STRONG MAXIMUM PRINCIPLES FOR ANISOTROPIC ELLIPTIC AND PARABOLIC EQUATIONS

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Abstract. We investigate vanishing properties of nonnegative solutions of anisotropic elliptic and parabolic equations. We describe the optimal vanishing sets, and we establish strong maximum principles.

1. Introduction and results

In dimension $n \geq 2$, given $\vec{p} = (p_1, \ldots, p_n)$ with $p_i > 1$ for $i = 1, \ldots, n$, the anisotropic Laplace operator $\Delta_{\vec{p}}$ is defined by

$$\Delta_{\vec{p}} u = \sum_{i=1}^{n} \frac{\partial}{\partial x_i} \nabla_{x_i}^{p_i} u,$$

where $\nabla_{x_i}^{p_i} u = |\partial u/\partial x_i|^{p_i-2} \partial u/\partial x_i$. We are concerned with equations of the type

$$\Delta_{\vec{p}} u = f(x, u, \nabla u) \quad \text{in } \Omega \quad \text{(1.2)}$$

and

$$-\frac{\partial u}{\partial t} + \Delta_{\vec{p}} u = f(x, t, u, \nabla u) \quad \text{in } \Omega \times (0, T), \quad \text{(1.3)}$$

where $\Omega$ is a domain in $\mathbb{R}^n$, $T$ is a positive real number, $f$ is a continuous function, and $\Delta_{\vec{p}}$ is as in (1.1). Anisotropic equations like (1.2) and (1.3) have strong physical background. They emerge, for instance, from the mathematical description of the dynamics of fluids with different conductivities in different directions. We refer to the extensive books by Antontsev–Díaz–Shmarev [3] and Bear [9] for discussions in this direction. They also appear in biology, see Bendahmane–Karlsen [10] and Bendahmane–Langlais–Saad [12], as a model describing the spread of an epidemic disease in heterogeneous environments.

In this paper, we investigate strong maximum principles for anisotropic equations of the type (1.2) and (1.3). Given a subset $K$ of $\Omega$, we say that equations (1.2) and (1.3) satisfy a strong maximum principle in $K$ if any nonnegative solution which vanishes at some point in $K$ is in fact identically zero on the whole set $K$. As is well known (see, for instance, Protter–Weinberger [41]), in case of the standard harmonic and heat equations, namely in case $f = 0$ and $p_i = 2$ for all $i = 1, \ldots, n$, equations (1.2) and (1.3) satisfy a strong maximum principle in the whole domain $\Omega$.

We show in this paper that in presence of anisotropy, the zeros of solutions may not spread over the whole domain $\Omega$, but they spread along directions where the anisotropic configuration is minimal. We illustrate this fact with a first example. In the anisotropic configuration

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\[ p_1 = \cdots = p_{n-1} = p_-, \quad p_n = p_+, \quad p_- < p_+ \]
one can check that a nonnegative stationary solution of equations (1.2) and (1.3) with \( f = 0 \) on \( \Omega = (0, +\infty)^{n-1} \times \mathbb{R} \) is given by
\[
U_\overline{\beta} (x_1, \ldots, x_n) = \frac{C |x_n|^{p_+/p_-}}{\left( \sum_{i=1}^{n-1} x_i^{p_/p_-} \right)^{p_-/p_-}}, \tag{1.4}
\]
for some constant \( C = C(n, \overline{\beta}) > 0 \) under the assumptions that \( p_+ > p_-(n-2)/(n-1-p_-) \)
and \( p_- < n-1 \). The function \( U_\overline{\beta} \) vanishes on the set \((0, +\infty)^{n-1} \times \{0\}\) without vanishing elsewhere in the domain. Functions of the form (1.4) were introduced, in a different context, by Giaquinta [26] and Marcellini [31]. This example can be generalized by observing that for any \( C > 0 \) and \( \varepsilon > 0 \), the function \( U_\overline{\beta} \) satisfies the inequality \( \Delta U_\overline{\beta} u \leq \lambda u^{p_-} \) on \( \Omega = (\varepsilon, +\infty)^{n-1} \times \mathbb{R} \) for \( \lambda > 0 \) large.

In Theorem 1.1 below, we establish a strong maximum principle for elliptic inequalities of the type
\[
\Delta \overline{\beta} u \leq f(u) \quad \text{in } \Omega. \tag{1.5}
\]
In presence of anisotropy, the vanishing sets are of the form
\[
\Omega_0 = \{ x \in \mathbb{R}^n; \quad [x, \xi_0] \subset \Omega \quad \text{and} \quad x_i = \xi_{0,i}, \quad \forall i \in \mathcal{I}_+ \}, \tag{1.6}
\]
for some point \( \xi_0 = (\xi_{0,1}, \ldots, \xi_{0,n}) \) in \( \mathbb{R}^n \), where \( \mathcal{I}_+ = \{ i \in \{1, \ldots, n\}; \quad p_i > p_- \} \) and \( p_- = \min(p_1, \ldots, p_n) \) is the minimum value in the anisotropic configuration. We prove our result under the assumptions that the function \( f \) in the right hand sides of (1.5) is continuous, nondecreasing, and such that
\[
f(u) = O(u^{p_-}) \quad \text{as } u \to 0. \tag{1.7}
\]
We let \( W_{\text{loc}}^{1, \overline{\beta}}(\Omega) \) be the Sobolev space defined by
\[
W_{\text{loc}}^{1, \overline{\beta}}(\Omega) = \left\{ u \in L^p_\text{loc}(\Omega); \quad \frac{\partial u}{\partial x_i} \in L^p_\text{loc}(\Omega) \quad \forall i = 1, \ldots, n \right\},
\]
where \( p_+ = \max(p_1, \ldots, p_n) \) and where, for any real number \( p \geq 1 \), \( L^p_\text{loc}(\Omega) \) is the space of all measurable functions on \( \Omega \) which belong to \( L^p(\Omega') \) for all compact subsets \( \Omega' \) of \( \Omega \). We say that a function \( u \) in \( W_{\text{loc}}^{1, \overline{\beta}}(\Omega) \cap C^0(\Omega) \) is a (weak) solution of the inequality (1.5) if for any nonnegative smooth function \( \varphi \) with compact support in \( \Omega \), there holds
\[
- \int_{\Omega} \frac{\partial u}{\partial x_i}^{p_-} \frac{\partial u}{\partial x_i} \frac{\partial \varphi}{\partial x_i} dx \leq \int_{\Omega} f(u) \varphi dx.
\]
An historic reference on strong maximum principles for elliptic equations is Hopf [27]. We refer to Protter–Weinberger [41] for a reference in book form on this topic. Our first result states as follows.

