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Local and global properties of solutions of quasilinear Hamilton-Jacobi equations

Marie-Françoise Bidaut-Véron
Marta Garcia-Huidobro
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Abstract We study some properties of the solutions of (E) $-\Delta_p u + |\nabla u|^q = 0$ in a domain $\Omega \subset \mathbb{R}^N$, mostly when $p \geq q > p - 1$. We give a universal priori estimate of the gradient of the solutions with respect to the distance to the boundary. We give a full classification of the isolated singularities of the positive solutions of (E), a partial classification of isolated singularities of the negative solutions. We prove a general removability result in expressed in terms of some Bessel capacity of the removable set. We extend our estimates to equations on complete non compact manifolds satisfying a lower bound estimate on the Ricci curvature, and derive some Liouville type theorems.

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Key words. p -Laplacian; a priori estimates; singularities; removable set; curvature.

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1 Introduction

Let $N \geq p > 1$, $q > p - 1$ and $\Omega \subset \mathbb{R}^N$ ($N > 1$) be a domain. In this article we study some local and global properties of solutions of

$$-\Delta_p u + |\nabla u|^q = 0 \quad (1.1)$$

in Ω , where $\Delta_p u := \operatorname{div}(|\nabla u|^{p-2} \nabla u)$. The main questions we consider are the following:

- 1- A priori estimates and Liouville type theorems.
- 2- Removability of singularities.
- 3- Description of isolated singularities of solutions.

Our technique allows us to handle both positive and signed solutions. We will speak of a problem with *absorption* when we consider positive solutions and a problem with *source* when we consider negative solutions (in which case we will often set $u = -\tilde{u}$). One of the main tools we use is a pointwise gradient estimate, valid for *any signed* solution of (1.1),

Theorem A. *Let $u \in C^1(\Omega)$ be a solution of (1.1) in Ω . Then*

$$|\nabla u(x)| \leq c_{N,p,q} (\operatorname{dist}(x, \partial\Omega))^{-\frac{1}{q+1-p}} \quad (1.2)$$

for any $x \in \Omega$. If $\Omega = \mathbb{R}^N$, u is a constant.

In the case $p = 2$ the existence of an upper bound of the gradient has first been obtained by Lasry and Lions [25] and then made explicit by Lions [26]; the idea there was based upon the Bernstein technique. In [29] Nguyen-Phuoc and Véron rediscovered this upper bound by a slightly different method. Our method of proof is a combination of the Bernstein approach and the Keller-Osserman construction of radial supersolutions of the elliptic inequality satisfied by $|\nabla u|^2$, a technique which will be fundamental for extension of this results in a geometric framework (see below).

Concerning solution of (1.1) in a domain $\Omega \subset \mathbb{R}^N$ we obtain that if $p \neq q$, any solution satisfies

$$|u(x)| \leq c_{p,q} \left(\operatorname{dist}(x, \partial\Omega)^{\frac{p-q}{q+1-p}} - \delta^* \frac{p-q}{q+1-p} \right) + \max\{|u(z)| : \operatorname{dist}(z, \partial\Omega) = \delta^*\} \quad (1.3)$$

if $\operatorname{dist}(x, \partial\Omega) \leq \delta^*$, where $\delta^* > 0$ depends on the curvature of $\partial\Omega$; when $p = q$ the formula holds provided the term $\operatorname{dist}(x, \partial\Omega)^{\frac{p-q}{q+1-p}} - \delta^* \frac{p-q}{q+1-p}$ is replaced by $\ln(\operatorname{dist}(x, \partial\Omega)/\delta^*)$. In the case $p = 2$ this estimate was a key element for the study of boundary singularity developed in [29]. This aspect of equation (1.1) will be developed in a forthcoming article.

In the study of singularities, we first give a general removability concerning interior singularities. The general removability result, expressed in terms of the

Bessel capacity $C_{1, \frac{q}{q+1-p}}$ relative to \mathbb{R}^N , deals with locally renormalized solutions (see Definition 3.4).

Theorem B *Let $p - 1 < q < p$ and $K \subset \Omega$ be a relatively closed set such that $C_{1, \frac{q}{q+1-p}}(K) = 0$. Then any locally renormalized solution u of (1.1) in $\Omega \setminus K$ can be extended as a locally renormalized solution in whole Ω . When u is positive, u is therefore a strong solution in whole Ω . When u is a signed renormalized solution, it is a strong solution provided $q < \frac{N(p-1)}{N-1}$.*

If K is reduced to a single point $0 \in \Omega$, the threshold of removability of an isolated singularity corresponds to the exponent $q = q_c := \frac{N(p-1)}{N-1}$, but the situation is different if we consider positive or negative solutions.

When $p - 1 < q < q_c$, there exists an explicit radial positive solution of (1.1) in $\mathbb{R}^N \setminus \{0\}$

$$U(x) = U(|x|) = \lambda_{N,p,q} |x|^{-\beta_q} \quad (1.4)$$

where

$$\beta_q = \frac{p-q}{q+1-p} \quad \text{and} \quad \lambda_{N,p,q} = \beta_q^{-1} (\beta_q(p-1) + p - N)^{\frac{1}{q+1-p}}. \quad (1.5)$$

When $p = 2$ Lions obtained in [26] the description of isolated singularities of positive solutions of (1.1) in the subcritical case $1 < q < \frac{N}{N-1}$. We extend his result to the general case $1 < p \leq N$ and provide a full classification of isolated singularities of positive solutions :

Theorem C *Assume $p - 1 < q < q_c$ and $u \in C^1(\Omega \setminus \{0\})$ is a positive solution of (1.1) in $\Omega \setminus \{0\}$. Then*

(i) *either there exists $c \geq 0$ such that*

$$\lim_{x \rightarrow 0} \frac{u(x)}{\mu_p(x)} = c \quad (1.6)$$

where μ_p is the fundamental solution of the p -Laplacian defined by $\mu_p(x) = \frac{p-1}{N-p} |x|^{\frac{p-N}{p-1}}$ if $1 < p < N$ and $\mu_N(x) = -\ln |x|$. Furthermore u satisfies

$$-\Delta_p u + |\nabla u|^q = c_{N,p} \delta_0 \quad \text{in } \mathcal{D}'(\Omega). \quad (1.7)$$

(ii) *or*

$$\lim_{x \rightarrow 0} |x|^{\beta_q} u(x) = \lambda_{N,p,q} \quad (1.8)$$

for some explicit positive constants $\lambda_{N,p,q}$ and $\beta_q = \frac{p-q}{q+1-p}$.

When $q > q_c$, there exists a radial negative singular solutions $V = -\tilde{U}$ of (1.1) in $\mathbb{R}^N \setminus \{0\}$ with

$$\tilde{U}(x) = \tilde{U}(|x|) = \tilde{\lambda}_{N,p,q} |x|^{-\beta_q}, \quad (1.9)$$

where

$$\tilde{\lambda}_{N,p,q} = \beta_q^{-1} (N - p - \beta_q(p-1))^{\frac{1}{q+1-p}}. \quad (1.10)$$

In this case we obtain a partial classification of isolated singularities of negative solutions of (1.1) in $\Omega \setminus \{0\}$.

Theorem D *Assume u is negative C^1 solution of (1.1) in $\Omega \setminus \{0\}$. Then*

(i) *When $p - 1 < q < q_c$ there exists $c \leq 0$ such that (1.6) and (1.7) hold.*

(ii) *When $q > q_c$ (1.6) and (1.7) hold with $c = 0$.*

Furthermore, when u is radial, there holds.

(iii) *When $q = q_c$, either*

$$\lim_{x \rightarrow 0} \frac{(-\ln |x|)^{\frac{N-1}{p-1}} u(x)}{\mu_p(x)} = c_{N,p} \quad (1.11)$$

or u is regular at 0.

(iv) *When $q > q_c$,*

$$\lim_{x \rightarrow 0} |x|^{\beta_q} u(x) = -\tilde{\lambda} c_{N,p,q}. \quad (1.12)$$

or u is regular at 0.

In the last section we obtain local and global estimates of solutions of when \mathbb{R}^N is replaced by a N -dimensional Riemannian manifold (M^N, g) and $-\Delta_p$ by the corresponding p -Laplacian $-\Delta_{g,p}$ in covariant derivatives. Our results emphasize the role of the Ricci curvature of the manifold if $p = 2$ and the sectional curvature if $p \neq 2$. In the case $1 < p < 2$ we need to introduce the notion of *convexity radius* of a point $x \in M$, denoted by $r_M(x)$, which is supremum of the $r > 0$ such that the geodesic ball $B_r(x)$ is strongly convex.

Theorem E. *Let $q > p - 1 > 0$, (M^N, g) be a Riemannian manifold with Ricci curvature Ric_g and sectional curvature Sec_g and $\Omega \subset M$ be a domain such that $\text{Ric}_g \geq (1 - N)B^2$ in Ω . Assume also $\text{Sec}_g \geq -\tilde{B}^2$ in Ω if $p > 2$ or $r_M(z) \geq \text{dist}(z, \partial\Omega)$ for any $z \in \Omega$ if $1 < p < 2$. Then any C^1 solution u of*

$$-\Delta_{g,p} u + |\nabla u|^q = 0 \quad (1.13)$$

in Ω satisfies

$$|\nabla u(x)| \leq c_{N,p,q} \max \left\{ B^{\frac{1}{q+1-p}}, (1 + B_p) \text{dist}_g(x, \partial\Omega)^{-\frac{1}{q+1-p}} \right\} \quad (1.14)$$

where $B_p = B + (p - 2)_+ \tilde{B}$ and $\text{dist}(x, \partial\Omega)$ is now the geodesic distance of x to $\partial\Omega$.

Notice that $r_M(x)$ is always infinite when $\text{Sec}_g \leq 0$. Furthermore if for some $a \in M$, $r_M(a) = \infty$ then $r_M(x) = \infty$ for any $x \in M$, in which case we say that the convexity radius r_M of M is infinite. As a consequence we obtain

Theorem F. *Let $0 < p - 1 < q$ and (M^N, g) be a complete noncompact Riemannian manifold such that $\text{Ric}_g \geq (1 - N)B^2$, ($B > 0$). Assume also $r_M = \infty$ if $1 < p < 2$ or*

$$\lim_{\text{dist}(x,a)} \frac{|\text{Sec}_g(x)|}{\text{dist}(x,a)} = 0 \quad (1.15)$$

for some $a \in M$ if $p > 2$. Then any solution u of (1.13) in M satisfies

$$|\nabla u(x)| \leq c_{N,p,q} B^{\frac{1}{q+1-p}} \quad \forall x \in M. \quad (1.16)$$

Since our estimate holds also in the case $p = q$, we obtain

Theorem F. *Assume M satisfies the assumptions of Theorem F. Then any positive p -harmonic function v on M satisfies*

$$v(a)e^{-\kappa B \text{dist}(x,a)} \leq v(x) \leq v(a)e^{\kappa B \text{dist}(x,a)} \quad (1.17)$$

for any points a, x in M , where $\kappa = \kappa(p, N) > 0$.

The case $p = 2$, $B = 0$ is due to Chen and Yau ([10]). Kortschwar and Li [21] obtain a similar estimate but with a global estimate of the sectional curvature which implies our assumption on the Ricci curvature.

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2 A priori estimates in a domain of \mathbb{R}^N

2.1 The gradient estimates

The next result is the extension to the p -Laplacian of result obtained by Lions [26] for the Laplacian. We denote by $d(x)$ the distance from $x \in \bar{\Omega}$ to $\partial\Omega$.

