, $\|v_n\|_{C^{1,\mu}(\overline{\Omega})} \leq C$ for any $\mu < 1$, and by compact embedding $v_n \rightarrow v$ in $C^{1,\beta}(\overline{\Omega})$ for any $\beta < \alpha$. Using the weak formulation of equation (1.1) $_\lambda$, passing to the limit, and taking into account that λ is fixed, we obtain that v is a weak solution to the equation (1.1) $_\lambda$. Hence $v(x) \geq \underline{u}_\lambda > 0$. Moreover, since (5.3), $v_n(x) \downarrow v(x)$ pointwise for $x \in \Omega$, so $\inf v_n(x) = v(x)$. Also, and due to (5.3), $\underline{u}_n(x) \downarrow v(x)$ pointwise for $x \in \Omega$, and $\inf \underline{u}_n(x) = v(x)$.

On the other hand, by construction $\underline{u}_n \leq u_{n+1}$, so, for each $x \in \Omega$, $v(x) = \inf \underline{u}_n(x) \leq \inf u_n(x) = \underline{u}_\lambda(x)$. Therefore, and by definition of \underline{u}_λ , necessarily $v = \underline{u}_\lambda$, proving that \underline{u}_λ solves (1.1) $_\lambda$, and achieving the proof of step 2.

(ii) The monotonicity of the minimal solutions is concluded from a sub-supersolution method. Reasoning as in step 1, u_μ is a strict supersolution to (1.1) $_\lambda$, so $w := u_\mu(x) - u_\lambda(x) \geq 0$, $w \not\equiv 0$. Moreover, $w = 0$ on $\partial\Omega$, and we can always choose $c_0 := C_0 \|a\|_\infty > 0$ where C_0 is defined by (1.6), so that $a^-(x)f'(s) + c_0 \geq 0$ and $a^+(x)f'(s) + c_0 \geq 0$ for all $s \geq 0$, then

$$\begin{aligned} \left(-\Delta + a^-(x)f'(\theta u_\mu + (1-\theta)u_\lambda) + c_0 \right) w &= (\mu - \lambda)u_\mu + \lambda w \\ &+ [a^+(x)f'(\theta u_\mu + (1-\theta)u_\lambda) + c_0] w > 0 \text{ in } \Omega, \end{aligned}$$

finally, the Maximum Principle implies that $w > 0$ in Ω , and $\frac{\partial w}{\partial \nu} < 0$ on $\partial\Omega$, ending the proof of step 3.

(iii) Since [4, Theorem 2] if there exists an ordered pair of L^∞ bounded sub and super-solution $\underline{u} \leq \bar{u}$ to (1.1) $_\lambda$, and neither \underline{u} nor \bar{u} is a solution to (1.1) $_\lambda$, then there exist a solution $\underline{u} < u < \bar{u}$ to (1.1) $_\lambda$ such that u is a local minimum of J_λ at $H_0^1(\Omega)$.

Reasoning as in (i), $\bar{u} := u_\mu$ with $\mu > \lambda$ is a strict super-solution to (1.1) $_\lambda$, and $\underline{u} := \delta \varphi_1$ is a strict sub-solution for $\delta > 0$ small enough, such that $\underline{u}(x) < \bar{u}(x)$ for each $x \in \Omega$. This achieves the proof. \square

Proof of Theorem 1.1. Theorem 3.3 provides the existence of positive solutions for $\lambda < \lambda_1$, and Proposition 5.1 provide the existence of minimal positive solutions for $\lambda \in (\lambda_1, \Lambda)$.

(a) *Step 1. Existence of a second positive solution for $\lambda \in (\lambda_1, \Lambda)$.*

Fix an arbitrary $\lambda \in (\lambda_1, \Lambda)$, and let u_λ be the minimal solution to $(1.1)_\lambda$ given by Proposition 5.1, minimizing J_λ . A second solution follows seeking a solution through variational arguments [14, Theorem 5.10] and the Mountain Pass procedure shown below.

First, reasoning as in Proposition 5.1(iii), we get a local minimum $\tilde{u}_\lambda > 0$ of J_λ . If $\tilde{u}_\lambda \neq u_\lambda$, then \tilde{u}_λ is the second positive solution, ending the proof. Assume that $\tilde{u}_\lambda = u_\lambda$.