**Theorem 1.1.** Let \( \Omega \) be a nonempty domain in \( \mathbb{R}^n \) and \( f \) be a continuous nondecreasing function on \( \mathbb{R}_+ \) satisfying (1.7). Let \( u \) be a nonnegative solution in \( W_{\text{loc}}^{1, \overline{\beta}}(\Omega) \cap C^0(\Omega) \) of inequality (1.5). If there holds \( u(\xi_0) = 0 \) for some point \( \xi_0 \) in \( \Omega \), then the function \( u \) is identically zero on the set \( \Omega_0 \), where \( \Omega_0 \) is as in (1.6).

The vanishing sets \( \Omega_0 \) are the maximal sets on which the strong maximum principle holds true, see (1.4).

Condition (1.7) is optimal among pure nonlinearities of the type \( f(u) = u^{p_-} \). Indeed, for any real number \( p \) in \( [1, p_-) \), letting \( i \) be such that \( p_i = p_- \), one can check that a nonnegative solution of the equation \( \Delta U_\overline{\beta} u = u^{p_-} \) in \( \mathbb{R}^n \) is given by the function \( U_{p,p_-}(x) = \frac{C |x_n|^{p_/p_-}}{\left( \sum_{i=1}^{n-1} x_i^{p_/p_-} \right)^{p_-/p_-}} \).
We let

\[ L \]

where the type

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space of all measurable functions

\[ \|f\|_{p} \leq \frac{1}{C_{p,p}-p} (p_{-}-p)/(p_{-}^{-1}p(p_{-}-1)^{2}/p_{-}) \]. Clearly, the functions

\[ U_{p_{-}} \]

do not satisfy strong maximum principles on sets of the form (1.6).

In Theorem 1.2 below, we establish strong maximum principles for parabolic inequalities of the type

\[ -\frac{\partial u}{\partial t} + \Delta \varphi u \leq f(u) \quad \text{in } \Omega \times (0, T) . \] (1.8)

We let

\[ L_{p}^{\infty}(0, T; W_{1}^{p_{-}}(\Omega)) \]

be the function space defined by

\[ L_{p}^{\infty}(0, T; W_{1}^{p_{-}}(\Omega)) = \left\{ u \in L_{p_{-}}^{\infty}(0, T; L_{p_{-}}^{p}(\Omega)) : \frac{\partial u}{\partial x_{i}} \in L_{p_{-}}^{p}(0, T; L_{p_{-}}^{p}(\Omega)) \quad \forall i = 1, \ldots, n \right\} , \]

where \( p_{+} = \max(p_{1}, \ldots, p_{n}) \) and where, for any real number \( p \geq 1, L_{p_{-}}^{p}(0, T; L_{p_{-}}^{p}(\Omega)) \) is the space of all measurable functions \( u \) on \( \Omega \times (0, T) \) such that \( \int_{0}^{T} \int_{\Omega} |u|^{p} \, dx \, dt < \infty \) for all real numbers \( 0 < t_{1} < t_{2} < T \) and all compact subsets \( \Omega' \subset \Omega \). We say that a function \( u \) in

\[ L_{p_{-}}^{p}(0, T; W_{1}^{p_{-}}(\Omega)) \cap C^{0} (\Omega \times (0, T)) \]

is a (weak) solution of the inequality (1.8) if for any nonnegative smooth function \( \varphi \) with compact support in \( \Omega \times (0, T) \), there holds

\[ \int_{0}^{T} \int_{\Omega} u \frac{\partial \varphi}{\partial t} \, dx \, dt - \int_{0}^{T} \int_{\Omega} \frac{\partial u}{\partial x_{i}} \frac{\partial \varphi}{\partial x_{i}} \, dx \, dt \leq \int_{0}^{T} \int_{\Omega} f(u) \varphi \, dx \, dt . \]

A strong maximum principle for parabolic equations involving the standard Laplace operator was obtained by Nirenberg [38]. We refer, once again, to the extensive book by Protter–Weinberger [41] on this topic. Our result states as follows.

**Theorem 1.2.** Let \( \Omega \) be a nonempty domain in \( \mathbb{R}^{n} \), \( T \) be a positive real number, and \( f \) be a continuous nondecreasing function on \( \mathbb{R}_{+} \) satisfying (1.7). Let \( u \) be a nonnegative solution in

\[ L_{p_{-}}^{p_{-}}(0, T; W_{1}^{p_{-}}(\Omega)) \cap C^{0} (\Omega \times (0, T)) \]

of inequality (1.8). Assume that there holds \( u(\xi_{0}, t_{0}) = 0 \)

for some point \( \xi_{0} \) in \( \Omega \) and some real number \( t_{0} \) in \( (0, T) \). Let \( \Omega_{0} \) be as in (1.6). Then we get the following assertions.

(i) If \( p_{-} < 2 \), then the function \( u \) is identically zero on the set \( \Omega_{0} \times \{ t_{0} \} \).

(ii) If \( p_{-} = 2 \), then the function \( u \) is identically zero on the set \( \Omega_{0} \times (0, t_{0}] \).

(iii) If \( p_{-} > 2 \), then the function \( u \) is identically zero on the set \( \{ \xi_{0} \} \times (0, t_{0}] \).

The vanishing sets in Theorem 1.2 are optimal in the sense that in case \( p_{-} < 2 \), we get existence of solutions which vanish on a compact subset of \( \Omega \times (0, T) \). In case \( p_{-} > 2 \), we get existence of solutions which vanish on a whole horizontal line segment. As an example in case \( p_{-} > 2 \), the function \( u \) is such that \( p_{1} = p_{-} \), one can consider the function \( U_{p_{-}}(x, t) = (1-C_{p_{-}}x_{i})^{p_{-}/(1-p_{-})} \). As easily checked, the function \( U_{p_{-}} \) is a nonnegative solution of the equation \( \partial u/\partial t = \Delta \varphi u \) in \( \mathbb{R}^{n} \times (0, 1/(p_{-}-2)) \), and we get \( U_{p_{-}}(x, t) = 0 \) if and only if \( x_{i} = 1/C_{p_{-}} \).