Proposition 2.1 *Assume $q > p - 1$ and u is a C^1 solution of (1.1) in a domain Ω . Then*

$$|\nabla u(x)| \leq c_{N,p,q} (d(x))^{-\frac{1}{q+1-p}} \quad \forall x \in \Omega. \quad (2.1)$$

Proof. In any open subset G of Ω where $|\nabla u| > 0$ we write (1.1) under the form

$$-\Delta u - (p-2) \frac{D^2 u(\nabla u, \nabla u)}{|\nabla u|^2} + |\nabla u|^{q+2-p} = 0 \quad (2.2)$$

and we recall the formula

$$\frac{1}{2} \Delta |\nabla u|^2 = |D^2 u|^2 + \langle \nabla \Delta u, \nabla u \rangle. \quad (2.3)$$

By Schwartz inequality

$$|D^2 u|^2 \geq \frac{1}{N} (\Delta u)^2.$$

We obtain

$$\frac{1}{2} \Delta |\nabla u|^2 \geq \frac{1}{N} (\Delta u)^2 + \langle \nabla \Delta u, \nabla u \rangle. \quad (2.4)$$

We write $z = |\nabla u|^2$ and derive from (2.2)

$$\Delta u = -\frac{(p-2)}{2} \frac{\langle \nabla z, \nabla u \rangle}{z} + z^{\frac{q+2-p}{2}}, \quad (2.5)$$

thus

$$\begin{aligned} \langle \nabla \Delta u, \nabla u \rangle &= -\frac{(p-2)}{2} \frac{\langle D^2 z(\nabla u), \nabla u \rangle}{z} - \frac{(p-2)}{4} \frac{|\nabla z|^2}{z} \\ &\quad + \frac{(p-2)}{2} \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} + \frac{q+2-p}{2} z^{\frac{q-p}{2}} \langle \nabla z, \nabla u \rangle. \end{aligned} \quad (2.6)$$

From (2.5),

$$(\Delta u)^2 \geq \frac{1}{2} z^{q+2-p} - \frac{(p-2)^2}{4} \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} \quad (2.7)$$

and from (2.4),

$$\begin{aligned} \Delta z + (p-2) \frac{\langle D^2 z(\nabla u), \nabla u \rangle}{z} &\geq \frac{1}{N} z^{q+2-p} - \frac{(p-2)^2}{2N} \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} \\ &\quad - \frac{(p-2)}{2} \frac{|\nabla z|^2}{z} + (p-2) \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} + (q+2-p) z^{\frac{q-p}{2}} \langle \nabla z, \nabla u \rangle. \end{aligned} \quad (2.8)$$

Noticing that $\frac{\langle \nabla z, \nabla u \rangle^2}{z^2} \leq \frac{|\nabla z|^2}{z}$, and for any $\epsilon > 0$

$$z^{\frac{q-p}{2}} |\langle \nabla z, \nabla u \rangle| \leq z^{\frac{q+2-p}{2}} \frac{|\nabla z|}{\sqrt{z}} \leq \epsilon z^{q+2-p} + \frac{1}{4\epsilon} \frac{|\nabla z|^2}{z},$$

we obtain that the right-hand side of (2.8) is bounded from below by the quantity

$$\frac{1}{2N} z^{q+2-p} - D \frac{|\nabla z|^2}{z},$$

where $D = D(p, q, N) > 0$. We define the operator

$$v \mapsto \mathcal{A}(v) := -\Delta v - (p-2) \frac{\langle D^2 v(\nabla u), \nabla u \rangle}{|\nabla u|^2} = - \sum_{i,j=1}^N a_{ij} v_{x_i x_j} \quad (2.9)$$

where the a_{ij} depend on ∇u ; since $|\nabla u|^2 = z$,

$$\theta |\xi|^2 := \min\{1, p-1\} |\xi|^2 \leq \sum_{i,j=1}^N a_{ij} \xi_i \xi_j \leq \max\{1, p-1\} |\xi|^2 := \Theta |\xi|^2 \quad \forall \xi = (\xi_1, \dots, \xi_N). \quad (2.10)$$

Consequently, \mathcal{A} is uniformly elliptic in G and z satisfies

$$\mathcal{L}(z) := \mathcal{A}(z) + \frac{1}{2N} z^{q+2-p} - D \frac{|\nabla z|^2}{z} \leq 0 \quad \text{in } \Omega. \quad (2.11)$$

Consider a ball $B_a(R) \subset \Omega$ and set $w(x) = \tilde{w}(|x - a|) = \lambda(R^2 - |x - a|^2)^{-\frac{2}{q+1-p}}$. Put $r = |x - a|$, then

$$w_{x_i} = \frac{4\lambda}{q+1-p}(R^2 - |x - a|^2)^{-\frac{2}{q+1-p}-1}x_i,$$

$$w_{x_i x_j} = \frac{4\lambda}{q+1-p}(R^2 - r^2)^{-\frac{2}{q+1-p}-1}\delta_{ij} + \frac{8(3+q-p)\lambda}{(q+1-p)^2}(R^2 - r^2)^{-\frac{2}{q+1-p}-2}x_i x_j,$$

Therefore

$$|\nabla w|^2 = \frac{16\lambda^2}{(q+1-p)^2}(R^2 - r^2)^{-\frac{4}{q+1-p}-2}r^2,$$

$$\frac{|\nabla w|^2}{w} = \frac{16\lambda}{(q+1-p)^2}(R^2 - r^2)^{-\frac{2}{q+1-p}-2}r^2,$$

$$w^{q+2-p} = \lambda^{q+2-p}(R^2 - r^2)^{-2\frac{q+2-p}{q+1-p}},$$

and finally

$$\mathcal{A}(w) \geq -\frac{4\Theta\lambda}{q+1-p}(R^2 - r^2)^{-\frac{2}{q+1-p}-2} \left(NR^2 + \left(\frac{3+q-p}{q+1-p} - N \right) r^2 \right).$$

At end, using the fact that $r \leq R$,

$$\mathcal{L}(w) \geq \lambda(R^2 - r^2)^{-\frac{2}{q+1-p}-2} (\lambda^{q+1-p} - cR^2),$$

where $c = c(N, p, q)$. We choose $\lambda = (cR^2)^{\frac{1}{q+1-p}}$ and derive $\mathcal{L}(w) \geq 0$. We take for G a connected component of $\{x \in B_R(a) : z(x) > w(x)\}$, thus $z(x) > 0$ in G and $\overline{G} \subset \overline{B}_R(a)$. If $x_0 \in G$ is such that $z(x_0) - w(x_0) = \max\{z(x) - w(x) : x \in G\}$, then $\nabla z(x_0) = \nabla w(x_0)$, $z(x_0) > w(x_0) > 0$ and

$$\mathcal{A}(z(x_0) - w(x_0)) + \frac{1}{2N} (z(x_0)^{q+2-p} - w(x_0)^{q+2-p}) - D |\nabla z|^2 \left(\frac{1}{z(x_0)} - \frac{1}{w(x_0)} \right) \leq 0,$$

which contradicts the fact that all the terms are nonnegative with the exception of $z(x_0)^{q+2-p} - w(x_0)^{q+2-p}$ which is positive. Therefore $z \leq w$ in $B_R(a)$. In particular

$$z(a) \leq w(a) = c'_{N,p,q} R^{-\frac{4}{q+1-p}}. \quad (2.12)$$

Letting $R \rightarrow d(x)$ yields (2.1). \square

2.2 Applications

The first estimate is a pointwise one for solutions with isolated singularities.

Corollary 2.2 Assume $q > p - 1 > 0$, Ω is a domain containing 0 and assume that $d(0) \geq 2R^*$. Then for any $x \in B_{R^*} \setminus \{0\}$, and $0 < R \leq R^*$, any $u \in C^2(\Omega \setminus \{0\})$ solution of (1.1) in $\Omega \setminus \{0\}$ satisfies

$$|u(x)| \leq c_{N,p,q} \left| |x|^{\frac{q-p}{q+1-p}} - R^{\frac{q-p}{q+1-p}} \right| (R - |x|) + \max\{|u(z)| : |z| = R\}, \quad (2.13)$$

if $p \neq q$, and

$$|u(x)| \leq c_{N,p} (\ln |R| - \ln |x|) + \max\{|u(z)| : |z| = R\}, \quad (2.14)$$

if $p = q$.

Proof. Let $X = \frac{R}{|x|}x$, then $\text{dist}(tx + (1-t)X, \partial B_R(X)) = t|x| + (1-t)R$ for any $0 < t < 1$, thus by (2.1) in $B_{R^*} \setminus \{0\}$

$$\begin{aligned} |u(x)| &= \left| u(X) + \int_0^1 \frac{d}{dt} u(tx + (1-t)X) dt \right| \\ &\leq |u(X)| + c_{N,p,q} |x - X| \int_0^1 (t|x| + (1-t)R)^{-\frac{1}{q+1-p}} dt. \end{aligned}$$

By integration, we obtain (2.13) or (2.14). In the particular case where $p > q$ and $|x| \leq \frac{R}{2}$, we obtain

$$|u(x)| \leq c'_{N,p,q} |x|^{\frac{q-p}{q+1-p}} + \max\{|u(z)| : |z| = R\}. \quad (2.15)$$

□

The second estimate corresponds to solutions with boundary blow-up.

Corollary 2.3 Assume $q > p - 1 > 0$, Ω is a bounded domain with a C^2 boundary. Then there exists $\delta^* > 0$ such that if we denote $\Omega_{\delta^*} := \{z \in \Omega : d(z) \leq \delta^*\}$, any $u \in C^2(\Omega)$ solution of (1.1) in Ω satisfies

$$|u(x)| \leq c_{N,p,q} \left| (d(x))^{\frac{q-p}{q+1-p}} - \delta^{*\frac{q-p}{q+1-p}} \right| + \max\{|u(z)| : d(z) = \delta^*\} \quad \forall x \in \Omega_{\delta^*} \quad (2.16)$$

if $p \neq q$ and

$$|u(x)| \leq c_{N,p,q} (\ln \delta^* - \ln d(x)) + \max\{|u(z)| : d(z) = \delta^*\} \quad \forall x \in \Omega_{\delta^*} \quad (2.17)$$

if $p = q$.

Proof. We denote by δ^* the maximal $r > 0$ such that any boundary point a belongs to a ball $B_r(a_i)$ of radius r such that $B_r(a_i) \subset \overline{\Omega}$ and to a ball $B_r(a_s)$ with radius r too such that $B_r(a_s) \subset \overline{\Omega}^c$. If $x \in \Omega_{\delta^*}$, we denote by $\sigma(x)$ its projection onto $\partial\Omega$ and by $\mathbf{n}_{\sigma(x)}$ the normal unit outward vector to $\partial\Omega$ at $\sigma(x)$ and $z^* = \sigma(x) - 2\delta^* \mathbf{n}_{\sigma(x)}$. Then

$$u(x) = u(z^*) + \int_0^1 \frac{d}{dt} u(tx + (1-t)z^*) dt = \int_0^1 \langle \nabla u(tx + (1-t)z^*), x - z^* \rangle dt$$

thus

$$|u(x)| \leq |u(z^*)| + c_{N,p,q}(\delta^* - d(x)) \int_0^1 (td(x) + (1-t)d(z^*))^{-\frac{1}{q+1-p}} dt.$$

Integrating this relation we obtain (2.16) and (2.17). \square

Remark. As a consequence of (2.16) there holds for $p > q > p - 1$

$$u(x) \leq (c_{N,p,q} + K \max\{|u(z)| : d(z) \geq \delta^*\}) (d(x))^{\frac{q-p}{q+1-p}} \quad \forall x \in \Omega \quad (2.18)$$

where $K = (\text{diam}(\Omega))^{\frac{p-q}{q+1-p}}$, with the standard modification if $p = q$.

As a variant of Corollary 2.3 we have estimate of solutions in an exterior domain

Corollary 2.4 *Assume $q > p - 1 > 0$, $R > 0$ and $u \in C^2(B_{R_0}^c)$ is any solution of (1.1) in $B_{R_0}^c$. Then for any $R > R_0$ there holds*

$$|u(x)| \leq c_{N,p,q} \left| (|x| - R_0)^{\frac{q-p}{q+1-p}} - (R - R_0)^{\frac{q-p}{q+1-p}} \right| + \max\{|u(z)| : |z| = R\} \quad \forall x \in B_R^c \quad (2.19)$$

if $p \neq p$ and

$$|u(x)| \leq c_{N,p,q} (\ln(|x| - R_0) - \ln(R - R_0)) + \max\{|u(z)| : |z| = R\} \quad \forall x \in B_R^c \quad (2.20)$$

if $p = q$.

Proof. The proof is a consequence of the identity

$$u(x) = u(z) + \int_0^1 \frac{d}{dt} u(tx + (1-t)z) dt = \int_0^1 \langle \nabla u(tx + (1-t)z), x - z \rangle dt$$

where $z = \frac{R}{|x|}x$. Since

$$|\nabla u(tx + (1-t)z)| \leq C_{N,p,q} (t|x| + (1-t)R - R_0)^{-\frac{1}{q+1-p}}$$

by estimate (2.1), the result follows by integration. \square

An important consequence of the gradient estimate is the Harnack inequality.