Now we reason as in [14, Theorem 5.10] on the nature of local minima. Thus, either

(i) there exists $\varepsilon_0 > 0$, such that $\inf \{J_\lambda(u) : \|u - \tilde{u}_\lambda\| = \varepsilon_0\} > J_\lambda(\tilde{u}_\lambda)$, in other words, \tilde{u}_λ is a strict local minimum, or

(ii) for each $\varepsilon > 0$, there exists $u_\varepsilon \in H_0^1(\Omega)$ such that J_λ has a local minimum at a point u_ε with $\|u_\varepsilon - \tilde{u}_\lambda\| = \varepsilon$ and $J_\lambda(u_\varepsilon) = J_\lambda(\tilde{u}_\lambda)$.

Let us assume that (i) holds, since otherwise case (ii) implies the existence of a second solution.

Consider now the functional $I_\lambda : H_0^1(\Omega) \rightarrow \mathbb{R}$ given by $I_\lambda[v] = J_\lambda[u_\lambda + v] - J_\lambda[u_\lambda]$, more specifically

$$I_\lambda[v] := \frac{1}{2} \int_\Omega |\nabla v|^2 dx - \frac{\lambda}{2} \int_\Omega (v^+)^2 dx - \int_\Omega \tilde{G}_\lambda(x, v^+) dx.$$

where

$$\begin{aligned} \tilde{G}_\lambda(x, s) &:= a(x) [F(u_\lambda(x) + s) - F(u_\lambda(x)) - f(u_\lambda(x))s] \\ &= a(x) \left[\frac{1}{2} f'(u_\lambda(x)) s^2 + o(s^2) \right]. \end{aligned}$$

Obviously $I_\lambda[v^+] \leq I_\lambda[v]$, and observe that $I'_\lambda[v] = 0 \iff J'_\lambda[u_\lambda + v] = 0$.

Fix now some element $0 \leq v_0 \in H_0^1(\Omega) \cap L^\infty(\Omega)$, $v_0 > 0$ in Ω^+ , $v_0 \equiv 0$ in Ω^- . Let $v = tv_0$ for a certain $t = t_0 > 0$ to be selected a posteriori, and evaluate

$$I_\lambda[tv_0] = \frac{1}{2} t^2 \left(\|\nabla v_0\|_{L^2(\Omega)}^2 - \lambda \|v_0\|_{L^2(\Omega)}^2 \right) - \int_\Omega \tilde{G}_\lambda(x, tv_0) dx.$$

Reasoning as in the proof of Theorem 3.3 for large positive t , since $F(t)/t^2 \rightarrow \infty$ as $t \rightarrow \infty$, and using also (3.1) we obtain that

$$\begin{aligned} I_\lambda[tv_0] &\leq C(1+t+t^2) - \int_{\Omega^+} a^+(x) \left[F(u_\lambda + tv_0) + \frac{1}{2}C_0(u_\lambda + tv_0)^2 \right] \\ &\leq C(1+t+t^2) - \delta \int_{\tilde{\Omega}_\delta^+} \left[F(u_\lambda + tv_0) + \frac{1}{2}C_0(u_\lambda + tv_0)^2 \right] dx, \end{aligned}$$

so

$$I_\lambda[tv_0] < 0$$

for $t = t_0$ big enough, and where $\tilde{\Omega}_\delta^+$ is defined by (3.18). Thus, the Mountain Pass Theorem implies that if

$$\Gamma := \{\mathbf{g} \in C([0, 1]; H_0^1(\Omega)) : \mathbf{g}(0) = 0, I_\lambda[\mathbf{g}(1)] < 0\},$$

then, there exists $c > 0$ such that

$$c := \inf_{\mathbf{g} \in \Gamma} \max_{0 \leq t \leq 1} I_\lambda[\mathbf{g}(t)]$$

is a critical value of I_λ , and thereby $\mathcal{K}_c := \{v \in H_0^1(\Omega) : I_\lambda[v] = c, I'_\lambda[v] = 0\}$ is non empty.