We refer to Antontsev–Shmarev [5–8] for several results on the existence of solutions with finite waiting time or finite extinction time and on the localization of solutions of parabolic equations like (1.3). Other possible references on anisotropic parabolic equations are Antontsev–Chipot [2], Bendarbane–Karlsen [10, 11], Bendarbane–Langlais–Saaed [12], and Lieberman [29]. Elliptic equations like (1.2) also received much attention in recent years. Possible references on elliptic equations like (1.2) are Alves–El Hamidi [1], Antontsev–Shmarev [4], Cianchi [13], D’Ambrosio [14], Di Castro [16], Di Castro–Montefusco [17], El Hamidi–Rakotoson [19, 20], El Hamidi–Vétois [21], Fragalà–Gazzola–Kawohl [23], Fragalà–Gazzola–Lieberman [24], García-Melián–Rossi–Sabina de Lis [25], Li [28], Lieberman [29, 30], Marcellini [32],
For any positive real numbers $r$ and $\emptyset$, where, by convention, $\inf_{B} \emptyset$ is the minimum and maximum values in the anisotropic configuration.

In the isotropic configuration where $p_i = p$ for all $i = 1, \ldots, n$, the operator (1.1) is comparable, though slight different, to the $p$-Laplace operator $\Delta_p = \text{div} (|\nabla u|^{p-2} \nabla u)$. We refer to Vázquez [44] where the strong maximum principle was established for elliptic equations involving the $p$-Laplace operator. As for parabolic equations involving the $p$-Laplace operator, the question of the strong maximum principle was addressed in Nazaret [37]. For more material on $p$-Laplace equations, we refer to the lecture notes by Peral [39].

We also mention the work by Fortini–Mugnai–Pucci [22] where maximum principles are established for a general class of anisotropic inequalities in divergence form, in particular in the case of variable exponents (see also Zhang [49] concerning this case).

The proofs of Theorems 1.1 and 1.2 rely on the comparison of solutions with a family of anisotropic test functions (see (2.5) and (3.3)). We prove Theorem 1.1 in Section 2, and we prove Theorem 1.2 in Section 3.

2. Anisotropic elliptic equations

In this section, we prove Theorem 1.1.

Proof of Theorem 1.1. Renumbering, if necessary, the coordinates, we may assume that there exists an index $n_-$ such that $p_1 = \cdots = p_{n_-} = p_- and p_- < p_i$ for all $i > n_-$. We let $\xi_0 = (\xi_{0,1}, \ldots, \xi_{0,n})$ be a point in $\Omega$ such that $u(\xi_0) = 0$. We proceed by contradiction and assume that the function $u$ is not identically zero on $\Omega_0$, where $\Omega_0$ is as in (1.6). We let $P$ be the set of points $x$ in $\Omega$ such that $u(x) > 0$. Since $\Omega_0$ is arcwise connected and since both the sets $P \cap \Omega_0$ and $\Omega_0 \setminus P$ are nonempty, we get that $\partial P \cap \Omega_0$ is nonempty. We choose a point $\xi_1 = (\xi_{1,1}, \ldots, \xi_{1,n})$ in $P \cap \Omega_0$ such that

$$\inf_{x \in \Omega_0 \setminus P} \sum_{i=1}^{n_-} |x_i - \xi_{1,i}|^{\frac{p_-}{p_- - 1}} < \inf_{x \in \partial \Omega} \sum_{i=1}^{n_-} |x_i - \xi_{1,i}|^{\frac{p_-}{p_- - 1}},$$

(2.1)

where, by convention, $\inf \emptyset = +\infty$. Since $P$ is open, it follows from (2.1) that there exist a positive real number $r_0$ and a point $\zeta_0 = (\zeta_{0,1}, \ldots, \zeta_{0,n})$ in $\Omega_0 \setminus P$ such that $\zeta_0 \in \partial B_{\xi_1}^{p_-}(r_0)$ and $B_{\xi_1}^{p_-}(r_0) \setminus \{\zeta_0\} \subset P$, where

$$B_{\xi_1}^{p_-}(r_0) = \left\{ x \in \mathbb{R}^n; \sum_{i=1}^{n_-} |x_i - \xi_{1,i}|^{\frac{p_-}{p_- - 1}} < r_0 \text{ and } x_i = \xi_{0,i} \text{ } \forall i > n_- \right\}$$

(2.2)

and

$$\partial B_{\xi_1}^{p_-}(r_0) = \left\{ x \in \mathbb{R}^n; \sum_{i=1}^{n_-} |x_i - \xi_{1,i}|^{\frac{p_-}{p_- - 1}} = r_0 \text{ and } x_i = \xi_{0,i} \text{ } \forall i > n_- \right\}. $$

(2.3)

For any positive real numbers $\lambda$, $\delta$, and $\epsilon$, we let $A_{\xi_1, \delta}^p (r_0, \lambda, \epsilon)$ be the annular set defined by

$$A_{\xi_1, \delta}^p (r_0, \lambda, \epsilon) = \left\{ x \in \mathbb{R}^n; r_0 - \epsilon < \lambda \sum_{i=1}^{n} \frac{p_- - p_i}{p_- - 1} |x_i - \delta \zeta_{0,i} - (1 - \delta) \xi_{1,i}|^{\frac{p_-}{p_- - 1}} < r_0 \right\}.$$
Since $B_{\xi_1}^-(r_0) \setminus \{\zeta_0\} \subset P$, we get that for $\delta, \lambda$ small and any $\varepsilon$, $A_{\xi_1,\delta}^{-\varepsilon} (r_0, \lambda, \varepsilon)$ is included in $\Omega$. Moreover, we get that for $\varepsilon$ fixed and $\delta$, $\lambda$ small, the point $\zeta_0$ belongs to $A_{\xi_1,\lambda}^\varepsilon (r_0, \lambda, \varepsilon)$. For any positive real numbers $\lambda$ and $\delta$, we define our test function $v_{\lambda,\delta}$ on $\mathbb{R}^n$ by

$$v_{\lambda,\delta} (x) = \lambda \delta \left( e^\lambda (r_0 - \sum_{i=1}^n (\lambda^2 \delta)^{p_i - p_1 \frac{\partial}{\partial x_i}} |x_i - \delta \zeta_{0,i} - (1 - \delta) \xi_{1,i}|^{\frac{p_i}{\gamma_i - 1}} - 1 \right). \quad (2.5)$$