Proposition 2.5 *Assume $q > p - 1$ and $u \in C^1(\Omega)$ is a positive solution of (1.1) in Ω . Then there exists a constant $C = C(n, p, q) > 0$ such that for $a \in \Omega$ and $R > 0$ such that any ball $\overline{B}_R(a) \subset \Omega$, there holds*

$$\max\{u(x) : x \in B_{R/2}(a)\} \leq C \min\{u(x) : x \in B_{R/2}(a)\}. \quad (2.21)$$

Proof. We can assume $a = 0$ in Ω and $R < d(0) = \text{dist}(0, \partial\Omega)$. Then we write (1.1)

$$-\Delta_p u + C(x) |\nabla u|^{p-1} = 0$$

with $|C(x)| = |\nabla u|^{q+1-p} \leq c_{N,p,q} R^{-1}$ by (2.1). Set $u_R(y) = u(Ry)$, then u_R satisfies

$$-\Delta_p u_R + RC(Ry) |\nabla u_R|^{p-1} = 0 \quad \text{in } B_1.$$

Since $RC(Ry)$ is bounded in B_1 , we can apply Serrin's results (see [34]) and obtain

$$\max\{u_R(y) : y \in B_{1/2}(0)\} \leq C \min\{u(y) : y \in B_{1/2}(0)\}. \quad (2.22)$$

Then (2.21) follows. \square

The following Liouville result which improves a previous result due to Farina and Serrin [13, Th 7] is a direct consequence of the gradient estimate.

Corollary 2.6 *Assume $q > p - 1 > 0$. Then any signed solution of (1.1) in \mathbb{R}^N is a constant.*

Proof. We apply of (2.1) in $B_R(a)$ for any $R > 0$ and $a \in \mathbb{R}^N$ and let $R \rightarrow \infty$. \square

3 Singularities in a domain

3.1 Radial solutions

If u is a radial function, we put $u(x) = u(|x|) = u(r)$, with $r = |x|$. If u is a radial solution of (1.1) in $B_1^* := B_1 \setminus \{0\}$, it satisfies

$$\left(|u'|^{p-2} u'\right)' + \frac{N-1}{r} |u'|^{p-2} u' - |u'|^q = 0 \quad (3.1)$$

in $(0, 1)$. We suppose $q < p$, then $p - 1 < q_c = \frac{N(p-1)}{N-1} < p \leq N$. We recall d

$$\beta_q = \frac{p-q}{q+1-p} \quad \text{and} \quad b = \frac{N(p-1) - (N-1)q}{q+1-p} = \frac{(N-1)(q_c - q)}{q+1-p}. \quad (3.2)$$

The next result provides the classification of radial solutions according to their sign near 0.

Proposition 3.1 *Let u be a nonconstant solution of (3.1), then*

$$u'(r) = \begin{cases} -r^{\frac{1-N}{p-1}} \left(b^{-1} r^{\frac{q+1-p}{p-1}} + K\right)^{\frac{1}{p-1-q}} & \text{if } q \neq q_c \\ -r^{\frac{1-N}{p-1}} (|\ln r^{N-1}| + K)^{\frac{1-N}{p-1}} & \text{if } q = q_c. \end{cases} \quad (3.3)$$

As a consequence there holds

1- If u is positive near 0. If $p - 1 < q < q_c$,

(i) either there exists $k > 0$ such that

$$u(r) = \begin{cases} k \frac{N-p}{p-1} r^{\frac{p-N}{p-1}} + O(r^{\frac{q+1-N}{p-1}b} \vee 1) & \text{if } p < N \\ -k \ln r + O(1) & \text{if } p = N \end{cases} \quad (3.4)$$

and u is a radial solution of

$$-\Delta_p u + |\nabla u|^q = c_{N,p} k^{p-1} \delta_0 \quad \text{in } \mathcal{D}'(B_1), \quad (3.5)$$

(ii) or

$$u(r) = \lambda_{N,p,q} r^{-\beta_q} + M \quad (3.6)$$

where

$$\lambda_{N,p,q} = \beta_q^{-1} b^{\frac{1}{q+1-p}}. \quad (3.7)$$

If $q \geq q_c$, u is constant.

2- If u is negative near 0. If $p-1 < q < q_c$, there exists $k < 0$ such that

$$u(r) = \begin{cases} k \frac{N-p}{p-1} r^{\frac{p-N}{p-1}} + O(r^{\frac{q+1-N}{p-1}b} \vee 1) & \text{if } p < N \\ -k \ln r + O(1) & \text{if } p = N \end{cases} \quad (3.8)$$

and u is a radial solution of

$$\Delta_p u - |\nabla u|^q = -c_{N,p} (-k)^{p-1} \delta_0 \quad \text{in } \mathcal{D}'(B_1). \quad (3.9)$$

If $q = q_c$

$$u(r) = \begin{cases} -\nu_{N,p} r^{\frac{p-N}{p-1}} (-\ln r)^{-\frac{p-1}{N-1}} (1 + o(1)) & \text{if } p < N \\ -\nu_N \ln(-\ln r) (1 + o(1)) & \text{if } p = N \end{cases} \quad (3.10)$$

for some for some constant $\nu_{N,p}$, $\nu_N > 0$.

If $q > q_c$,

$$u(r) = -\lambda_{N,p,q} r^{-\beta_q} + M. \quad (3.11)$$

Proof. We set

$$w(r) = r^{N-1} |u'|^{p-2} u', \quad (3.12)$$

then

$$w'(r) = r^{-\frac{(q+1-p)(N-1)}{p-1}} |w|^{\frac{q}{p-1}} \quad (3.13)$$

Thus

$$-|w|^{-\frac{q}{p-1}} w = \begin{cases} b^{-1} r^{\frac{q+1-p}{p-1}b} + K & \text{if } q \neq q_c \\ \ln(K r^{\frac{1}{N-1}}) & \text{if } q = q_c \end{cases} \quad (3.14)$$

for some K .

1-Case $p-1 < q < q_c$, then $b > 0$. If $K > 0$ then w' and u' are negative and

$$u'(r) = -r^{\frac{1-N}{p-1}} \left[b^{-1} r^{\frac{q+1-p}{p-1}b} + K \right]^{-\frac{1}{q+1-p}} = -k' r^{\frac{p-N}{p-1}} + O(r^{\frac{q+2-p-N}{p-1}}). \quad (3.15)$$

Integrating again, we get (3.4) From the asymptotic of $u'(r)$ we derive that u is a radial solution of (3.5). If $K = 0$, then $u'(r) = -r^{-\frac{N-1+b}{p-1}} b^{\frac{1}{q+1-p}}$ and we get (3.6), (3.7). This is the explicit particular solution.

If $K = -\tilde{K} < 0$, then $w' > 0$ near 0. We set $\tilde{w} = -w$, $\tilde{u} = -u$ and $\tilde{w}(r) = r^{N-1} |\tilde{u}'|^{p-2} \tilde{u}'$. Thus,

$$\tilde{u}(r) = \tilde{k}'' r^{\frac{p-N}{p-1}} + O(r^{\frac{q+1-N}{p-1}b} \vee 1) \text{ or } u(r) = -\tilde{k}'' \ln r + O(1), \quad (3.16)$$

according $p < N$ or $p = N$, and \tilde{u} satisfies

$$-\Delta_p \tilde{u} - |\nabla u|^q = c_{N,p} \tilde{k}' \delta_0 \quad \text{in } \mathcal{D}'(B_1). \quad (3.17)$$

2-Case $q \geq q_c$. Then $b \leq 0$. If $q > q_c$ (equivalently $b < 0$), (3.6) implies

$$u'(r) = r^{\frac{1-N}{p-1}} \left[-b^{-1} r^{\frac{q+1-p}{p-1}b} + K \right]^{-\frac{1}{q+1-p}} = (-b)^{\frac{1}{q+1-p}} r^{-\frac{1}{q+1-p}} (1 + o(1)), \quad (3.18)$$

then

$$u(r) = -\lambda_{N,p,q} r^{-\beta_q} (1 + o(1)). \quad (3.19)$$

If $q = q_c$,

$$u'(r) = r^{\frac{1-N}{p-1}} \left[(1-N)^{-1} \ln r + K \right]^{-\frac{p-1}{N-1}} (1 + o(1)), \quad (3.20)$$

and, either $p < N$ and

$$u(r) = -\nu_{N,p} r^{\frac{p-N}{p-1}} (-\ln r)^{-\frac{p-1}{N-1}} (1 + o(1)), \quad (3.21)$$

or $p = N$ and

$$u(r) = -\nu_N \ln(-\ln r) (1 + o(1)), \quad (3.22)$$

for some constant $\nu_{N,p}, \nu_N > 0$. \square

Proposition 3.2 *Assume $1 < p \leq N$ and $p-1 < q < q_c$, then for any $k > 0$ there exists a unique positive solution $u = u_k$ of (3.1) in $(0, 1)$ vanishing for $r = 1$ satisfying*

$$\lim_{r \rightarrow 0} \frac{u_k(r)}{\mu_p(r)} = k. \quad (3.23)$$

When $k \rightarrow \infty$, $u_k \uparrow u_\infty$ which is a solution of (3.1) in $(0, 1)$ vanishing on ∂B_1 satisfying

$$\lim_{r \rightarrow 0} r^{\beta_q} u_\infty(r) = \lambda_{N,p,q}. \quad (3.24)$$

Proof. Using (3.15) we see that K is completely determined by $K = k^{p-1-q}$ and u by

$$u_k(r) = \int_r^1 s^{\frac{1-N}{p-1}} \left[b^{-1} s^{\frac{q+1-p}{p-1}b} + k^{p-1-q} \right]^{-\frac{1}{q+1-p}} ds. \quad (3.25)$$

Conversely, asymptotic expansion in (3.25) yields to (3.23). The unique characterization of K yields to uniqueness although uniqueness is also a consequence of the maximum principle as we will see it in the non radial case. Clearly the function u_k defined by (3.25) is increasing and $u_\infty = \lim_{k \rightarrow \infty} u_k$ satisfies

$$u_\infty(r) = \int_r^1 s^{\frac{1-N}{p-1}} \left[b^{-1} s^{\frac{q+1-p}{p-1}} b \right]^{-\frac{1}{q+1-p}} ds = \lambda_{N,p,q} (r^{-\beta_q} - 1). \quad (3.26)$$

Proposition 3.3 *Assume $1 < p \leq N$ and $p-1 < q < q_c$. If u is a positive radial solution of (3.1) in $(0, \infty)$. Then*

- (i) *either $u(r) \equiv M$ for some $M \geq 0$,*
- (ii) *either there exist $k > 0$ and $M \geq 0$ such that*

$$u(r) = u_{k,M}(r) := \int_r^\infty s^{\frac{1-N}{p-1}} \left[b^{-1} s^{\frac{q+1-p}{p-1}} b + k^{p-1-q} \right]^{-\frac{1}{q+1-p}} ds + M, \quad (3.27)$$

- (ii) *or there exists $M \geq 0$ such that*

$$u(r) = u_{\infty,M}(r) := \lambda_{N,p,q} r^{-\beta_q} + M \quad (3.28)$$

Proof. From identity (3.15), valid for any *nonconstant* solution u , we see that for a global positive solution we must have $K \geq 0$. If $K = 0$ then $u = u_\infty$ defined by (3.27). If $K > 0$, then $u' \in L^1(1, \infty)$, thus $u(\infty) = \lim_{s \rightarrow \infty} u(s)$ exists and

$$u(r) = u(\infty) \int_r^\infty s^{\frac{1-N}{p-1}} \left[b^{-1} s^{\frac{q+1-p}{p-1}} b + K \right]^{-\frac{1}{q+1-p}} ds, \quad (3.29)$$

and $K = k^{p-1-q}$ in order to have (3.23). \square

3.2 Removable singularities

3.2.1 Removable singularities of renormalized solutions

For $k > 0$ and $s \in \mathbb{R}$, we set $T_k(s) = \max\{-k, \min\{k, s\}\}$. If u is measurable in Ω and finite a.e. and if $T_k(u) \in W_{loc}^{1,p}(\Omega)$, we define the gradient a.e. of u by $\nabla T_k(u) = \chi_{|u| \leq k} \nabla u$, for any $k > 0$. The following numbers play an important role in the sequel.

$$q_c = \frac{N(p-1)}{N-1}, \quad \ell = \frac{q}{q+1-p} \quad \text{and} \quad \tilde{q} = p-1 + \frac{p}{N}. \quad (3.30)$$

Hence $q_c < \tilde{q}$ if $1 < p < N$ and $q_c = \tilde{q} = N$ if $p = N$. In order to study removability results it is natural to introduce other notions of solutions than the strong ones

Definition 3.4 *1- If Ω is bounded, we say that u is a renormalized solution (abridged R -solution) of*

$$\begin{aligned} -\Delta_p u + \nabla u^q &= 0 & \text{in } \Omega \\ u &= 0 & \text{in } \partial\Omega \end{aligned} \quad (3.31)$$

if u is measurable and finite a.e., $T_k(u) \in W_0^{1,p}(\Omega)$ for any $k > 0$, $|\nabla u|^q \in L^1(\Omega)$, $|\nabla u|^{p-1} \in L^\tau(\Omega)$ for all $\tau \in [1, \frac{N}{N-1})$ and for any $h \in W^{1,\infty}(\mathbb{R})$ such that h' has compact support and $\phi \in W^{1,s}(\Omega)$ for some $s > N$, such that $h(u)\phi \in W_0^{1,p}(\Omega)$, there holds

$$\int_{\Omega} |\nabla u|^{p-2} \nabla u \cdot \nabla (h(u)\phi) dx + \int_{\Omega} |\nabla u|^q h(u)\phi dx = 0. \quad (3.32)$$

In particular $|u|^{p-1} \in L^\sigma(\Omega)$ for all $\sigma \in [1, \frac{N}{N-p})$.