Since for any $\mathbf{g} \in \Gamma$ we have $I_\lambda[\mathbf{g}^+(t)] \leq I_\lambda[\mathbf{g}(t)]$ for all $t \in [0, 1]$, it follows that $\mathbf{g}^+ \in \Gamma$, and we derive the existence of a sequence v_n such that

$$I_\lambda[v_n] \rightarrow c, \quad \|I'_\lambda[v_n]\| \rightarrow 0, \quad v_n \geq 0.$$

On the other hand, $w_n := u_\lambda + v_n$ is a (PS) sequence for the original functional J_λ . Since Theorem 3.2, if $\lambda < \lambda_1(\text{int } \Omega^0)$, $v_n \rightarrow v_\lambda$ en $H_0^1(\Omega)$, so $I'_\lambda[v] = 0$ and $I_\lambda[v] = c > 0$, hence $v_\lambda \geq 0$ is a nontrivial critical point of I_λ . Consequently, $w_\lambda := u_\lambda + v_\lambda$ is a positive critical point of J_λ , such that, for each $\psi \in H_0^1(\Omega)$, we have

$$\int_{\Omega} \nabla w_\lambda \cdot \nabla \psi \, dx = \int_{\Omega} \left(\lambda w_\lambda + a(x)f(w_\lambda) \right) \psi \, dx,$$

and thereby $w_\lambda := u_\lambda + v_\lambda \geq u_\lambda$, $w_\lambda \neq u_\lambda$ is a second positive solution to (1.1) $_\lambda$.

(b) *Step 2. Existence of a classical positive solution for $\lambda = \Lambda$.*

We prove the existence of a solution for $\lambda = \Lambda$. For each $\lambda \in (\lambda_1, \Lambda)$, problem (1.1) admits a minimal positive weak solution u_λ and $\lambda \rightarrow u_\lambda$ is increasing, see Proposition 5.1. Taking the monotone pointwise limit, let us define

$$u_\Lambda(x) := \lim_{\lambda \uparrow \Lambda} u_\lambda(x).$$

We next see that $\|u_\Lambda\| < +\infty$, reasoning on the contrary. Assume that there exists a sequence of solutions $u_n := u_{\lambda_n}$ such that $\|u_{\lambda_n}\| \rightarrow +\infty$ as $\lambda_n \rightarrow \Lambda$. Set $v_n := u_n/\|u_n\|$, then there exists a subsequence, again denoted by v_n such that $v_n \rightharpoonup v$ in $H_0^1(\Omega)$, and $v_n \rightarrow v$ in $L^p(\Omega)$ for any $p < 2^*$ and a.e. Arguing as in the claim of Proposition 3.1, $v \equiv 0$. Moreover

$$(5.4) \quad \lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n)}{\|u_n\|} v_n dx = 1.$$

On the other hand, from the weak formulation, for all $\psi \in C_c^\infty(\Omega)$,

$$(5.5) \quad \int_{\Omega} \nabla v_n \nabla \psi dx = \lambda_n \int_{\Omega} v_n \psi dx + \int_{\Omega} a(x) \frac{f(u_n)}{\|u_n\|} \psi dx.$$

Taking the limit, and since $C_c^\infty(\Omega)$ is dense in $L^2(\Omega)$

$$(5.6) \quad \lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n)}{\|u_n\|} \psi dx = 0, \quad \text{for all } \psi \in L^2(\Omega).$$

Since Lemma 2.1, $u \in C^2(\Omega) \cap C^{1,\mu}(\bar{\Omega})$ and so $a(x) \frac{f(u_n)}{\|u_n\|} \in L^2(\Omega)$. Moreover $v_n \rightarrow v = 0$ in $L^2(\Omega)$. Hence [2, Proposition 3.13 (iv)], and (5.6) imply

$$\lim_{n \rightarrow \infty} \int_{\Omega} a(x) \frac{f(u_n)}{\|u_n\|} v_n dx = 0,$$

which contradicts (5.4) and yields $\|u_\Lambda\| < +\infty$.

By Sobolev embedding and the Lebesgue dominated convergence theorem, $u_n \rightarrow u_\Lambda$ in $L^{2^*}(\Omega)$.

Now, by substituting $\psi = u_n$ in (5.5), using Hölder inequality and Sobolev embeddings we obtain

$$\left[\|u_n\| \leq \Lambda \|v_n\|_{L^2(\Omega)} \|u_n\| + C, \quad \text{with } \|v_n\|_{L^2(\Omega)} \rightarrow 0 \right] \Rightarrow \|u_n\| \leq C.$$

By compactness, for a subsequence again denoted by u_n , $u_n \rightharpoonup u^*$ in $H_0^1(\Omega)$, $u_n \rightarrow u^*$ in $L^p(\Omega)$ for any $p < 2^*$ and a.e. By uniqueness of the limit, $u_\Lambda = u^*$. Finally, by taking limits in the weak formulation of u_n as $\lambda_n \rightarrow \Lambda$, we get

$$\int_{\Omega} \nabla u_\Lambda \nabla \psi = \Lambda \int_{\Omega} u_\Lambda \psi + \int_{\Omega} a(x) f(u_\Lambda) \psi.$$

Hence u_Λ is a positive weak solution to $(1.1)_\Lambda$. Lemma 2.1 yields that $u_\Lambda \in C^2(\Omega) \cap C^{1,\mu}(\bar{\Omega})$ is a classical solution.