Letting $\Delta v_{\lambda,\delta}$ be as in (1.1), we find

$$\Delta v_{\lambda,\delta} (x) = (\lambda^2 \delta)^{p_i - 1} \sum_{i=1}^n \left( \frac{p_i}{p_i - 1} \right) \frac{p_i - 1}{p_i} \frac{p_i - 1}{p_i} e(\rho_i - 1) \lambda \left( r_0 - \sum_{j=1}^n (\lambda^2 \delta)^{p_j - 1} |x_j - \delta \zeta_{0,j} - (1 - \delta) \xi_{1,j}|^{\frac{p_j}{\gamma_j - 1}} \right) \times \left( p_i \lambda^{\frac{p_i - p_j - 1}{p_i - 1}} \delta \frac{p_i - p_j}{p_i - 1} |x_i - \delta \zeta_{0,i} - (1 - \delta) \xi_{1,i}|^{\frac{p_i}{\gamma_i - 1}} - 1 \right). \quad (2.6)$$

For any point $x$ in $A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$, by (1.7), (2.5), and (2.6), we get

$$- \Delta v_{\lambda,\delta} (x) + f (v_{\lambda,\delta} (x)) \leq (\lambda \delta)^{p_i - 1} \left( \sum_{i=1}^n \left( \frac{p_i}{p_i - 1} \right) \frac{p_i}{p_i} \lambda^{p_i - 1} e(\rho_i - 1) \lambda \left( p_i - 1 \right)^{p_i - 1} \delta (p_i - 1)^{p_i - 1} + C \left( e^\delta - 1 \right)^{p_i - 1} \right) \quad (2.7)$$

when $\lambda \delta$ and $\lambda \varepsilon$ are small, for some positive constant $C$ independent of $\lambda, \delta, \varepsilon$, and $x$. Choosing $\lambda$ large enough so that

$$\lambda > \left( \frac{p_i - 1}{p_i - 1} \right)^{p_i - 1} \sum_{i=1}^n \left( \frac{p_i}{p_i - 1} \right)^{p_i - 1} \delta \frac{p_i - p_i}{p_i - 1} |x_i - \delta \zeta_{0,i} - (1 - \delta) \xi_{1,i}|^{\frac{p_i}{\gamma_i - 1}} - 1 \right) \quad (2.7)$$

and then, choosing $\delta$ and $\varepsilon$ small, it follows from (2.7) that $v_{\lambda,\delta}$ is a $C^1$-solution of the inequality

$$- \Delta v_{\lambda,\delta} + f (v_{\lambda,\delta}) < 0 \quad \text{in} \quad A_{\xi_1,\lambda}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon), \quad (2.8)$$

where $A_{\xi_1,\lambda}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ is as in (2.4). We let $\partial_1 A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ and $\partial_2 A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ stand for the respective interior and exterior boundaries of the annular set $A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$. Since the function $u$ is positive on $B_{\xi_1}^\varepsilon (r_0)$, by continuity, we get the existence of a positive constant $C_\varepsilon$ such that $u > C_\varepsilon$ on $B_{\xi_1}^\varepsilon (r_0)$, where $B_{\xi_1}^\varepsilon (r_0)$ is as in (2.2). Still by continuity of $u$, it follows that $u \geq C_\varepsilon$ on $\partial_1 A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ for $\delta$ small. Since $v_{\lambda,\delta} = \lambda \delta (e^\lambda - 1)$ on $\partial_1 A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ and $v_{\lambda,\delta} = 0$ on $\partial_2 A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$, we then get $v_{\lambda,\delta} \leq u$ on $\partial A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$ for $\delta$ small. In particular, there holds $(v_{\lambda,\delta} - u)_+ = 0$ on $\partial A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$, where $(v_{\lambda,\delta} - u)_+ = \max (v_{\lambda,\delta} - u, 0)$. Testing (1.5) and (2.8) against $(v_{\lambda,\delta} - u)_+$ and integrating by parts on $A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon)$, we then get

$$\sum_{i=1}^n \int_{W_{\lambda,\delta,\varepsilon}} \left( \left| \frac{\partial v_{\lambda,\delta}}{\partial x_i} \right|^{p_i - 2} \frac{\partial v_{\lambda,\delta}}{\partial x_i} - \frac{\partial u}{\partial x_i} \right) \left( \frac{\partial v_{\lambda,\delta}}{\partial x_i} - \frac{\partial u}{\partial x_i} \right) \frac{\partial u}{\partial x_i} \, dx$$

$$+ \int_{W_{\lambda,\delta,\varepsilon}} (f (v_{\lambda,\delta}) - f (u)) (v_{\lambda,\delta} - u) \, dx \leq 0, \quad (2.9)$$

where

$$W_{\lambda,\delta,\varepsilon} = \left\{ x \in A_{\xi_1,\delta}^\varepsilon (r_0, \lambda^2 \delta, \varepsilon) ; \ v_{\lambda,\delta} (x) > u (x) \right\}.$$
Since the function $f$ is nondecreasing, it follows from (2.9) that
\[
\sum_{i=1}^{n} \int_{W_{\lambda,\delta}} \left( \left| \frac{\partial v_{\lambda,\delta}}{\partial x_i} \right|^{p-2} \frac{\partial v_{\lambda,\delta}}{\partial x_i} - \left| \frac{\partial u}{\partial x_i} \right|^{p-2} \frac{\partial u}{\partial x_i} \right) \left( \frac{\partial v_{\lambda,\delta}}{\partial x_i} - \frac{\partial u}{\partial x_i} \right) \, dx = 0,
\]
and thus that $\nabla u = \nabla v_{\lambda,\delta}$ almost everywhere in $W_{\lambda,\delta}$. Since $W_{\lambda,\delta}$ is open, we then get that the function $v_{\lambda,\delta} - u$ is constant in $W_{\lambda,\delta}$. By continuity of $u$ and $v_{\lambda,\delta}$, it follows that $|W_{\lambda,\delta}| = 0$, i.e. $v_{\lambda,\delta} \leq u$ in $A_{\xi,\lambda,\delta,\epsilon}(r_0,\lambda^2 \delta, \epsilon)$. In particular, we get $u(\zeta_0) \geq v_{\lambda,\delta}(\zeta_0) > 0$. There is a contradiction. This ends the proof of Theorem 1.1.