2- We say that u is a local renormalized (abridged LR-solution) of solution of (1.1) if u is measurable and finite a.e., $T_k(u) \in W_{loc}^{1,p}(\Omega)$ for any $k > 0$, $|\nabla u|^q \in L_{loc}^1(\Omega)$, $|u|^{p-1} \in L_{loc}^\sigma(\Omega)$ for all $\sigma \in [1, \frac{N}{N-p})$, $|\nabla u|^{p-1} \in L_{loc}^\tau(\Omega)$ for all $\tau \in [1, \frac{N}{N-1})$ and u satisfies (3.32) for any h as above and $\phi \in W^{1,s}(\Omega)$ for some $s > N$ with compact support, such that $h(u)\phi \in W_0^{1,p}(\Omega)$. In particular, any LR-solution is a solution of (1.1) in $\mathcal{D}'(\Omega)$.

Remark. These notions are well adapted to treat singularity questions for nonnegative functions. Indeed, if $\Omega = B_1$ and $q_c < q < p < N$, the function $V = -\tilde{U} = -\lambda_{N,p,q} |\cdot|^{-\beta_q}$ is a solution of (1.1) in $\mathbb{R}^N \setminus \{0\}$, thus $v = V + \lambda_{N,p,q}$ is a negative solution of (3.32). Therefore the function $\tilde{v} = -v$ satisfies $-\Delta_p \tilde{v} \geq 0$. By [4, Th 1.1, Prop 1.1], there exists $c \geq 0$ such that

$$-\Delta_p \tilde{v} = |\nabla \tilde{v}|^q + c\delta_0 \quad \text{in } \mathcal{D}'(B_1), \quad (3.33)$$

and necessarily $c = 0$ because $q > q_c$. This means that the singularity of the solution is not seen in the sense of distributions. When $\tilde{q} < q$, $v \in W_0^{1,p}(B_1)$, thus it is still a R-solution in B_1 . If $q_c < q < \tilde{q}$, $\tilde{v} \notin W_0^{1,p}(B_1)$, but it is still a R-solution in B_1 , since for any $k > 0$, $T_k(v)$ satisfies

$$-\Delta_p T_k(v) = |\nabla T_k(v)|^q + \mu_k \quad \text{in } \mathcal{D}'(B_1), \quad (3.34)$$

with $\mu_k = c_k \delta_{|x|=\rho_k}$ with $\rho_k = (k/\tilde{\lambda}_{N,p,q})$ and $c_k = (\beta_q \tilde{\lambda}_{N,p,q} \rho_k^{-1-\beta_q})^{p-1}$. Then for any $\phi \in C_0^\infty(B_1)$, $\lim_{k \rightarrow \infty} \langle \mu_k, \phi \rangle = 0$. Thus it is a R-solution by using [12, Def 2.29].

We denote by $C_{\alpha,p}$ ($\alpha > 0$, $1 \leq p < \infty$) the Besov capacity in \mathbb{R}^N defined by

$$C_{\alpha,p}(K) := \inf\{\|\zeta\|_{W^{\alpha,p}(\mathbb{R}^N)} : \zeta \in C_0^\infty(\mathbb{R}^N), 0 \leq \zeta \leq 1, \zeta = 1 \text{ on } K\} \quad (3.35)$$

if K is compact and extended to capacitable sets by the standard rule.

Our main removability result concerning LR-solutions is the following.

Theorem 3.5 *Assume $0 < p-1 < q \leq p$. If $F \subset \Omega$ is a relatively closed set such that $C_{1,p}(F) = 0$, then any LR-solution u of (1.1) in $\Omega \setminus \{F\}$ can be extended as a LR-solution of (1.1) in whole Ω .*

Proof. Notice that a set F with $C_{1,\ell}(F) = 0$, has zero measure; since a L. R. solution is defined up to a set of zero measure, any extension of u to F is valid. From our assumption $T_k(u) \in W_{loc}^{1,p}(\Omega \setminus \{F\})$ for any $k > 0$, $|u|^{p-1} \in L_{loc}^\sigma(\Omega)$ for all $\sigma \in [1, \frac{N}{N-p})$, $|\nabla u|^{p-1} \in L_{loc}^\tau(\Omega)$ for all $\tau \in [1, \frac{N}{N-1})$, and $|\nabla u|^q \in L_{loc}^1(\Omega)$. Since $p \leq \ell$, for any compact $K \subset \Omega$, $C_{1,p}(F \cap K) = 0$. Thus $T_k(u) \in W_{loc}^{1,p}(\Omega)$ by [17, Th 2.44]. Because u is measurable and finite a.e. we can define ∇u a.e. in Ω by the formula $\nabla u = \nabla T_k(u)$ a.e. on the set $\{x \in \Omega : |u(x)| \leq k\}$.

Let $\zeta \in C_0^\infty(\Omega)$ with support in $\omega \subset \bar{\omega} \subset \Omega$ and set $K_\zeta = F \cap \text{supp } \zeta$. Then K_ζ and $C_{1,\ell}(K_\zeta) = 0$, thus there exists $\zeta_n \in C_0^\infty(\Omega)$ such that $0 \leq \zeta_n \leq 1$, $\zeta_n = 1$ in a neighborhood of K_ζ that we can assumed contained in ω , such that $\zeta_n \rightarrow 0$ in $W^{1,\ell}(\mathbb{R}^N)$. It can also be assumed that $\zeta_n(x) \rightarrow 0$ for all $x \in \mathbb{R}^N \setminus N$ where N is a Borel set such that $C_{1,\ell}(N) = 0$ (see e.g. [2, Lemmas 2.1, 2.2]). Let $\xi_n = \zeta(1 - \zeta_n)$. Then

$$\int_{\Omega} \left(|\nabla u|^q \xi_n^\ell + \ell \xi_n^{\ell-1} |\nabla u|^{p-2} \nabla u \cdot \nabla \xi_n \right) dx = 0.$$

By Hölder's inequality, there holds for any $\eta > 0$,

$$\int_{\Omega} |\nabla u|^q \xi_n^\ell dx \leq \ell \int_{\Omega} \xi_n^{\ell-1} |\nabla u|^{p-1} |\nabla \xi_n| dx \leq (\ell-1) \eta^{\frac{q}{p-1}} \int_{\Omega} |\nabla u|^q \xi_n^\ell dx + \eta^{-\ell} \int_{\Omega} |\nabla \xi_n|^\ell dx.$$

Hence, taking η small enough,

$$\int_{\Omega} |\nabla u|^q \xi_n^\ell dx \leq c \int_{\Omega} |\nabla \xi_n|^\ell dx \leq \int_{\Omega} \left(|\nabla \zeta|^\ell + |\nabla \zeta_n|^\ell \right) dx.$$

From Fatou's lemma, $|\nabla u|^q \zeta^\ell \in L^1(\Omega)$ and

$$\int_{\Omega} |\nabla u|^q \zeta^\ell dx \leq c_\zeta := c \int_{\Omega} |\nabla \zeta|^\ell dx. \quad (3.36)$$

Taking $T_k(u) \xi_n^\ell$ for test function, we obtain

$$\int_{\Omega} |\nabla(T_k(u))|^p \xi_n^\ell dx + \int_{\Omega} |\nabla u|^q T_k(u) \xi_n^\ell dx = - \int_{\Omega} T_k(u) |\nabla u|^{p-2} \nabla u \cdot \nabla \xi_n^\ell dx.$$

Then we deduce, from Hölder's inequality,

$$\begin{aligned} \frac{1}{k} \left| \int_{\Omega} T_k(u) |\nabla u|^{p-2} \nabla u \cdot \nabla \xi_n^\ell dx \right| &\leq \ell \int_{\Omega} (\zeta^{\ell-1} |\nabla u|^{p-1} |\nabla \zeta| + \ell \zeta^\ell |\nabla u|^{p-1} |\nabla \zeta_n|) dx \\ &\leq (2\ell - 1) \int_{\Omega} (|\nabla u|^q \zeta^\ell + |\nabla \zeta|^\ell + \ell \zeta^\ell |\nabla \zeta_n|^\ell) dx \\ &\leq 2\ell c_\zeta + \int_{\Omega} |\nabla \zeta|^\ell dx + \epsilon(n). \end{aligned}$$

Therefore, up to changing c_ζ into another constant c_ζ depending on ζ ,

$$\int_{\Omega} |\nabla(T_k(u))|^p \xi_n^\ell dx \leq (k+1) c_\zeta + \epsilon(n),$$

and by Fatou's lemma,

$$\int_{\Omega} |\nabla(T_k(u))|^p \zeta^\ell dx \leq (k+1)c_\zeta. \quad (3.37)$$

It follows by a variant of the results in [7],[8] that the regularity statements (??) hold.

Finally, we show that u is a LR-solution in Ω . Let $h \in W^{1,\infty}(\mathbb{R})$ with h' with compact support, and let $\phi \in W^{1,m}(\Omega)$ with $m > N$, such that $h(u)\phi \in W^{1,p}(\Omega)$. let $\omega \subset \bar{\omega} \subset \Omega$, such that $\text{supp } \zeta \subset \omega$. We set $K = \text{supp } \zeta \cap F$ and consider $\zeta_n \in C_0^\infty(\mathbb{R}^N)$ as above. Then $(1-\zeta_n)\phi \in W^{1,m}(\Omega \setminus F)$ and $h(u)(1-\zeta_n) \in W^{1,p}(\Omega \setminus F)$ with compact support in $\Omega \setminus F$, thus if we set

$$\begin{aligned} I_1 &= \int_{\Omega} |\nabla u|^p h'(u)(1-\zeta_n)\phi dx, \quad I_2 = - \int_{\Omega} h(u)\phi |\nabla u|^{p-2} \nabla u \cdot \nabla \zeta_n dx, \\ I_3 &= \int_{\Omega} h(u)(1-\zeta_n) |\nabla u|^{p-2} \nabla u \cdot \nabla \phi dx, \quad I_4 = \int_{\Omega} |\nabla u|^q (1-\zeta_n)\phi dx. \end{aligned}$$

Then $I_1 + I_2 + I_3 + I_4 = 0$. Since there exists $a > 0$ such that

$$|\nabla u|^p (1-\zeta_n) h'(u)\phi = |\nabla(T_a u)|^p (1-\zeta_n) h'(T_a u)\phi,$$

it follows from dominated convergence that

$$\lim_{n \rightarrow \infty} \int_{\Omega} |\nabla u|^p (1-\zeta_n) h'(u)\phi dx = \int_{\Omega} |\nabla u|^p h'(u)\phi dx.$$

Furthermore

$$|I_2| \leq \|h\|_{L^\infty} \left(\int_{\Omega} |\nabla u|^q \phi dx \right)^{\frac{p-1}{q}} \|\nabla \zeta_n\|_{L^\ell(\mathbb{R}^N)} \rightarrow 0 \text{ as } n \rightarrow \infty.$$

We can let $n \rightarrow \infty$ in I_3 because $\nabla \phi \in L^m(\Omega)$ and $|\nabla u|^{p-1} \in L_{loc}^\tau(\Omega)$ for any $\tau \in [1, \frac{N}{N-1})$ and in I_4 since $|\nabla u|^q \in L_{loc}^1(\Omega)$. Thus

$$\int_{\Omega} (|\nabla u|^{p-2} \nabla u \cdot \nabla (h(u)\phi) + |\nabla u|^q h(u)\phi) dx = 0, \quad (3.38)$$

which ends the proof. \square

3.2.2 Regularity results

The natural question concerning LR-solutions obtained in Theorem 3.5 is their regularity. Suprisingly the results are very different according we are considering positive or signed solutions of (1.1). We first recall some local estimates of the gradient of renormalized solutions.