(c) *Step 3. Existence of a classical positive solution for $\lambda \leq \lambda_1$.*

The existence of a classical positive solution for $\lambda < \lambda_1$ is done in Theorem 3.3. Let's look for a solution when $\lambda = \lambda_1$.

Since step 1, for any $\lambda \in (\lambda_1, \Lambda)$ there exists a second positive solution to (1.1) $_\lambda$. Let's denote it by $\tilde{u}_\lambda \neq u_\lambda$. Now, define the pointwise limit

$$(5.7) \quad \tilde{u}_{\lambda_1}(x) := \limsup_{\lambda \rightarrow \lambda_1} \tilde{u}_\lambda(x).$$

Reasoning as in step 2, $\|\tilde{u}_{\lambda_1}\| < +\infty$ and $\tilde{u}_{\lambda_1} \in C^2(\Omega) \cap C^{1,\mu}(\bar{\Omega})$ is a classical solution to (1.1) $_{\lambda_1}$.

Moreover, $\tilde{u}_{\lambda_1} > 0$. Assume on the contrary that $\tilde{u}_{\lambda_1} = 0$. By the Crandall-Rabinowitz's Theorem [10], the only nontrivial solutions to (1.1) in a neighborhood of the bifurcation point $(\lambda_1, 0)$ are given by (4.1). Since Proposition 5.1, those are the minimal solutions u_λ , and due to $\tilde{u}_\lambda \neq u_\lambda$, \tilde{u}_λ are not in a neighbourhood of $(\lambda_1, 0)$, contradicting the definition of $\tilde{u}_{\lambda_1}(x)$, (5.7)

Hence, $\tilde{u}_{\lambda_1} \geq 0$, and reasoning as in (1.8), the Maximum Principle implies that $\tilde{u}_{\lambda_1} > 0$. \square

APPENDIX A. SOME ESTIMATES

First, we prove an useful estimate of $\frac{\ln(e+s)}{\ln(e+as)}$.

Lemma A.1. *Let $0 < a \leq 1$ be fixed. Then for all $s \geq 0$,*

$$(A.1) \quad \frac{\ln(e+s)}{\ln(e+as)} \leq \ln\left(\frac{e}{a}\right) \leq \frac{1}{a}.$$

Proof. Denote $\ell(s) = \frac{\ln(e+s)}{\ln(e+as)}$ for all $s \geq 0$. Then $1 \leq \ell(s) \leq \ell(s_0)$ where $s_0 > 0$ is the unique value where $\ell'(s) = 0$. When computing s_0 we find

$$\ell'(s_0) = 0 \iff (e + as_0) \ln(e + as_0) - a(e + s_0) \ln(e + s_0) = 0$$

and therefore

$$\max \ell = \ell(s_0) = \frac{\ln(e + s_0)}{\ln(e + as_0)} = \frac{e + as_0}{a(e + s_0)}.$$

Notice that we have $\ell(s_0) \leq \frac{1}{a}$. In order to find a better upper bound of $\ln\left(\frac{e+as_0}{e+s_0}\right)$ let us denote for all $s \geq 0$

$$\theta(s) = (e + as) \ln(e + as) - a(e + s) \ln(e + s).$$

Then, there exists $\chi \in (0, s_0)$ such that

$$0 - e(1 - a) = \theta(s_0) - \theta(0) = \theta'(\chi)s_0 \implies \frac{e(1 - a)}{s_0} = -\theta'(\chi).$$

Then

$$-\theta'(s) = a \ln\left(\frac{e + s}{e + as}\right) \leq a \ln\left(\frac{1}{a}\right),$$

and

$$\frac{e(1-a)}{s_0} \leq a \ln\left(\frac{1}{a}\right) \implies s_0 \geq \frac{e(1-a)}{a \ln\left(\frac{1}{a}\right)}.$$