3. ANISOTROPIC PARABOLIC EQUATIONS

This section is devoted to the proof of Theorem 1.2. Replacing, if necessary, the coordinates, we may assume in what follows that there exists an index $n_-$ such that $p_1 = \cdots = p_{n_-} = \rho_- $ and $p_- < p_i$ for all $i > n_-$. For any positive real numbers $\mu$, $r$, and any point $(\xi, t)$ in $\mathbb{R}^n \times \mathbb{R}_+$, we define the sets $B^-_{(\xi,t)}(\mu, r)$ and $\partial B^-_{(\xi,t)}(\mu, r)$ by
\[
B^-_{(\xi,t)}(\mu, r) = \left\{ (x, s) \in \mathbb{R}^n \times \mathbb{R}_+; \sum_{i=1}^{n} |x_i - \xi_i|^{p_{-i}} + \mu |s-t|^{p_{-1}} < r \quad \text{and} \quad x_i = \xi_i \forall i > n_- \right\}
\]
and
\[
\partial B^-_{(\xi,t)}(\mu, r) = \left\{ (x, s) \in \mathbb{R}^n \times \mathbb{R}_+; \sum_{i=1}^{n} |x_i - \xi_i|^{p_{-i}} + \mu |s-t|^{p_{-1}} = r \quad \text{and} \quad x_i = \xi_i \forall i > n_- \right\}.
\]

As a preliminary step in the proof of Theorem 1.2, we prove the following lemma.

**Lemma 3.1.** Let $\Omega$, $T$, $f$, and $u$ be as in Theorem 1.2. Let $\mu$ be a positive real number. Assume that there exist a positive real number $r_0$ and two points $(\xi_0, t_0)$ and $(\xi_1, t_1)$ in $\Omega \times (0, T)$ such that $u(\xi_0, t_0) = 0$, $(\xi_0, t_0) \in \partial B^-_{(\xi_0, t_1)}(\mu, r_0)$, $B^-_{(\xi_1, t_1)}(\mu, r_0) \subset \Omega_0 \times (0, T)$, and $u(x, t) > 0$ for all points $(x, t)$ in $B^-_{(\xi_1, t_1)}(\mu, r_0) \setminus \{(\xi_0, t_0)\}$, where $\Omega_0$ is as in (1.6). $B^-_{(\xi_1, t_1)}(\mu, r_0)$ is as in (3.1), and $\partial B^-_{(\xi_1, t_1)}(\mu, r_0)$ is as in (3.2). Then we get the following assertions.

(i) If $p_- \leq 2$, then $\xi_0 = \xi_1$.

(ii) If $p_- = 2$ and $\mu > \frac{1}{4r_0} \left( \sum_{i=1}^{n} \left( \frac{p_i}{p_{-i-1}} \right)^{p_{-i}} \right)^2$, then $t_0 = t_1 - \sqrt{r_0/\mu}$.

(iii) If $p_- > 2$, then $t_0 \leq t_1$.

**Proof of Lemma 3.1.** We proceed by contradiction and assume that $\xi_0 \neq \xi_1$ if $p_- < 2$, either $\xi_0 \neq \xi_1$ or $t_0 > t_1$ if $p_- = 2$, and $t_0 > t_1$ if $p_- > 2$. Moreover, decreasing, if necessary, the real number $r_0$, we may assume that $u(x, t) > 0$ for all points $(x, t)$ on $\partial B^-_{(\xi_1, t_1)}(\mu, r_0) \setminus \{(\xi_0, t_0)\}$, where $\partial B^-_{(\xi_1, t_1)}(\mu, r_0)$ is as in (3.2). For any positive real numbers $\lambda$, $\mu$, and $\delta$, we define our test function $v_{\lambda,\mu,\delta}$ on $\mathbb{R}^n \times \mathbb{R}_+$ by
\[
v_{\lambda,\mu,\delta}(x) = \lambda \delta \left( e^{\lambda (r_0 - \sum_{i=1}^{n} (\lambda^2 \delta^{p_{-i}}))^{p_{-i}} |x_i - \xi_0, i = 1 \delta |^{p_{-i}} - p_{-i} \mu (r_0 - (1-i) \delta t_i)^{p_{-i}} - \delta t_0 - (1-i) \delta t_i)^{p_{-i}} - 1 \right),
\]
where $\xi_0 = (\xi_{0,1}, \ldots, \xi_{0,n})$ and $\xi_1 = (\xi_{1,1}, \ldots, \xi_{1,n})$. We find
\[
\frac{\partial v_{\lambda,\mu,\delta}}{\partial t}(x, t) = \frac{p_-}{p_- - 1} \lambda^2 \mu^{p_-} e^{\lambda (r_0 - \sum_{i=1}^{n} (\lambda^2 \delta^{p_{-i}}))^{p_{-i}} |x_i - \xi_0, i = 1 \delta |^{p_{-i}} - p_{-i} \mu (r_0 - (1-i) \delta t_i)^{p_{-i}} - \delta t_0 - (1-i) \delta t_i)^{p_{-i}} - 1} \times \left| \delta t_0 + (1-i) \delta t_i - t_1 \right|^{2-p_{-i}} \left( \delta t_0 + (1-i) \delta t_i - t_1 \right)^{p_{-i}}.
\]
Moreover, letting $\Delta_{\overline{p}}$ be as in (1.1), we find

$$
\Delta_{\overline{p}} v_{\lambda, \mu, \delta} (x, t) = \left( \lambda^2 \delta \right)^{p_-} \sum_{i=1}^{n} \left( \frac{p_i}{p_i - 1} \right)^{p_-} \times e^{(p_1 - 1)} \left( r_{0 - \sum_{j=1}^{n} (\lambda^2 \delta)_{p_j}^{p_j - p_i} |x_j - \delta \xi_{0,j} - (1 - \delta) \xi_{1,j}|^{p_j} - \mu |t - \delta t_0 - (1 - \delta) t_1|^{p_-} \right)
$$