Lemma 3.6 Assume Ω is a bounded C^2 domain. Let u be a R -solution of the problem

$$\begin{aligned} -\Delta_p u &= f && \text{in } \Omega \\ u &= 0 && \text{on } \partial\Omega \end{aligned} \quad (3.39)$$

where $f \in L_{loc}^m(\Omega)$ with $1 < m < N$ and set $\bar{m} = \frac{Np}{Np-N-p} = \frac{p}{\tilde{q}}$, where \tilde{q} is defined in (3.30).

(i) If $m > \frac{N}{p}$, then $u \in L^\infty(\Omega)$. If $m = \frac{N}{p}$, then $u \in L^k(\Omega)$ for $1 \leq k < \infty$. If $m < \frac{N}{p}$, then $|u|^{p-1} \in L^k(\Omega)$ with $k = \frac{Nm}{N-mp}$.

(ii) $\nabla u^{p-1} \in L^{m^*}(\Omega)$ with $m^* = \frac{Nm}{N-mp}$. Furthermore, if $\bar{m} \leq m$, then $u \in W_0^{1,p}(\Omega)$.

Proof. The estimates in the case $m < \bar{m}$ are obtained in [6] following [8] and [21], by using for test functions $\phi_{\beta,\epsilon}(T_k(u))$ where

$$\phi_{\beta,\epsilon}(w) = \int_0^w (\epsilon + |t|)^{-\beta} dt$$

for some $\beta < 1$. In the case $m \geq \bar{m}$ and $1 < p < N$ there holds $L^m(\Omega) \subset W^{-1,p'}(\Omega)$, thus u is a variational solution in $W_0^{1,p}(\Omega)$. In the case $m = \bar{m}$, then $m^* = p'$ and the conclusion follows. Next, if $m > \bar{m}$ or equivalently $m^* > p'$, then for any $\sigma > p$ and $F \in (L^\sigma(\Omega))^N$, there exists a unique $w \in W_0^{1,\sigma}(\Omega)$, weak solution of

$$\begin{aligned} -\Delta_p w &= \operatorname{div}(|F|^{p-2}F) && \text{in } \Omega \\ w &= 0 && \text{on } \partial\Omega, \end{aligned} \quad (3.40)$$

see [18], [22], [23]. Let v be the unique solution in $W_0^{1,1}(\Omega)$

$$\begin{aligned} -\Delta v &= f && \text{in } \Omega \\ v &= 0 && \text{on } \partial\Omega. \end{aligned} \quad (3.41)$$

From the classical L^p -theory, $v \in W^{2,m}(\Omega)$, thus $\nabla v \in L^{m^*}(\Omega)$. Let F be defined by $|F|^{p-2}F = \nabla v$. Then $F \in (L^\sigma(\Omega))^N$ with $\sigma = (p-1)m^* > p$. Then

$$-\Delta_p w = -\Delta v = f.$$

Thus $w = u$. This implies $u \in W_0^{1,\sigma}(\Omega)$ and therefore $|\nabla u|^{p-1} \in L^{m^*}(\Omega)$. \square

Our first regularity result deals with signed solutions of (1.1).

Theorem 3.7 Assume Ω is a bounded C^2 domain. Let $p-1 < q < \tilde{q}$, $N \geq 2$ and u is a R -solution of problem (3.31), such that

$$|\nabla u|^q \in L^{m_0}(\Omega) \quad \text{for some } m_0 > \max\{1, \frac{N(q+1-p)}{q}\}. \quad (3.42)$$

Then $u \in C^{1,\alpha}(\bar{\Omega})$ for some $\alpha \in (0,1)$. In particular (3.42) is satisfied if $q < q_c$, or if $q_c \leq q < \tilde{q}$ and $u \in W_0^{1,p}(\Omega)$.

Proof. Set $f = -|\nabla u|^q \in L^{m_0}(\Omega)$. If $m_0 \geq N$, $f \in L^{N-\delta}(Gw)$ for any $\delta \in (0, N-1]$. Then $f \in L^{m_1}(\Omega)$ with $m_1 = \frac{(p-1)m_0^*}{q}$. Note that $\frac{m_1}{m_0} = \frac{N(p-1)}{qN-p} > 1$ since $q < \tilde{q}$. By induction, starting from m_1 , we can define m_n as long as it is smaller than N by $m_n = \frac{(p-1)m_{n-1}^*}{q}$, and we find $m_n < m_{n+1}$. If $m_n < N$ for any $n \in \mathbb{N}$, the sequence $\{m_n\}$ would converge to $L = \frac{N(q+1-p)}{q}$, which is impossible since we have assumed $m_0 > L$. Therefore there exists some n_0 such that $m_{n_0} \geq N$. If $m_{n_0} = N$, (or if $m_0 = N$ we can modify it so that $m_{n_0} < N$, but $m_{n_0+1} > N$). Then we conclude as above.

If $q < q_c$, then $|\nabla u|^{p-1} \in L^{\frac{N(1-\delta)}{N-1}}(\Omega)$ for $\delta > 0$ small enough. Then we can choose m_0 such that $\max\{1, \frac{N(q+1-p)}{q}\} < m_0 < \frac{N}{N-1}$. If $q_c \leq q < \tilde{q}$ and $u \in W_0^{1,p}(\Omega)$, we choose $m_0 = \frac{p}{q}$. \square

Remark. The result which holds without sign assumption on u is sharp. Indeed, the function $v = V + \tilde{\lambda}_{N,p,q}$ defined above does not satisfy assumption (3.42), since $|\nabla u|^q \in L^m(\Omega)$ if and only if $m < \frac{N}{q(\beta_q+1)} = \frac{N(q+1-p)}{q}$.

In the next result we consider only nonnegative solutions of (1.1).

Theorem 3.8 *Let $p-1 < q$, $N \geq 2$ and u is a nonnegative LR-solution of (1.1). Then $u \in L_{loc}^\infty(\Omega) \cap W_{loc}^{1,p}(\Omega)$. As a consequence, if $q \leq p$, $u \in C^{1,\alpha}(\Omega)$ for some $\alpha \in (0, 1)$.*

Proof. Since $-\Delta_p \leq 0$, $u \in L_{loc}^\infty(\Omega)$ from [20] and u satisfies the weak Harnack inequality

$$\sup_{B_\rho(x_0)} \leq \rho^{-N} \left(\int_{B_{2\rho}(x_0)} u^\ell dx \right)^{\frac{1}{\ell}}$$

with $C = C(N, p, \ell)$. Then u coincides with $T_k(u)$ in any ball $B_\rho(x_0)$ such that $\overline{B_{2\rho}(x_0)} \subset \Omega$, for k large enough. Thus $u \in W_{loc}^{1,p}(\Omega)$. If $q \leq p$, it implies $u \in C^{1,\alpha}(\Omega)$. \square

3.3 Classification of isolated singularities

3.3.1 Positive solutions

The next result provides the complete classifications of isolated singularities of positive solutions of (1.1). We suppose that Ω is an open subset of \mathbb{R}^N containing 0 and set $\Omega^* = \Omega \setminus \{0\}$. Without loss of generality, we can suppose that $\Omega \supset \overline{B}_1$ and we recall that $B_1^* = B_1 \setminus \{0\}$. We recall that the fundamental solution of the p -Laplacian is defined in $\mathbb{R}^N \setminus \{0\}$ by

$$\mu_p(x) = \begin{cases} |x|^{\frac{p-N}{p-1}} & \text{if } 1 < p < N \\ -\ln|x| & \text{if } p = N. \end{cases} \quad (3.43)$$

It satisfies

$$-\Delta_p \mu_p = c_{N,p} \delta_0 \quad \text{in } \mathcal{D}'(\Omega). \quad (3.44)$$

Theorem 3.9 *Let $p-1 < q < q_c$ and $1 < p \leq N$. If u is a positive solution of (1.1) in Ω^* , then we have the following alternative.*

(i) *Either there exists $k \geq 0$ such that*

$$\lim_{x \rightarrow 0} \frac{u(x)}{\mu_p(x)} = k \quad (3.45)$$

and u is the unique nonnegative solution of

$$-\Delta_p v + |\nabla v|^q = c_{N,p} k^{p-1} \delta_0 \quad \text{in } \mathcal{D}'(\Omega) \quad (3.46)$$

which coincides with u on ∂B_R .

(ii) *Or*

$$\lim_{x \rightarrow 0} |x|^{\beta_q} u(x) = \lambda_{N,p,q}, \quad (3.47)$$

where β_q and $\lambda_{N,p,q}$ are defined in (1.5). Furthermore, if Ω is bounded, a positive solution u in $C(\overline{\Omega} \setminus \{0\})$ is uniquely determined by its data on $\partial\Omega$ and its behaviour at 0.

We need several lemmas for proving this theorem.

Lemma 3.10 *Assume p, q are as in Theorem 3.9 and $\phi : (0, 1] \mapsto \mathbb{R}_+$ is a continuous decreasing function such that $\lim_{r \rightarrow 0} \phi(r) = \infty$ and $r^{\frac{p-q}{q+1-p}} \phi(r) \leq c$. If u is a solution of (1.1) in B_1^* such that*

$$|u(x)| \leq \phi(|x|) \quad \forall x \in B_1^*. \quad (3.48)$$

Then there exists $C > 0$ and $\alpha \in (0, 1)$, both depending on N, p, q , such that

$$|\nabla u(x)| \leq C \phi(|x|) |x|^{-1} \quad \forall x \in B_{\frac{1}{2}} \setminus \{0\}. \quad (3.49)$$

$$|\nabla u(x) - \nabla u(x')| \leq C \phi(|x|) |x|^{-1-\alpha} |x - x'|^\alpha \quad \forall x, x' \text{ s.t. } 0 < |x| \leq |x'| \leq \frac{1}{2}. \quad (3.50)$$

Proof. Define $\Gamma := \{y \in \mathbb{R}^N : 1 < |y| < 7\}$ and $\Gamma' = \{y \in \mathbb{R}^N : 2 \leq |y| \leq 6\}$. For $0 < |x| < \frac{1}{2}$ there exists $\beta \in (0, \frac{1}{4})$ such that $2\beta \leq |x| \leq 3\beta$. We set

$$u_\beta(y) = \frac{1}{\phi(\beta)} u(\beta y).$$

Then the equation

$$-\Delta_p u_\beta + \beta^{p-q} (\phi(\beta))^{q+1-p} |\nabla u_\beta|^q = 0$$

holds in Γ . Because of (3.48) and the fact that ϕ is decreasing, $u_\beta(y) \leq 1$ on Γ . Since $\beta^{p-q} (\phi(\beta))^{q+1-p}$ remains bounded for $\beta \in (0, 1]$, we can apply the classical a priori estimates and derive that

$$|\nabla u_\beta(y)| \leq C \quad \forall y \in \Gamma^*, \quad (3.51)$$

$$|\nabla u_\beta(y) - \nabla u_\beta(y')| \leq C |y - y'|^\alpha \quad \forall y, y' \in \Gamma^*, \quad (3.52)$$

for some $C = C(N, p, q, \|u_\beta\|_{L^\infty(\Gamma)})$ and $\alpha \in (0, 1)$. Putting $x = \beta y$, $x' = \beta y'$ where x, x' are such that $0 < |x| \leq |x'| \leq 2|x| \leq 1$ we have $|y'| = \frac{|x'|}{\beta} \leq \frac{2|x|}{\beta} \leq 6$

$$|\nabla u(x) - \nabla u(x')| \leq C\phi(\beta)\beta^{-1-\alpha} |x - x'|^\alpha \leq C\phi(|x|) |x|^{-1-\alpha} |x - x'|^\alpha.$$

If $|x'| > 2|x|$ we have

$$|\nabla u(x) - \nabla u(x')| \leq C \left(\frac{\phi(|x|)}{|x|} + \frac{\phi(|x'|)}{|x'|} \right) \leq \frac{2C\phi(|x|)}{|x|} \leq \frac{2C\phi(|x|)}{|x|^{1+\alpha}} |x - x'|^\alpha.$$

□

Lemma 3.11 *Assume p, q are as in Theorem 3.9. Let u be a positive solution of (1.1) in Ω^* such that*

$$\liminf_{x \rightarrow 0} \frac{u(x)}{\mu_p(x)} < \infty. \quad (3.53)$$

Then there exists $k \geq 0$ such that (3.45) and (3.46) hold.