Since $\frac{e+as}{a(e+s)}$ is decreasing,

$$\begin{aligned} \max_{s \geq 0} \ell(s) &= \ell(s_0) = \frac{e + as_0}{a(e + s_0)} \leq \frac{e + \frac{e(1-a)}{\ln\left(\frac{1}{a}\right)}}{ae + \frac{e(1-a)}{\ln\left(\frac{1}{a}\right)}} \\ &= \frac{\ln(1/a) + 1 - a}{a \ln(1/a) + 1 - a} \leq \ln(1/a) + 1, \end{aligned}$$

and the first inequality of (A.1) is achieved. The second one is obvious. \square

Next lemma is about the variations of $h(s) = \frac{s^{2^*-1}}{[\ln(e+s)]^\alpha}$ for $s \geq 0$.

Lemma A.2. *There exists $\alpha^* > 2(2^* - 1)$ such that h is an increasing function on $]0, +\infty[$ if and only if $\alpha \leq \alpha^*$. Moreover, if $\alpha > \alpha^*$ there exists $s_1 < s_2$ such that h is increasing in $[0, +\infty[\setminus]s_1, s_2[$.*

Proof. We have

$$h'(s) = \frac{s^{2^*-2}}{[\ln(e+s)]^{\alpha+1}} \left((2^* - 1) \ln(e+s) - \frac{\alpha s}{s+e} \right),$$

so

$$h'(s) \geq 0 \iff \ln(e+s) \geq \frac{\alpha}{2^* - 1} \frac{s}{s+e}.$$

Let us define for $s \geq 0$,

$$\theta(s) := \ln(e+s) - \frac{\alpha}{2^* - 1} \frac{s}{s+e}.$$

We have:

$$\begin{cases} \theta(0) = 1, \\ \theta(s) \rightarrow +\infty \quad \text{as } s \rightarrow +\infty, \\ \theta'(s) = \frac{s+e(1-\frac{\alpha}{2^*-1})}{(e+s)^2}. \end{cases}$$

Hence:

(1) If $\frac{\alpha}{2^*-1} \leq 1$ then $\theta'(s) \geq 0$ for all $s \geq 0$ and in particular $\theta(s) \geq 0$ and therefore $h'(s) \geq 0$ for all $s \geq 0$;

(2) if $\frac{\alpha}{2^*-1} > 1$ then

$$\theta'(s_0) = 0 \quad \text{for } s_0 = e \left(\frac{\alpha}{2^* - 1} - 1 \right).$$

Let us compute $\theta(s_0)$:

$$\theta(s_0) = \ln \left(\frac{\alpha}{2^* - 1} \right) - \frac{\alpha}{2^* - 1} + 2,$$

and hence:

(i) if $\theta(s_0) \geq 0$ then $\theta(s) \geq 0$ for all $s \geq 0$ and therefore $h'(s) \geq 0$ for all $s \geq 0$;

(ii) if $\theta(s_0) < 0$ then there exists $s_1 < s_2$ such that

$$\theta(s) > 0 \quad \forall s \in [0, +\infty[\setminus]s_1, s_2[\implies h'(s) > 0 \quad \forall s \in [0, +\infty[\setminus]s_1, s_2[.$$

Notice that $t \rightarrow \ln t$ is greater than $t \rightarrow t - 2$ somewhere between some $t_1 < 1$ and the value t^* = the unique solution > 2 of the equation

$$\ln t^* = t^* - 2.$$

Finally the statement of the lemma holds for $\alpha^* = t^*(2^* - 1)$. \square

APPENDIX B. A COMPACT EMBEDDING USING ORLICZ SPACES

For references on Orlicz spaces see [15, 20]. Throughout $\Omega \subset \mathbb{R}^N$ is an bounded open set. We will denote

$$\mathcal{L}(\Omega) = \{\varphi : \Omega \rightarrow \mathbb{R} : \varphi \text{ is Lebesgue measurable}\}.$$

Definition B.1. *We will say that a function $M : [0, +\infty[\rightarrow [0, +\infty[$ is a **N-function** if and only if*

(N1) *M is convex, increasing and continuous,*

(N2) $\lim_{s \rightarrow 0^+} \frac{M(s)}{s} = 0,$

(N3) $\lim_{s \rightarrow +\infty} \frac{M(s)}{s} = +\infty.$

The proof of the following property is trivial, we just quoted it for the sake of completeness.