As is easily seen, for $\delta$ small, for any $i = 1, \ldots, n$ and any point $(x, t)$ in $\mathbb{R}^n \times \mathbb{R}_+$, there holds

$$
|x_i - \delta \xi_{0,i} - (1 - \delta) \xi_{1,i}|^{\frac{p_i}{p_i - 1}} - |\xi_{0,i} - \xi_{1,i}|^{\frac{p_i}{p_i - 1}} \leq C \left( |\xi_{0,i} - \xi_{1,i}|^{\frac{1}{p_i - 1}} |x_i - \xi_{0,i}| + |x_i - \xi_{0,i}|^{\frac{p_i}{p_i - 1}} + \delta |\xi_{0,i} - \xi_{1,i}|^{\frac{p_i}{p_i - 1}} \right),
$$

and

$$
|t - \delta t_0 - (1 - \delta) t_1|^{\frac{1}{p_i - 1}} + |t - t_0|^{\frac{1}{p_i - 1}} \leq C \left( |t - t_0|^{\frac{1}{p_i - 1}} + |t - t_0|^{\frac{1}{p_i - 1}} + \delta |t - t_0 - (1 - \delta) t_1|^{\frac{1}{p_i - 1}} \right),
$$

for some positive constant $C$ independent of $\delta$, $x$, and $t$. For any positive real numbers $\mu$, $\delta$, and $\epsilon$, we define the ellipsoidal ball $B_{(\xi_{0, t_0})} (\mu, \delta, \epsilon)$ by

$$
B_{(\xi_{0, t_0})} (\mu, \delta, \epsilon) = \left\{ (x, s) \in \mathbb{R}^n \times \mathbb{R}_+; \sum_{i=1}^{n} \delta_{\frac{p_i}{p_i - 1}} |x_i - \xi_{0,i}|^{\frac{p_i}{p_i - 1}} + \mu |t - t_0|^{\frac{p_i}{p_i - 1}} < \epsilon \right\}.
$$

Clearly, for $\delta$ and $\epsilon$ small, $B_{(\xi_{0, t_0})} (\mu, \delta, \epsilon)$ is included in $\Omega \times (0, T)$. For any positive real numbers $\lambda$, $\mu$, $\delta$, $\epsilon$, and any point $(x, t)$ in $B_{(\xi_{0, t_0})} (\mu, \lambda^2 \delta, \epsilon)$, by (1.7), (3.3)–(3.8), and since
\((\xi_0, t_0) \in \partial B^p_{(\xi_1, t_1)} (\mu, r_0)\), we get

\[
\frac{\partial v_{\lambda, \mu, \delta}}{\partial t}(x, t) \leq \frac{p_-}{p_- - 1} \mu \lambda^2 \delta
\]

(3.10)

\[
\begin{aligned}
e^{C\lambda(\mu+1)}(\varepsilon^{-1(p_{i-1}+\delta)}) \left| t_1 - t_0 \right|^{2-p_-} (t_1 - t_0) + C \mu \left( \varepsilon^{-1(p_{i-1}+\delta)} \right) ) & \text{ if } p_- \leq 2 \text{ and } t_0 \leq t_1 \\
e^{-C\lambda(\mu+1)}(\varepsilon^{-1(p_{i-1}+\delta)} \left| t_1 - t_0 \right|^{2-p_-} (t_1 - t_0) \\
+ C \mu \left( \varepsilon^{-1(p_{i-1}+\delta)} \right) ) & \text{ if } p_- > 2 \text{ and } t_0 > t_1
\end{aligned}
\]

and

\[
-\Delta^p_{\varepsilon} v_{\lambda, \mu, \delta}(x, t) + f(v_{\lambda, \mu, \delta}(x, t)) \leq (\lambda \delta)^{p_- - 1} \left( \sum_{i=1}^{n} \left( \frac{p_i}{p_i - 1} \right) p_{i-1} \right) \lambda^{p_- - 1} e^{(p_{i-1} - 1)C\lambda(\mu+1)}(\varepsilon^{-1(p_{i-1}+\delta)}) \\
- \frac{p_- \lambda^{p_-}}{p_- - 1} \varepsilon^{-1(p_{i-1} - 1)C\lambda(\mu+1)}(\varepsilon^{-1(p_{i-1}+\delta)}) \left( r_0 - \mu \left| t_1 - t_0 \right|^{-\frac{p_-}{p_- - 1}} \right) \\
+ C e^{C\lambda(\mu+1)}(\varepsilon^{-1(p_{i-1}+\delta)}) \left( \varepsilon^{-1(p_{i-1}+\delta)} \right) + C \left( \varepsilon^{-1(p_{i-1}+\delta)} \right) - 1 \right]^{p_- - 1}) (3.11)
\]

when \(\delta, \varepsilon, \lambda (\mu + 1) (\varepsilon^{(p_{i-1})} + \delta)\) are small, for some positive constant \(C\) independent of \(\lambda, \mu, \delta, \varepsilon, x, \) and \(t\). In case \(p_- \leq 2\) and \(\xi_0 \neq \xi_1\), since \((\xi_0, t_0) \in \partial B^p_{(\xi_1, t_1)} (\mu, r_0)\), we get \(\mu \left| t_1 - t_0 \right|^{p_-/(p_- - 1)} < r_0\). We choose \(\lambda\) large enough so that

\[
\begin{aligned}
\lambda > \frac{(p_- - 1)^{p_- - 1}}{p_- - 1} \left( r_0 - \mu \left| t_1 - t_0 \right|^{-\frac{p_-}{p_- - 1}} \right) \sum_{i=1}^{n} \left( \frac{p_i}{p_i - 1} \right) p_{i-1} & \text{ if } p_- < 2 \text{ and } \xi_0 \neq \xi_1 \\
\lambda > \frac{1}{4(r_0 - \mu \left( t_1 - t_0 \right)^3) \left( 2\mu \left( t_1 - t_0 \right) + \sum_{i=1}^{n} \left( \frac{p_i}{p_i - 1} \right) p_{i-1} \right)} & \text{ if } p_- = 2 \text{ and } \xi_0 \neq \xi_1.
\end{aligned}
\]

(3.12)