Proof. Let $y \in B_{\frac{1}{2}}$. By Proposition 2.5 there exists $C = C(N, p, q) > 0$ such that

$$\max_{|z-y| \leq \frac{|y|}{4}} u(z) \leq C \min_{|z-y| \leq \frac{|y|}{4}} u(z)$$

If $|y'| = |y|$ there exist at most 13 balls $B_{\frac{|y|}{4}}(y_j)$ with center y_j on $\{z : |z| = |y|\}$ such that $y_1 = y$, $y_{13} = y'$ and $B_{\frac{|y|}{4}}(y_j) \cap B_{\frac{|y|}{4}}(y_{j+1}) \neq \emptyset$. This implies $u(y) \leq C^{13}u(y')$ and, since μ_p is radial (and we note $\mu_p(x) = \mu_p(|x|)$),

$$\limsup_{x \rightarrow 0} \frac{u(x)}{\mu_p(x)} = k < \infty. \quad (3.54)$$

If $k = 0$, then $u \leq \epsilon\mu_p + M$ for any $\epsilon > 0$, where $M = \max\{u(x) : |x| = 1\}$, by the maximum principle. Thus u remains bounded near 0 and thus the singularity is removable. Next we assume $k > 0$, thus $u \leq k(\mu_p - \mu_p(1)) + M$ by the maximum principle.

We first assume that $M = 0$. It implies $u(x) \leq m\mu_p(x)$ for some $m \geq k$. Since $q \leq q_c$, $(\mu_p(r))^{q+1-p}r^{p-q} \leq c$, it follows from Lemma 3.10 that

$$|\nabla u(x)| \leq C\mu_p(|x|) |x|^{-1} \quad \forall x \in B_{\frac{1}{2}} \setminus \{0\} \quad (3.55)$$

and

$$|\nabla u(x) - \nabla u(x')| \leq C\mu_p(|x|) |x|^{-1-\alpha} |x - x'|^\alpha \quad \forall x, x' \text{ s.t. } 0 < |x| \leq |x'| \leq \frac{1}{2}. \quad (3.56)$$

If we define

$$u_r(y) = \frac{u(r y)}{\mu_p(r)} \quad \forall y \in B_{\frac{1}{r}}, \quad (3.57)$$

it satisfies

$$-\Delta_p u_r + (\mu_p(r))^{q+1-p} r^{p-q} |\nabla u_r|^q = 0 \quad (3.58)$$

in $B_{\frac{1}{r}}$ and the following estimates:

$$0 \leq u_r(y) \leq m \frac{\mu_p(r|y|)}{\mu_p(r)} \quad \forall y \in B_{\frac{1}{r}} \setminus \{0\}, \quad (3.59)$$

$$|\nabla u_r(y)| \leq C \frac{\mu_p(r|y|)}{\mu_p(r)} |y|^{-1} \quad \forall y \in B_{\frac{1}{2r}} \setminus \{0\}, \quad (3.60)$$

and

$$|\nabla u_r(y) - \nabla u_r(y')| \leq C \frac{\mu_p(r|y|)}{\mu_p(r)} |y|^{-1-\alpha} |y - y'|^\alpha \quad \forall y, y' \text{ s.t. } 0 < |y| \leq |y'| \leq \frac{1}{2r}. \quad (3.61)$$

let $0 < a < b$. If we assume that $0 < a \leq |y| \leq b$, then $\frac{\mu_p(r|y|)}{\mu_p(r)}$ remains bounded independently of $r \in (0, 1]$ and the set of functions $\{u_r\}_{0 < r < 1}$ is relatively sequentially compact in the C^1 topology of $\overline{B}_b \setminus B_a$. There exist a sequences $\{r_n\}$ converging to 0 and a function $v \in C^1(\overline{B}_b \setminus B_a)$ such that $u_{r_n} \rightarrow v$ in $C^1(\overline{B}_b \setminus B_a)$. Since $(\mu_p(r_n))^{q+1-p} r_n^{p-q} \rightarrow 0$ as $q < q_c$, v is p -harmonic in $B_b \setminus \overline{B}_a$ and nonnegative. Notice that a and b are arbitrary, therefore, using Cantor diagonal process, we can assume that v is defined in $\mathbb{R}^N \setminus \{0\}$ and $u_{r_n} \rightarrow v$ in the C^1 -loc topology of $\mathbb{R}^N \setminus \{0\}$. If $p = N$, the positivity of v implies that v is a constant [19, Corollary 2.2], say θ . If $1 < p < N$, there holds, by [19, Theorem 2.2] and (3.59)

$$v(y) = \theta \mu_p(y) + \sigma \leq m \mu_p(y) \quad \forall y \in \mathbb{R}^N \setminus \{0\}, \quad (3.62)$$

for some $\theta, \sigma \geq 0$, thus $\sigma = 0$. In order to make θ precise we set

$$\gamma(r) = \sup_{|x|=r} \frac{u(x)}{\mu_p(x)},$$

then $u(x) \leq \gamma(r) \mu_p(x)$ in $B_1 \setminus B_r$. This implies in particular that, for $r < s < 1$, $u(x) \leq \gamma(r) \mu_p(x)$ for any x such that $|x| = s$ and finally

$$\gamma(s) \leq \gamma(r). \quad (3.63)$$

It follows from (3.54), (3.63) that $\lim_{r \rightarrow 0} \gamma(r) = k$. There exists y_{r_n} with $|y_{r_n}| = 1$ such that $u(r_n y_{r_n}) = \mu_p(r_n) \gamma(r_n)$. Therefore

$$\lim_{r_n \rightarrow 0} \frac{u(r_n y_{r_n})}{\mu_p(r_n)} = k = \theta. \quad (3.64)$$

Consequently

$$\lim_{r \rightarrow 0} \frac{u(r y)}{\mu_p(r)} = \begin{cases} k \mu(y) & \text{if } 1 < p < N \\ k & \text{if } p = N. \end{cases} \quad (3.65)$$

This implies in particular

$$\lim_{x \rightarrow 0} \frac{u(x)}{\mu_p(|x|)} = k. \quad (3.66)$$

Since the convergence of u_r holds in the C^1 -loc topology, we also deduce that

$$\lim_{x \rightarrow 0} |x|^{\frac{N-1}{p-1}} \nabla u(x) = \begin{cases} \frac{p-N}{p-1} k \frac{x}{|x|} & \text{if } 1 < p < N \\ -k \frac{x}{|x|} & \text{if } p = N. \end{cases} \quad (3.67)$$

If we plug these estimates into the weak formulation of (1.1) we obtain (3.46).

General case. If $M > 0$, for any $0 < \epsilon < 1$ we denote by u_ϵ the solution of

$$\begin{cases} -\Delta_p u_\epsilon + |\nabla u_\epsilon|^q = 0 & \text{in } B_1 \setminus \overline{B}_\epsilon \\ u_\epsilon = u & \text{in } \partial B_\epsilon \\ u_\epsilon = 0 & \text{in } \partial B_1 \end{cases} \quad (3.68)$$

By the comparison principle $u_\epsilon \leq u \leq u_\epsilon + M$ and $u_\epsilon \leq u_{\epsilon'}$ for $0 < \epsilon < \epsilon'$, thus $u_\epsilon \rightarrow u_0$ and $u_0 \leq u \leq u_0 + M$ in B_1^* . Since $u_\epsilon \leq m \mu_p$ in $B_1 \setminus \overline{B}_\epsilon$ and since for any $\epsilon < |x| \leq \frac{1}{2}$ there exists $\beta \in (\epsilon, 1]$ such that $\beta \leq |x| \leq 2\beta$, we see by the same technique as the one uses in Lemma 3.10, that the gradient of u_ϵ satisfies

$$|\nabla u_\epsilon(x)| \leq C |x|^{-1} \mu_p(x) \quad \forall x \in B_{\frac{1}{2}} \setminus \overline{B}_{2\epsilon}$$

and

$$|\nabla u_\epsilon(x) - \nabla u_\epsilon(x')| \leq C |x|^{-1-\alpha} \mu_p(x) |x - x'|^\alpha \quad \forall x, x' \in B_{\frac{1}{2}} \setminus \overline{B}_{2\epsilon} \text{ s.t. } |x| \leq |x'|.$$

Therefore $\{u_\epsilon\}$ is relatively sequentially compact in the C^1 -loc topology of B_1^* , which implies that u_0 is a solution of (1.1) in B_1^* which vanishes on ∂B_1 and satisfies the same estimate (3.54) as u . Therefore u_0 and u satisfy (3.66) and (3.46). \square

Lemma 3.12 *Assume p, q and R are as in Theorem 3.9. Let u be a positive solution of (1.1) in Ω^* such that*

$$\liminf_{x \rightarrow 0} \frac{u(x)}{\mu_p(x)} = \infty. \quad (3.69)$$

Then (3.47) holds.

Proof. If (3.53) holds, then for any $k > 0$ u is larger than the radial solution u_k of (1.1) in B_1^* which vanishes on ∂B_1 and satisfies (3.45). When $k \rightarrow \infty$ we derive from Proposition 3.2 that

$$u(x) \geq u_\infty(|x|) = \lambda_{N,p,q}(|x|^{-\beta_q} - 1). \quad (3.70)$$

Next, for any $\epsilon > 0$ we denote by \tilde{u}_ϵ the solution of (3.1) on $(\epsilon, 1)$ which satisfies $\tilde{u}_\epsilon(\epsilon) = \infty$. This solution is expressed from (3.15) with a negative K , namely

$$\tilde{u}_\epsilon(r) = b^{\frac{1}{q+1-p}} \int_r^1 s^{\frac{1-N}{p-1}} \left[s^{\frac{q+1-p}{p-1}b} - \epsilon^{\frac{q+1-p}{p-1}b} \right]^{-\frac{1}{q+1-p}} ds. \quad (3.71)$$

and existence of the blow-up at $r = \epsilon$ follows from $p > q$. By comparison principle $u \leq \tilde{u}_\epsilon + M$ in $B_1 \setminus B_\epsilon$ where $M = \sup\{u(z) : |z| = 1\}$. When $\epsilon \rightarrow 0$, formula (??) implies that

$$\lim_{\epsilon \rightarrow 0} \tilde{u}_\epsilon(r) = b^{\frac{1}{q+1-p}} \int_r^1 s^{\frac{1-N}{p-1}} \left[s^{\frac{q+1-p}{p-1}b} \right]^{-\frac{1}{q+1-p}} ds = u_\infty(r). \quad (3.72)$$

Therefore $u_\infty(|x|) \leq u(x) \leq u_\infty(|x|) + M$. \square

Proof of Theorem 3.9. By combining Lemma 3.11 and Lemma 3.12 we have the alternative between (i) and (ii). Assuming now that Ω is bounded and u and u' are two solutions of (1.1) in Ω^* continuous in $\overline{\Omega} \setminus \{0\}$ coinciding on $\partial\Omega$ and satisfying either (i) with the same k or (ii), then, for any $\epsilon > 0$, $(1 + \epsilon)u + \epsilon$ is a supersolution which dominates u' in a neighborhood of 0 and a neighborhood of $\partial\Omega$. Therefore $(1 + \epsilon)u + \epsilon \geq u'$, which implies $u \leq u'$, and vice versa. \square

We end this section with a result dealing with global singular solutions.