Proposition B.2. *Any N-function M admits a representation of the form*

$$M(s) = \int_0^s m(t) dt$$

where $m : [0, +\infty[\rightarrow [0, +\infty[$ is a non-decreasing right-continuous function satisfying $m(0) = 0$ and

$$\lim_{s \rightarrow +\infty} m(s) = +\infty.$$

Thus, m is the right-derivative of M .

Our first aim is to prove the following result:

Theorem B.3. *Let $M : [0, +\infty[\rightarrow \mathbb{R}$ be a N -function such that*

$$\lim_{s \rightarrow +\infty} \frac{s^{2^*}}{M(s)} = +\infty.$$

Assume also that M satisfies the Δ_2 -condition, that is,

$$(B.1) \quad \exists K > 0, \quad \forall s \in [0, +\infty[, \quad M(2s) \leq KM(s).$$

Let $\{u_n\}_{n \in \mathbb{N}}$ in $H_0^1(\Omega)$ be a sequence satisfying

- (1) $\sup_{n \in \mathbb{N}} \|u_n\|_{2^*} < \infty,$
- (2) *there exists $u \in H_0^1(\Omega)$ such that $\lim_{n \rightarrow +\infty} u_n(x) = u(x)$ a.e.*

Then there exists a subsequence $\{u_{n_k}\}_{k \in \mathbb{N}}$ such that

$$(B.2) \quad \lim_{k \rightarrow \infty} \int_{\Omega} M(|u_{n_k}(x) - u(x)|) dx = 0.$$

In order to proof this theorem we need some definitions.

Definition B.4. *Let $\mathcal{K} \subset \mathcal{L}(\Omega)$. We say that \mathcal{K} has **equi-absolutely continuous integrals** if and only if $\forall \varepsilon > 0$ there exists $h > 0$ such that*

$$\forall \varphi \in \mathcal{K}, \forall A \subset \Omega \text{ measurable}, |A| < h \implies \int_A |\varphi(x)| dx < \varepsilon.$$

Lemma B.5. *Let $M : [0, +\infty[\rightarrow \mathbb{R}$ be a N -function satisfying the Δ_2 condition (B.1). Let $\{u_n\}_{n \in \mathbb{N}}$ be a sequence of measurable functions converging a.e. to some function u and such that the set*

$$\left\{ M(|u_n|) : n \in \mathbb{N} \right\}$$

has equi-absolutely continuous integrals. Then (B.2) holds.

Proof. Let fix $\varepsilon > 0$ and let $\delta > 0$ be such that

$$\forall n \in \mathbb{N}, \forall A \subset \Omega \text{ measurable}, |A| < \delta \implies \int_A M(|u_n|) dx \leq \varepsilon.$$

Using Fatou's lemma we infer that also

$$\forall A \subset \Omega \text{ measurable}, |A| < \delta \implies \int_A M(|u|) dx \leq \varepsilon.$$

Let $\Omega_n = \{x \in \Omega : |u_n(x) - u(x)| > M^{-1}(\varepsilon)\}$. As a consequence of Egoroff's theorem, the sequence $(u_n)_{n \in \mathbb{N}}$ converge in measure to u so there exists $n_0 \in \mathbb{N}$ such that

$$|\Omega_n| < \delta.$$

Then, using the convexity of M and (B.1) it comes

$$\begin{aligned} \int_{\Omega} M(|u_n - u|) dx &= \int_{\Omega_n} M(|u_n - u|) dx + \int_{\Omega \setminus \Omega_n} M(|u_n - u|) dx \\ &\leq \frac{1}{2} \left(\int_{\Omega_n} (M(2|u_n|) + M(2|u|)) dx \right) + |\Omega| M(M^{-1}(\varepsilon)) \\ &\leq \frac{K}{2} \left(\int_{\Omega_n} (M(|u_n|) + M(|u|)) dx \right) + |\Omega| \varepsilon \leq (K + |\Omega|) \varepsilon. \end{aligned}$$

□

In order to prove that, for the sequence of our theorem, the set

$$\left\{ M(|u_n|) : n \in \mathbb{N} \right\}$$

has equi-absolutely continuous integrals we are going to use the following lemma :

Lemma B.6. *Let $\mathcal{K} \subset \mathcal{L}(\Omega)$ and let $\Phi : [0, +\infty[\rightarrow [0, +\infty[$ be an increasing function satisfying*

$$(B.3) \quad \lim_{s \rightarrow +\infty} \frac{\Phi(s)}{s} = +\infty.$$

Suppose that there exists $D > 0$ such that

$$(B.4) \quad \sup_{u \in \mathcal{K}} \int_{\Omega} \Phi(|u|) dx \leq D.$$

Then all the functions $u \in \mathcal{K}$ are integrable and \mathcal{K} has equi-absolutely continuous integrals (Valle Poussin's theorem).