It follows from (3.10), (3.11), and (3.12) that in case \(p_- \leq 2\) and \(\xi_0 \neq \xi_1\), for \(\delta\) and \(\varepsilon\) small, the function \(v_{\lambda, \mu, \delta}\) is a \(C^1\)-solution of the inequality

\[
\frac{\partial v_{\lambda, \mu, \delta}}{\partial t} - \Delta^p_{\varepsilon} v_{\lambda, \mu, \delta} + f(v_{\lambda, \mu, \delta}) < 0 \quad \text{in } B^p_{(\xi_0, t_0)} (\mu, \lambda^2 \delta, \varepsilon),
\]

(3.13)

where \(B^p_{(\xi_0, t_0)} (\mu, \lambda^2 \delta, \varepsilon)\) is as in (3.9). In case \(p_- = 2\) and \(t_0 = t_1 + \sqrt{r_0/\mu}\), we assume that \(\mu > \frac{1}{4\varepsilon} \left( \sum_{i=1}^{n} \left( \frac{p_i}{p_i - 1} \right) p_{i-1} \right)^2\), we let \(\lambda\) be an arbitrary positive real number, and we also find (3.13) for \(\delta\) and \(\varepsilon\) small. In case \(p_- > 2\) and \(t_0 > t_1\), without assumption on \(\lambda\) and \(\mu\), we still get (3.13) for \(\delta\) and \(\varepsilon\) small. Now, we claim that there exists a positive constant \(C\) such that \(u \geq C \varepsilon \) on \(B^p_{(\xi_1, t_1 - \delta)} (\mu, \lambda^2 \delta, r_0) \cap \partial B^p_{(\xi_0, t_0)} (\mu, \lambda^2 \delta, \varepsilon)\) for \(\delta\) small, where \((\xi_1, t_1 - \delta) := \delta (\xi_0, t_0) + (1 - \delta) (\xi_1, t_1)\), and \(B^p_{(\xi_1, t_1 - \delta)} (\mu, \lambda^2 \delta, r_0)\), \(B^p_{(\xi_0, t_0)} (\mu, \lambda^2 \delta, \varepsilon)\) are as in (3.9). In order to prove this claim, we proceed by contradiction and assume that there exist a sequence of
positive real numbers $\left(\delta_{\alpha}\right)_{\alpha}$ and a sequence of points $\left(\xi_{\alpha}, t_{\alpha}\right)_{\alpha}$ such that $\delta_{\alpha} \to 0$, $u(\xi_{\alpha}, t_{\alpha}) \to 0$ as $\alpha \to +\infty$, and $\left(\xi_{\alpha}, t_{\alpha}\right) \in B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, r_0) \cap \partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{P}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$ for all $\alpha$. Up to a subsequence, we get that $\left(\xi_{\alpha}, t_{\alpha}\right)$ converges to a point $(\xi_\infty, t_\infty)$ in $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, r_0) \cap \partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{P}}(\mu, \varepsilon)$, where $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, r_0)$ and $\partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{P}}(\mu, \varepsilon)$ are as in (3.1) and (3.2). By continuity of the function $u$, we get $u(\xi_\infty, t_\infty) = 0$, and thus $(\xi_\infty, t_\infty) = (\xi_0, t_0)$. Since $(\xi_{\alpha}, t_{\alpha}) \in B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, r_0)$ for all $\alpha$ and since $\xi_{1,i} = \xi_{0,i}$ for all $i > n$, then it follows that

$$
\sum_{i=n+1}^{n} \left(\lambda^2 \delta_{\alpha}\right) \frac{p_{\alpha,i} - p_{i}}{p_{\alpha,i}} \left|\xi_{\alpha,i} - \xi_{0,i}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - p_i}} < r_0 - \mu \left|t_{\alpha} - t_{1-\delta_{\alpha}}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - 1}} - \sum_{i=1}^{n} \left|\xi_{\alpha,i} - \xi_{1-\delta_{\alpha},i}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - 1}} = o(1) \tag{1}
$$

as $\alpha \to +\infty$. On the other hand, since $(\xi_{\alpha}, t_{\alpha}) \in \partial B_{(\xi_0, t_0)}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$ for all $\alpha$, we get

$$
\sum_{i=n+1}^{n} \left(\lambda^2 \delta_{\alpha}\right) \frac{p_{\alpha,i} - p_{i}}{p_{\alpha,i}} \left|\xi_{\alpha,i} - \xi_{0,i}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - p_i}} = \varepsilon - \mu \left|t_{\alpha} - t_{0}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - 1}} - \sum_{i=1}^{n} \left|\xi_{\alpha,i} - \xi_{0,i}\right|^{\frac{p_{\alpha,i}}{p_{\alpha,i} - 1}} = \varepsilon + o(1) \tag{1.15}
$$

as $\alpha \to +\infty$. There is a contradiction between (3.14) and (3.15). This ends the proof of our claim, namely that $u \geq C_\varepsilon$ on $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, r_0) \cap \partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{P}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$ for $\delta$ small, for some positive constant $C_\varepsilon$. Since $v_{\lambda, \mu, \delta} \leq \lambda^2 \mu (e^{\lambda^2 \mu - 1})$ in $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, r_0)$ and $v_{\lambda, \mu, \delta} \leq 0$ in $(\mathbb{R}^n \times \mathbb{R}_+)^c \setminus B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, r_0)$, we then get $v_{\lambda, \mu, \delta} \leq u$ on $\partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$ for $\delta$ small. In particular, there holds $(v_{\lambda, \mu, \delta} - u)_+ = 0$ on $\partial B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon) = (\lambda, \mu, \delta, u_+), \max(v_{\lambda, \mu, \delta} - u_+)$, testing (1.8) and (3.13) against $(v_{\lambda, \mu, \delta} - u)_+$ on $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$ (up to an approximation in terms of Steklov averages, see, for instance, DiBenedetto [15]), we get

$$
\frac{1}{2} \int_{W_{\lambda, \mu, \delta, t}} \left|v_{\lambda, \mu, \delta} - u\right|^2 dx
$$

$$
+ \sum_{i=1}^{n} \int_{0}^{t} \int_{W_{\lambda, \mu, \delta, t}} \left(\frac{\partial v_{\lambda, \mu, \delta}}{\partial x_i} \right|_{t}^{p_{\alpha,i} - p_{i}} \frac{\partial v_{\lambda, \mu, \delta}}{\partial x_i} - \frac{\partial u}{\partial x_i} \left|_{t}^{p_{\alpha,i} - p_{i}} \frac{\partial u}{\partial x_i} \right) \left(\frac{\partial v_{\lambda, \mu, \delta}}{\partial x_i} - \frac{\partial u}{\partial x_i} \right) dx ds
$$

$$
+ \int_{0}^{t} \int_{W_{\lambda, \mu, \delta, t}} \left( f(v_{\lambda, \mu, \delta}) - f(u) \right) (v_{\lambda, \mu, \delta} - u) dx ds \leq 0 \tag{1.16}
$$

for all real numbers $t$ in $(0, T)$, where

$$
W_{\lambda, \mu, \delta, t} = \left\{ x \in \mathbb{R}^n ; \ (x, t) \in B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon) \text{ and } v_{\lambda, \mu, \delta}(x, t) > u(x, t) \right\}.
$$