Theorem 3.13 *Let $p - 1 < q < q_c$ and $1 < p \leq N$. If u is a positive solution of (1.1) in $\mathbb{R}^{N*} = \mathbb{R}^N \setminus \{0\}$, then u is radial and we have the following dichotomy:*

- (i) *either there exists $M \geq 0$ such that $u(x) \equiv M$,*
- (ii) *either there exist $k > 0$, $M \geq 0$ such that $u(x) = u_{k,M}(|x|)$ defined by (3.27),*
- (ii) *or there exists some $M \geq 0$ such that $u(x) = u_{\infty,M}(|x|)$ defined by (3.28).*

Proof. Step 1: Asymptotic behaviour. If u is a solution of (1.1) in an exterior domain $G \supset B_R^c$, it is bounded by Corollary 2.4 and satisfies

$$|\nabla u(x)| = (u_r^2 + r^{-2} |\nabla' u|^2)^{\frac{1}{2}}(r, \sigma) \leq C_{N,p,q} (r - R)^{-\frac{1}{q+1-p}} \quad \forall x = (r, \sigma) \in [R, \infty) \times S^{N-1} \quad (3.73)$$

by Proposition 2.1. Since $p > q$,

$$\int_{R+1}^\infty \int_{S^{N-1}} |u_r| d\sigma dt < \infty,$$

therefore there exists $\phi \in L^1(S^{N-1})$ such that $u(r, \cdot) \rightarrow \phi(\cdot)$ in $L^1(S^{N-1})$ as $r \rightarrow \infty$. The gradient estimate implies that the set of functions $\{u(r, \cdot)\}_{r \geq R+1}$ is relatively compact in $C(S^{N-1})$, therefore $u(r, \cdot) \rightarrow \phi(\cdot)$ uniformly on S^{N-1} when $r \rightarrow \infty$. If σ and σ' belong to S^{N-1} , there exists a smooth path $\gamma := \{\gamma(t) : t \in [0, 1]\}$ such that $\gamma(t) \in S^{N-1}$, $\gamma(0) = \sigma$, $\gamma(1) = \sigma'$. Then

$$u(r, \sigma) - u(r, \sigma') = \int_0^1 \frac{d}{dt} u(r, \gamma(t)) dt = \int_0^1 \langle \nabla' u(r, \gamma(t)), \gamma'(t) \rangle dt,$$

and finally, using (3.73),

$$|u(r, \sigma) - u(r, \sigma')| \leq \|\gamma'\|_{L^\infty} |\nabla' u(r, \gamma(t))| \leq C_{N,p,q} \|\gamma'\|_{L^\infty} r(r-R)^{-\frac{1}{q+1-p}} \quad (3.74)$$

Letting $r \rightarrow \infty$, it implies that ϕ is a constant, say M . As a consequence we have proved that

$$\lim_{|x| \rightarrow \infty} u(x) = M. \quad (3.75)$$

Notice that we did not use the fact that u is a positive solution in order to derive (3.74). Next we assume the positivity.

Step 2: End of the proof. If u satisfies (3.45) for some $k > 0$, then for any $\epsilon > 0$, there holds with the notations of Proposition 3.3

$$(1 - \epsilon)u_{k,M}(|x|) \leq u(x) \leq (1 + \epsilon)u_{k,M}(|x|) \quad \forall x \in \mathbb{R}^{N*}$$

This implies $u = u_{k,M}$. Similarly, if satisfies (3.47), we derive $u = u_{\infty,M}$. \square

3.3.2 Negative solutions

The next result explicits the behaviour of negative solutions near an isolated singularities

Theorem 3.14 *Let $p - 1 < q < q_c$ and $1 < p \leq N$. If u is a negative solution of (1.1) in $\Omega \setminus \{0\}$, then there exists $k \leq 0$ such that 3.45 and cl2 hold. Furthermore, if $k = 0$, u can be extended as a $C^{1,\alpha}$ of (1.1) in Ω .*

Proof. We can assume $\overline{B_1} \subset \Omega$. Since $\tilde{u} := -u$ satisfies

$$-\Delta_p \tilde{u} = |\nabla u|^q \quad \text{in } \Omega \setminus \{0\}$$

It follows from [3, Th 1.1] that $|\nabla u|^q \in L_{loc}^1(\Omega)$ and there exists $k \geq 0$ such that

$$-\Delta_p \tilde{u} = |\nabla u|^q + k\delta_0 \quad \text{in } \mathcal{D}'(\Omega). \quad (3.76)$$

Furthermore $|\nabla u|^{p-1} \in M_{loc}^{\frac{N}{N-1}}(\Omega)$, where M^p denotes the weak L^p space (or Marcinkiewicz space). This implies $B := |\nabla u|^{q+1-p} \in M_{loc}^{\frac{N(p-1)}{(q+1-p)(N-1)}}(\Omega) \subset L_{loc}^{\frac{N(p-1)}{(q+1-p)(N-1)}-\sigma}(\Omega)$ for any $\sigma > 0$. Since $q < q_c$, it follows $B \in L_{loc}^{N+\epsilon}(\Omega)$ for some $\epsilon > 0$. We write the equation under the form

$$-\Delta_p \tilde{u} = B |\nabla \tilde{u}|^{p-1} \quad (3.77)$$

It follows by [35, Th 1] that either there exists $k' > 0$ such as

$$\frac{1}{c'} \leq \frac{\tilde{u}}{\mu_p} \leq c' \quad \text{near } 0, \quad (3.78)$$

or u has a removable singularity at 0. If the singularity is removable, then (3.76) holds with $k = 0$. If the singularity is not removable, we set

$$\gamma = \limsup_{x \rightarrow 0} \frac{\tilde{u}(x)}{\mu_p(x)}. \quad (3.79)$$

Then there exists a sequence $\{x_n\}$ converging to 0 such that

$$\gamma = \lim_{n \rightarrow \infty} \tilde{u}(x_n)/\mu_p(x_n) \quad (3.80)$$

We set $\delta_n = |x_n|$, $\xi_n = x_n/\delta_n$ and

$$\tilde{u}_{\delta_n}(\xi) = \frac{\tilde{u}(\delta_n \xi)}{\mu_p(\delta_n)}.$$

Then

$$-\Delta_p \tilde{u}_{\delta_n} - C(\delta_n) |\nabla \tilde{u}_{\delta_n}|^q = 0$$

in $B_{\delta_n^{-1}} \setminus \{0\}$ where

$$C(\delta_n) = \delta_n^{p-q} (\mu(\delta_n))^{q+1-p}.$$

Since $u_{\delta_n}(\xi) \leq c\mu_p(\xi)$, we derive from Lemma 3.10

$$\begin{aligned} |\nabla u_{\delta_n}(\xi)| &\leq c |\xi|^{-1} \mu_p(\xi) & \text{for } |\xi| \leq \frac{1}{2\delta_n} \\ |\nabla u_{\delta_n}(\xi) - \nabla u_{\delta_n}(\xi')| &\leq c |\xi - \xi'|^\alpha |\xi|^{-1-\alpha} \mu_p(\xi) & \text{for } |\xi| \leq |\xi'| \leq \frac{1}{2\delta_n}. \end{aligned}$$

Thus, by Ascoli's theorem, the set of functions $\{u_{\delta_n}\}$ is relatively compact in the C_{loc}^1 -topology of $\mathbb{R}^N \setminus \{0\}$. Since $C(\delta_n) \rightarrow 0$, there exists a subsequence $\{\tilde{u}_{\delta_{n_k}}\}$ and a nonnegative p -harmonic function \tilde{w} such that $\tilde{u}_{\delta_{n_k}} \rightarrow \tilde{w}$ as well as its gradient, uniformly on any compact subset of $\mathbb{R}^N \setminus \{0\}$. All the positive p -harmonic functions in $\mathbb{R}^N \setminus \{0\}$ are known (see[19]: either they are a positive constant, if $N = p$ or have the form $\lambda\mu_p + \tau$ for some $\lambda, \tau \geq 0$ if $1 < p < N$).

If $p = N$, we obtain from (3.80)

$$\lim_{n_k \rightarrow \infty} \frac{\tilde{u}(x_{n_k})}{\mu_p(x_{n_k})} = \gamma = \lim_{n \rightarrow \infty} \frac{\tilde{u}(x_n)}{\mu_p(x_n)} \quad (3.81)$$

Thus $\tilde{w} = \gamma$ and the limit is locally uniform with respect to ξ . Therefore for any $\epsilon > 0$, there exists $n_\epsilon \in \mathbb{N}$ such that for $n \geq n_0$, there holds

$$\tilde{u}(x) \geq (\gamma - \epsilon)\mu_N(x) \quad \forall x \text{ s.t. } |x| = \delta_n.$$

By comparison it implies

$$\tilde{u}(x) \geq (\gamma - \epsilon)\mu_N(x) \quad \forall x \text{ s.t. } \delta_n \leq |x| \leq \delta_{n_0}.$$

This holds for any $n \geq n_0$ and any $\epsilon > 0$, therefore,

$$\liminf_{x \rightarrow 0} \frac{\tilde{u}(x)}{\mu_N(x)} \geq \gamma. \quad (3.82)$$

Combining with (3.79), it implies

$$\lim_{x \rightarrow 0} \frac{\tilde{u}(x)}{\mu_N(x)} = \gamma. \quad (3.83)$$

If $1 < p < N$, estimate $u_{\delta_n}(\xi) \leq C\mu_p(\xi)$ implies $\tau = 0$, thus $\tilde{w} = \lambda\mu_p$. Clearly $\lambda = \gamma$ because of (3.79). Similarly as in the case $p = N$, (3.82) and (3.83) hold. Since the convergence is C^1 , we also get

$$\lim_{x \rightarrow 0} \frac{\tilde{u}_{x_j}(x)}{\mu_{N_{x_j}}(x)} = \gamma. \quad (3.84)$$

This implies that there holds

$$-\Delta_p \tilde{u} = |\nabla \tilde{u}|^q + c_{N,p} \gamma \delta_0 \quad \text{in } \mathcal{D}'(\Omega). \quad (3.85)$$

□

Remark. In the case $q > q_c$ the description of the isolated singularities is much more difficult, as it is the case if one considers the positive solutions of

$$-\Delta_p \tilde{u} = \tilde{u}^m \quad \text{in } \Omega \setminus \{0\} \quad (3.86)$$

in the case $m > m_c := \frac{N(p-1)}{N-p}$ (see [36] for partial but very deep results). In the case of equation

$$-\Delta_p \tilde{u} = |\nabla \tilde{u}|^q \quad \text{in } \mathbb{R}^N \setminus \{0\} \quad (3.87)$$

the main difficulty is to prove that there exists only one positive solution under the form $\tilde{u}(x) = \tilde{u}(r, \sigma)$, which is the function \tilde{U} . Equivalently it is to prove that the only positive solution of

$$\begin{aligned} -\operatorname{div} \left((\beta_q^2 \omega^2 + |\nabla' \omega|^2)^{\frac{p-2}{2}} \nabla \omega \right) - (\beta_q^2 \omega^2 + |\nabla' \omega|^2)^{\frac{q}{2}} \\ - \beta_q (\beta_q (p-1 + p-N)) ((\beta_q^2 \omega^2 + |\nabla' \omega|^2)^{\frac{p-2}{2}} \omega) = 0 \quad \text{in } S^{N-1} \end{aligned} \quad (3.88)$$

is the constant $\tilde{\lambda}_{N,p,q}$.