Moreover, if $M : [0, +\infty[\rightarrow [0, +\infty[$ is a continuous increasing function satisfying

$$\lim_{s \rightarrow +\infty} \frac{M(s)}{s} = +\infty \text{ and } \lim_{s \rightarrow +\infty} \frac{\Phi(s)}{M(s)} = +\infty,$$

then the family $\mathcal{K}_1 = \{M(|u|) : u \in \mathcal{K}\}$ has equi-absolutely continuous integrals.

Proof. For the Valle Poussin's theorem see [18] page 159. To prove the second statement remark that the function $\tilde{\Phi} = \Phi \circ M^{-1}$ satisfies (B.3). Here M^{-1} stand for the right-hand inverse. □

Proof of theorem B.3. Let us take $\Phi(s) = |s|^{2^*}$. From hypothesis (1) of the theorem, the set $\mathcal{K} = \{u_n : n \in \mathbb{N}\}$ satisfies (B.4) for some $D > 0$. Then the conclusion follows from lemma B.5 and Lemma B.6 . □

Remark B.7. *Whenever (B.2) is satisfied we say that the sequence $\{u_{n_k}\}_{k \in \mathbb{N}}$ converges in M -mean to u .*

One can formulate Theorem B.3 as a compact embedding of $H_0^1(\Omega)$ in some vector space endowed of the *Luxembourg norm associate to M* (see [15, 20]). Instead, we are going to use the Orlicz-norm which is more suitable to our purposes. We will see later in Theorem B.12 that the convergence in M -mean implies the convergence with respect to the Orlicz-norm, provided that the Δ_2 -condition is satisfied.

Definition B.8. *Let M be a N -function. The **complementary of M** defined for all $s \geq 0$ is the function*

$$M^*(s) := \max \{st - M(t) : t \geq 0\}.$$

As before, we give the following trivial result for the sake of completeness:

Proposition B.9. *If m is the right derivative of M then*

$$m^*(s) = \sup \{t : m(t) \leq s\}$$

is the right derivative of M^ and M^* is a N -function. Furthermore, for all $s \geq 0$ we have*

$$sm(s) = M(s) + M^*(m(s)), \quad sm^*(s) = M(m^*(s)) + M^*(s).$$

Next, let us introduce the Orlicz norm associated to M :

Definition B.10. *Let M be a N -function and let M^* be its complementary. Let us denote for any $v \in \mathcal{L}(\Omega)$*

$$\rho(v, M^*) = \int_{\Omega} M^*(|v|) dx$$

*and define the **Orlicz norm** of any $u \in \mathcal{L}(\Omega)$ by*

$$\|u\|_M := \sup \left\{ \int_{\Omega} uv dx : v \in \mathcal{L}(\Omega), \rho(v, M^*) \leq 1 \right\}.$$

$\|\cdot\|_M$ is a norm in the real vector space

$$L_M(\Omega) = \{u \in \mathcal{L}(\Omega) : \|u\|_M < +\infty\}.$$

(see [15] for the details). Let us prove the following less trivial properties:

Proposition B.11.

(i) *For all $u \in \mathcal{L}(\Omega)$,*

$$(B.5) \quad \|u\|_M \leq \int_{\Omega} M(|u|) dx + 1.$$

(ii) For any u and v in $\mathcal{L}(\Omega)$ it holds

$$(B.6) \quad \left| \int_{\Omega} uv \, dx \right| \leq \|u\|_M \|v\|_{M^*} \quad (\text{Holder's inequality}).$$

(iii) For any u and v in $\mathcal{L}(\Omega)$ we have $\|u\|_M \leq \|v\|_M$ if $|u| \leq |v|$ a.e.

Proof. (i) This follows from the definition of $\|\cdot\|_M$ and the inequality $|uv| \leq M(|u|) + M^*(|v|)$.

(ii) We divide the proof in 3 steps.