Since the function $f$ is nondecreasing, it follows from (3.16) that for any real number $t$ in $(0, T)$, there holds

$$
\int_{W_{\lambda, \mu, \delta, t}} \left|v_{\lambda, \mu, \delta} - u\right|^2 dx = 0.
$$

We then get $|W_{\lambda, \mu, \delta, t}| = 0$, i.e. $v_{\lambda, \mu, \delta} \leq u$ in $B_{(\xi_{\alpha}, t_{\alpha})}^{\mathbb{B}}(\mu, \lambda^2 \delta_{\alpha}, \varepsilon)$. In particular, we get $u(\xi_0, t_0) \geq v_{\lambda, \mu, \delta}(\xi_0, t_0) > 0$. There is a contradiction. This ends the proof of Lemma 3.1.

Now, we can prove Theorem 1.2 by using Lemma 3.1.

**Proof of Theorem 1.2.** To begin with, we assume that $p_- \leq 2$ and prove that the function $u$ is identically zero on the set $\Omega_0 \times \{t_0\}$, where $\Omega_0$ is as in (1.6). We let $P$ be the set of points $(x, t)$ in $\Omega \times (0, T)$ such that $u(x, t) > 0$. We proceed by contradiction and assume
that $P \cap (\Omega_0 \times \{t_0\})$ is not empty. In a similar way as in the proof of Theorem 1.1, we can choose a positive real number $r_0$ and two points $z_0 = (z_{0,1}, \ldots, z_{0,n})$ and $\xi_1 = (\xi_{1,1}, \ldots, \xi_{1,n})$ in $\Omega_0$ such that $u(z_0, t_0) = 0$, $z_0 \in \partial B^P_{\xi_1}(r_0)$, and $B^P_{\xi_1}(r_0) \times \{t_0\} \subset P$, where $B^P_{\xi_1}(r_0)$ and $\partial B^P_{\xi_1}(r_0)$ are as in (2.2) and (2.3). We let $h : [0, 1] \to \mathbb{R}_+$ be defined by

$$h(\delta) = \inf_{(x, t) \in (\Omega_0 \times (0, T)) \setminus P} \left( \sum_{i=1}^n |x_i - \xi_{1,i} - (1 - \delta) z_{0,i}|^{p_{i,-1}} + |t - t_0|^{1/p_{i,-1}} \right).$$

(3.17)

Since $u(z_0, t_0) = 0$, we get $h(\delta) \to 0$ as $\delta \to 0$. In particular, we get $\partial B^P_{\xi_1 + (1 - \delta) z_0, t_0}(1, h(\delta)) \subset \Omega_0 \times (0, T)$ and $B^P_{\xi_1 + (1 - \delta) z_0, t_0}(1, h(\delta)) \subset P$ for $\delta$ small, where $B^P_{\xi_1 + (1 - \delta) z_0, t_0}(1, h(\delta))$ and $\partial B^P_{\xi_1 + (1 - \delta) z_0, t_0}(1, h(\delta))$ are as in (3.1) and (3.2). Since $P$ is open, it follows that for $\delta$ small, the infimum in (3.17) is achieved, i.e. there exists a point $(z_\delta, t_\delta)$ on $\partial B^P_{\xi_1 + (1 - \delta) z_0, t_0}(1, h(\delta))$ such that $u(z_\delta, t_\delta) = 0$. By Lemma 3.1, we get $z_\delta = \delta \xi_1 + (1 - \delta) z_0$, and thus $h(\delta) = |t_\delta - t_0|^{p_{i,-1}}$ for $\delta$ small. It follows from (3.17) that for $\delta_1$ and $\delta_2$ small, there holds

$$h(\delta_1) \leq \sum_{i=1}^n |\xi_{1,i} - z_{0,i}|^{p_{i,-1}} |\delta_2 - \delta_1|^{1/p_{i,-1}} + h(\delta_2).$$

In particular, for $\delta$ small, the function $h$ is differentiable and $h' = 0$ on $[0, \delta]$. It follows that the function $h$ is constant on $[0, \delta]$. Since $h(0) = 0$, we then get $h = 0$ on $[0, \delta]$, i.e. $u = 0$ on $[\delta \xi_1 + (1 - \delta) z_0, 0] \times \{t_0\}$. There is a contradiction. This ends the proof of the first part of Theorem 1.2. Now, we assume that $p_\ast \geq 2$, and we prove that the function $u$ is identically zero on the set $\{z_0\} \times (0, t_0)$. We proceed by contradiction and assume that there exists a real number $t_1$ in $(0, t_0)$ such that $u(z_0, t_1) > 0$. Since $P$ is open, we get $B^P_{z_0, t_1}(\mu, \varepsilon) \subset P$ for $\mu$ large and $\varepsilon$ small, where $B^P_{z_0, t_1}(\mu, \varepsilon)$ is as in (3.1). We may assume that the real number $\mu$ is large enough so that $\mu > \frac{1}{2\varepsilon} \sum_{i=1}^n \left( \frac{p_{i}}{p_{i,-1}} \right)^{p_{i,-1}}$. Increasing, if necessary, the real number $t_1$, since $P$ is open, we may assume that

$$t_1 = \sup \left\{ t \in (0, t_0); \quad B^P_{z_0, t_1}(\mu, \varepsilon) \subset P \right\}.$$

It follows that there exists a point $(z_2, t_2)$ on $\partial B^P_{z_0, t_1}(\mu, \varepsilon)$ such that $t_2 > t_1$ and $u(z_2, t_2) = 0$. We get a contradiction with Lemma 3.1. This ends the proof of Theorem 1.2.

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