4 Quasilinear equations on Riemannian manifolds

4.1 Gradient geometric estimates

In this section we assume that (M^N, g) is a N -dimensional Riemannian manifold, TM its tangent bundle, ∇u is the covariant gradient, $\langle \cdot, \cdot \rangle$ the scalar product expressed in the metric $g := (g_{ij})$, $Ricc_g$ the Ricci tensor and Sec_g the sectional curvature. Formula (2.3) is a particular case of the Böchner-Weitzenböck formula which is the following: if $u \in C^3(M)$ there holds

$$\frac{1}{2} \Delta_g |\nabla u|^2 = |D^2 u|^2 + \langle \nabla \Delta_g u, \nabla u \rangle + Ricc_g(\nabla u, \nabla u), \quad (4.1)$$

where $D^2 u$ is the Hessian, $\Delta_g = \operatorname{div}_g(\nabla u)$ is the Laplace-Beltrami operator on (M^N, g) and div_g is the divergence operator acting on $C^1(M, TM)$. For $p > 1$, we also denote by $\Delta_{g,p}$ the p -Laplacian operator on M defined by

$$\Delta_{g,p} u = \operatorname{div}_g(|\nabla|^{p-2} \nabla u), \quad (4.2)$$

with the convention $\Delta_{2,g} = \Delta_g$. A natural geometric assumption is that the Ricci curvature is bounded from below and more precisely

$$\text{Ric}_g(x)(\xi, \xi) \geq -(N-1)B^2 |\xi|^2 \quad \forall \xi \in T_x M \quad (4.3)$$

for some $B \geq 0$. If $u \in C^3(M)$ is a solution of

$$-\Delta_{p,g}u + |\nabla u|^q = 0 \quad \text{in } M, \quad (4.4)$$

then (2.8) is replaced by

$$\begin{aligned} \Delta_g z + (p-2) \frac{\langle D^2 z(\nabla u), \nabla u \rangle}{z} &\geq \frac{2a^2}{N} z^{q+2-p} - \frac{1}{Na^2} \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} - \frac{(p-2)}{2} \frac{|\nabla z|^2}{z} \\ &+ (p-2) \frac{\langle \nabla z, \nabla u \rangle^2}{z^2} + (q+2-p) z^{\frac{q-p}{2}} \langle \nabla z, \nabla u \rangle - (N-1)B^2 z. \end{aligned} \quad (4.5)$$

and by

$$\mathcal{L}^*(z) := \mathcal{A}(z) + Cz^{q+2-p} - D \frac{|\nabla z|^2}{z} - (N-1)B^2 z \leq 0 \quad \text{in } \Omega. \quad (4.6)$$

We recall that the convexity radius $r_M(a)$ of some $a \in M$ is the supremum of all the $r > 0$ such that the ball $B_r(a)$ is convex.

Lemma 4.1 *Assume $q > p-1 \geq 0$ and let $a \in M$ and $R > 0$ and $B \geq 0$ such that $\text{Ric}_g \geq -(N-1)B^2$ in $B_R(a)$. Assume also $\text{Sec}_g \geq -\tilde{B}^2$ in $B_R(a)$ for some $\tilde{B} \geq 0$ if $p > 2$, or $r_M(a) \geq R$ if $1 < p < 2$. Then there exists $c = c(N, p, q) > 0$ such that the function*

$$w(x) = \lambda (R^2 - r^2(x))^{-\frac{2}{q+1-p}} + \mu \quad \text{with } r = r(x) = d(x, a), \quad (4.7)$$

satisfies

$$\mathcal{L}^*(w) \geq 0 \quad \text{in } B_R(a), \quad (4.8)$$

provided

$$\lambda = c \max \left\{ (R^4 B^2)^{\frac{1}{q+1-p}}, ((1+B+(p-2)_+ \tilde{B})R^2)^{\frac{1}{q+1-p}} \right\} \quad (4.9)$$

and

$$\mu = ((N-1)B^2)^{\frac{1}{q+1-p}}. \quad (4.10)$$

Proof. We recall that

$$\Delta_g w = w'' + w' \Delta_g r \quad (4.11)$$

and [32, Lemma 1]

$$\Delta_g r \leq (N-1)B \coth(Br) \leq \frac{N-1}{r} (1+Br).$$

Then

$$\Delta_g w \leq \frac{4}{q+1-p} (R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} \left(\frac{2r^2(q+3-p)}{q+1-p} + (R^2 - r^2)(1 + (N-1)(1+Br)) \right). \quad (4.12)$$

Moverover [16, Chapt 2, Theorem A]

$$D^2 w = w'' dr \otimes dr + w' D^2 r. \quad (4.13)$$

If $r_M(a) \geq r(x)$ the ball $B_{r(x)}(a)$ is convex This implies that r is convex and therefore $D^2 r \geq 0$ (see [33, IV-5]). Furthermore, if $\text{Sec}_g(x) \geq -\tilde{B}^2$, then [33, IV-Lemma 2.9]

$$D^2 r \leq \tilde{B} \coth(\tilde{B}r) g_{ij} \leq \frac{\tilde{B}}{r} (1 + \tilde{B}r) g_{ij}, \quad (4.14)$$

therefore

$$\begin{aligned} 0 &\leq \frac{\langle D^2 w(\nabla u), \nabla u \rangle}{|\nabla u|^2} \\ &\leq \frac{4}{q+1-p} (R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} \left(\frac{2r^2(q+3-p)}{q+1-p} + (R^2 - r^2)(2 + \tilde{B}r) \right) \end{aligned} \quad (4.15)$$

We obtain

$$\begin{aligned} \mathcal{A}(w) &= -\Delta w - (p-2) \frac{\langle D^2 w(\nabla u), \nabla u \rangle}{|\nabla u|^2} \\ &\geq -k\lambda(R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} (R^2 + (p-2)_+(R^2 - r^2)\tilde{B}r \coth \tilde{B}r) \\ &\geq -k\lambda(R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} (R^2 + (R^2 - r^2)B_p r) \end{aligned} \quad (4.16)$$

for some $k = k(N, p, q)$, where $B_p = B + (p-2)_+\tilde{B}$. Since

$$w^{q+2-p} \geq \lambda^{q+2-p} (R^2 - r^2)^{-\frac{2(q+1-p)}{q+1-p}} + \mu^{q+2-p}.$$

we have

$$\begin{aligned} \mathcal{L}^*(w) &\geq \lambda(R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} \left(-k(R^2 + (R^2 - r^2)B_p r) - D \frac{16}{(q+1-p)^2} r^2 + C\lambda^{q+1-p} \right) \\ &\quad + \mu^{q+2-p} - (N-1)B^2\lambda(R^2 - r^2)^{-\frac{2}{q+1-p}} - (N-1)B^2\mu. \end{aligned} \quad (4.17)$$

We first take

$$\mu = ((N-1)B^2)^{\frac{1}{q+1-p}} \quad (4.18)$$

Next we choose λ in order to have, uniformly for $0 \leq r < R$,

$$2^{-1}C\lambda^{q+1-p} \geq k(R^2 + (R^2 - r^2)B_p r) + D \frac{16}{(q+1-p)^2} r^2$$

and

$$2^{-1}C\lambda^{q+2-p}(R^2 - r^2)^{-\frac{2(q+2-p)}{q+1-p}} \geq (N-1)B^2\lambda(R^2 - r^2)^{-\frac{2}{q+1-p}}$$

There exists $c = c(N, p, q)$ such that, if

$$\lambda = c \max \left\{ (R^4 B^2)^{\frac{1}{q+1-p}}, ((1+B_p)R^2)^{\frac{1}{q+1-p}} \right\} \quad (4.19)$$

then (4.8) holds. \square

Proposition 4.2 *Assume $q > p - 1 > 0$. Let Ω be an open subset of M such that $Ricc_g \geq (1-N)B^2$ in Ω . Assume also $Sect_g \geq -\tilde{B}^2$ in Ω if $p > 2$, or $r_M(x) \geq \text{dist}(x, \partial\Omega)$ for any $x \in M$ if $1 < p < 2$. Then any solution u of (4.4) in Ω satisfies*

$$|\nabla u(x)| \leq c_{N,p,q} \max \left\{ B^{\frac{1}{q+1-p}}, (1+B_p)^{\frac{1}{2(q+1-p)}} (d(a, \partial\Omega))^{-\frac{1}{q+1-p}} \right\} \quad \forall x \in \Omega, \quad (4.20)$$

where $B_p = B + (p-2)_+\tilde{B}$.

Proof. Assume $a \in \Omega$ and $R < d(a, \partial\Omega)$. Let w be as in Lemma 4.1, then

$$\mathcal{A}(z-w) + C(z^{q+2-p} - w^{q+2-p}) - (N-1)B^2(z-w) - D \left(\frac{|\nabla z|^2}{z} - \frac{|\nabla w|^2}{w} \right) \leq 0 \quad (4.21)$$

in $B_R(a)$. Let G be a connected component of the set $\{x \in B_R(a) : z(x) - w(x) > 0\}$. Then there holds by the mean value theorem and the fact that $w(a)$ is the minimum of w in

$$C(z^{q+2-p} - w^{q+2-p}) - (N-1)B^2(z-w) > 0 \quad \text{in } G, \quad (4.22)$$

provided $C(q+2-p)(w(a))^{q+1-p} > (N-1)B^2$. Since $w(a) \geq \mu = ((N-1)B^2)^{\frac{1}{q+1-p}}$ and $q+2-p > 1$, this condition is fulfilled up to replacing μ by $A\mu$, $A = A(p, q) > 1$. We conclude as in the proof of Proposition 2.1 that $G = \emptyset$. Therefore $z \leq w$ in $B_R(a)$. In particular,

$$z(a) \leq c_{N,p,q} \max \left\{ B^{\frac{2}{q+1-p}}, (1+B_p)^{\frac{1}{q+1-p}} R^{-\frac{2}{q+1-p}} \right\} \quad (4.23)$$

where $c_{N,p,q} > 0$. Then (4.20) follows. \square

Remark. The convexity radius $r_M(x)$

Since $Ricc_g(x)(\xi, \xi) = (N-1) \sum_V Sec_g(x)(V)$, where V denotes the set of two planes in $T_x M$ which contain ξ there holds

$$Sec_g \geq -\tilde{B}^2 \implies Ricc_g \geq (1-N)\tilde{B}^2.$$

However, in the previous estimate, the long range estimate on ∇u depends only on the Ricci curvature.

4.2 Growth of solutions and Liouville type results

Corollary 4.3 *Assume (M^N, g) is a complete noncompact N -dimensional Riemannian manifold such that $\text{Ric}_g \geq (1 - N)B^2$ and let $q > p - 1 > 0$. Assume also that if $p > 2$, the scalar curvature scal_g satisfies for some $a \in M$*

$$\lim_{\text{dist}(a, x) \rightarrow \infty} \frac{|\text{scal}_g(x)|}{\text{dist}(a, x)} = 0. \quad (4.24)$$

Then any solution u of (4.4) satisfies

$$|\nabla u(x)| \leq c_{N,p,q} B^{\frac{2}{q+1-p}} \quad \forall x \in M. \quad (4.25)$$

In particular, u is constant if $\text{Ric}_g \geq 0$, while in the general case u has at most a linear growth with respect to the distance function.

Application An example of complete manifold with constant negative Ricci curvature is the standard hyperbolic space (\mathbb{H}^N, g_0) for which $\text{Ric}_{g_0} = -(N - 1)g_0$. Another application deals with positive p -harmonic functions (for related results see with $p = 2$ [39], [11]).

Corollary 4.4 *Assume (M^N, g) is as in Corollary 4.3. Let $p > 1$ and assume that (4.24) holds if $p > 2$. If v is a positive p -harmonic function, then*

(i) *if $\text{Ric}_g \geq 0$, v is constant.*

(ii) *if $\inf\{\text{Ric}_g(x) : x \in M\} = (1 - N)B^2 < 0$, v satisfies*

$$v(a)e^{-c_{N,p}B\text{dist}(x,a)} \leq v(x) \leq v(a)e^{c_{N,p}B\text{dist}(x,a)} \quad \forall x \in M. \quad (4.26)$$

Proof. We take $q = p$ and assume that v is p -harmonic and positive. If we write $v = e^{-\frac{u}{p-1}}$, then u satisfies

$$-\Delta_{g,p}u + |\nabla u|^p = 0.$$

If $\text{Ric}_g(x) \geq 0$, u , and therefore v is constant by Corollary 4.3. If $\inf\{\text{Ric}_g(x) : x \in M\} = (1 - N)B^2 < 0$ we apply (4.25) to ∇u . If γ is a minimizing geodesic from a to x , then $|\gamma'(t)| = 1$ and

$$u(x) - u(a) = \int_0^{d(x,a)} \frac{d}{dt} u \circ \gamma(t) dt = \int_0^{d(x,a)} \langle \nabla u \circ \gamma(t), \gamma'(t) \rangle dt$$

Since

$$|\langle \nabla u \circ \gamma(t), \gamma'(t) \rangle| \leq |\nabla u \circ \gamma(t)| \leq c_{N,p} \kappa$$

we obtain

$$u(a) - c_{N,p}B\text{dist}(x, a) \leq u(x) \leq u(a) + c_{N,p}B\text{dist}(x, a) \quad \forall x \in M, \quad (4.27)$$

Then (4.26) follows since $u = (1 - p) \ln v$. Notice that (i) follows from (ii). \square

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