Step 1: For all $v \in \mathcal{L}(\Omega)$,

$$\left| \int_{\Omega} uv \, dx \right| \leq \begin{cases} \|u\|_M & \text{if } \rho(v, M^*) \leq 1 \\ \rho(v, M^*) \|u\|_M & \text{if } \rho(v, M^*) > 1 \end{cases}$$

Indeed, the first case follows directly from the definition. If $\rho(v, M^*) > 1$ then by convexity

$$M^* \left(\frac{|v|}{\rho(v, M^*)} \right) \leq \frac{M^*(|v|)}{\rho(v, M^*)}$$

and therefore

$$\rho \left(\frac{|v|}{\rho(v, M^*)}, M^* \right) \leq \frac{1}{\rho(v, M^*)} \int_{\Omega} M^*(|v|) \, dx = 1$$

and

$$\left| \int_{\Omega} u \frac{v}{\rho(v, M^*)} \, dx \right| \leq \|u\|_M.$$

Step 2: If $\|u\|_M \leq 1$ then $\rho(m(|u|), M^*) \leq 1$.

Set $u_n = u \chi_{\{|u| \leq n\}}$ for all $n \in \mathbb{N}$. Since u_n is bounded then $\rho((m(|u_n|), M^*) < +\infty$. Assume by contradiction that $\int_{\Omega} M^*(m(|u|)) \, dx > 1$ and let $n_0 \in \mathbb{N}$ be such that $\int_{\Omega} M^*(m(|u_{n_0}|)) \, dx > 1$. We have

$$M^*(m(|u_{n_0}|)) < M(|u_{n_0}|) + M^*(m(|u_{n_0}|)) = |u_{n_0}| m(|u_{n_0}|)$$

and therefore, by (i),

$$\rho(m(|u_{n_0}|), M^*) < \int_{\Omega} |u_{n_0}| m(|u_{n_0}|) \, dx \leq \|u_{n_0}\|_M \rho(m(|u_{n_0}|), M^*)$$

which contradicts $\|u_{n_0}\|_M \leq \|u\|_M \leq 1$.

This is trivial from the definition of $\|u\|_M$, step 1 and the fact that $|u|m(|u|) = M(|u|) + M^*(m(|u|))$.

Step 3: If $\|u\|_M \leq 1$ then $\rho(u, M) \leq \|u\|_M$.

Let us remark that for all $s \geq 0$

$$M^*(m(s)) + M(s) = sm(s).$$

Set $v_0 = m(|u|)$. From step 2, $\rho(v_0, M^*) \leq 1$ and then

$$\rho(u, M) \leq \rho(u, M) + \rho(v_0, M^*) = \int_{\Omega} uv_0 dx \leq \|u\|_M.$$

Now we prove Holder's inequality. From step 2 applied to M^* and $\frac{v}{\|v\|_{M^*}}$ we have $\rho\left(\frac{v}{\|v\|_{M^*}}, M^*\right) \leq 1$, so then

$$\left| \int_{\Omega} u \frac{v}{\|v\|_{M^*}} dx \right| \leq \|u\|_M$$

and Holder's inequality follows.

The proof of (iii) is trivial. \square

Finally, we give the following compact embedding result:

Theorem B.12. *Let M be a N -function satisfying the Δ_2 -condition (B.1) and let $\{u_n\}_{n \in \mathbb{N}}$ be a sequence in $\mathcal{L}(\Omega)$ such that*

$$\lim_{n \rightarrow \infty} \rho(u_n, M) = 0.$$

Then

$$\lim_{n \rightarrow \infty} \|u_n\|_M = 0.$$

Thus, the convergence in M -mean implies the converge with respect to the $\|\cdot\|_M$ norm.

Proof. Let $\varepsilon > 0$ and take $m \in \mathbb{N}$ such that $\frac{1}{2^{m-1}} < \varepsilon$. Using condition (B.1) we also have

$$\lim_{n \rightarrow \infty} \int_{\Omega} M(2^m |u_n|) dx = 0.$$

Let $n_0 \in \mathbb{N}$ be such that for all $n \geq n_0$ we have

$$\int_{\Omega} M(2^m |u_n|) dx < 1.$$

From step 1 of the proof in the previous proposition we have that for all $n \geq n_0$

$$\|2^m u_n\|_M \leq \rho(2^m |u_n|, M) + 1 < 2,$$

which implies that

$$\|u_n\|_M < \frac{1}{2^{m-1}} < \varepsilon.$$

\square

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