A FREE BOUNDARY PROBLEM ARISING IN MAGNETOHYDRODYNAMIC SYSTEM

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A FREE BOUNDARY PROBLEM ARISING IN MAGNETOHYDRODYNAMIC SYSTEM

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1. The plasma problem. We shall consider a two-dimensional problem arising in magnetohydrodynamic (MHD) system, modeling the plasma confinement in the Tokamak machine.

Let $\Omega$ be a bounded domain in $\mathbb{R}^2$, representing the cross-section of perfectly electrically conducting shell. As shown in Figure 1, the plasma fills a subdomain $\Omega_p$ of $\Omega$, with boundary $\Gamma_p$; the complimentary domain $\Omega \setminus \Omega_p$ is the vacuum region $\Omega_v$.

![Figure 1](image)

Let $\vec{B}, \vec{J}$ and $P$ denote the magnetic induction, the current density and the fluid pressure, respectively. In equilibrium, the triple $(\vec{B}, \vec{J}, P)$ satisfies the MHD system:

\begin{align}
\text{(1.1) } \quad \text{div } \vec{B} &= 0, \quad \text{rot } \vec{B} = \mu_0 \vec{J}, \quad \text{grad } P = \vec{J} \times \vec{B} \quad \text{in } \Omega_p, \\
\text{(1.2) } \quad \text{div } \vec{B} &= 0, \quad \text{rot } \vec{B} = 0, \quad P = 0 \quad \text{in } \Omega_v, \\
\text{(1.3) } \quad \vec{B} \cdot \nu &= 0 \quad \text{on } \Gamma_p \text{ and on } \partial \Omega, \\
\text{(1.4) } \quad P + \frac{1}{2\mu_0} B_p^2 &= \frac{1}{2\mu_0} B_v^2 \quad \text{on } \Gamma_p
\end{align}

where $\mu_0$ is the magnetic permeability of the vacuum, $\nu$ is the outward unit normal, $B^2 = \vec{B} \cdot \vec{B}$, and the subscripts $p$ and $v$ denote, respectively, the subscripted quantities from the interior of the plasma region $\Omega_p$ and the vacuum region $\Omega_v$.

The first two equations in (1.1) and (1.2) are Maxwell's equations, the third equation in (1.1) is the equation of plasma motion in the stationary case, and (1.4) is the pressure balance condition.

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Since we are considering here the two-dimensional problem (where \( \Omega \) is viewed as a cross-section \( x_3 = 0 \) of an infinite cylinder), \( \vec{B}, \vec{J} \) and \( P \) depend only on the variables \( x_1, x_2 \).

Since \( \text{div} \vec{B} = 0 \), we can introduce locally a flux function \( u \) by

\[
\vec{B} = (u_{x_2}, -u_{x_1}, 0)
\]

(assuming that the vector \( \vec{B} \) lies in the two-dimensional space \( \mathbb{R}^2 \)); since, by (1.3), \( \partial u / \partial \tau = 0 \) on \( \Gamma_p \) where \( \tau \) is the unit tangent vector, \( u \) is a single-valued function in the whole domain \( \Omega \), uniquely determined up to an additive constant. It is easy to verify that

\[
\text{rot} \vec{B} = - (\Delta u) \hat{k},
\]

and then, by (1.1) and (1.2),

\[
\Delta u = - \mu_0 J \text{ in } \Omega_p \text{ where } \vec{J} = (0, 0, J),
\]

\[
\Delta u = 0 \text{ in } \Omega_v.
\]

Since \( \vec{J} \times \vec{B} = J \nabla u \), the third equation in (1.1) becomes

\[
\nabla P = J \nabla u.
\]

Therefore \( \nabla P \) is parallel to \( \nabla u \). This implies that \( P \) depends only on \( u \), that is,

\[
P = g(u)
\]

where \( g \) is an unknown function. This function cannot be determined by the Maxwell equations; it is a constitutive function for the plasma. Equations (1.9) and (1.10) imply that

\[
J = g'(u),
\]

so that (1.7) can be written in the form

\[
\Delta u = - \mu_0 g'(u) \text{ in } \Omega_p.
\]

The boundary condition (1.3) implies that

\[
\frac{\partial u}{\partial \tau} = 0 \text{ on } \Gamma_p \cup \partial \Omega
\]

where \( \tau \) is the unit tangent vector. It follows that \( u \) is constant on \( \Gamma_p \) and on \( \partial \Omega \), and we determine \( u \) uniquely by taking

\[
u = 0 \text{ on } \Gamma_p.
\]

We also set

\[
u = \gamma \text{ on } \partial \Omega,
\]

where \( \gamma \) is an unspecified constant which we take to be positive.
Finally, condition (1.4) can be written as

\[ |\nabla u|^2 - |\nabla u_p|^2 = 2 \mu_0 P = 2 \mu_0 g(0) \quad \text{on} \quad \Gamma_p \]

and, in general, \( g(0) > 0 \). This condition formally coincides with Bernoulli’s condition for two-fluid flow.

Temam [21, 22] considered the model with

\[ P = g(u) = au^2 \quad (a > 0); \]

in this case \( P = 0 \) on \( \Gamma_p \) and the system (1.8), (1.12), (1.14)–(1.16) reduces to

\[ \Delta u - \lambda u_\gamma = 0 \quad \text{in} \quad \Omega, \quad u = \gamma \quad \text{on} \quad \partial \Omega, \]

where \( u_\gamma = -\min\{u, 0\} \).

More realistic models with \( P > 0 \) on \( \Gamma_p \) were considered by Grad, Kadish and Stevens [15] and by Ushijima [23]. Here we shall assume the constitutive law

\[ g(u) = au^2 + b \quad \text{with} \quad a > 0, \quad b > 0, \]

so that \( P > 0 \) on \( \Gamma_p \).

In [21] \( \lambda = 2a\mu_0 \) is unspecified positive constant whereas either the constant \( \gamma \) or the flux

\[ \int_{\partial \Omega} \frac{\partial u}{\partial n} ds = I \]

are specified; furthermore, the condition

\[ \int_{\Omega} u_\gamma^2 = K \quad (K \text{ is given}) \]

is imposed. In [22] \( \lambda \) is prescribed but the condition (1.20) is dropped.

In our formulation of the plasma problem we shall assume that \( \gamma \) and \( b \) are given, and that \( a \) is unknown (which means that \( \Delta u_\gamma + \lambda u_\gamma = 0 \) holds in \( \Omega_p \) with unknown positive constant \( \lambda \)). We also impose the additional condition (1.20), where \( K \) is given.

Other formulations are also possible; for example, one may prescribe \( \lambda \) and drop the condition (1.20). Since we do not prove here uniqueness and continuous dependence of the solution on the parameter \( K \), the two formulations may not be equivalent. Furthermore, when \( \gamma \) is unprescribed and, instead, the condition (1.19) is imposed, we get yet another different version of the problem. We have chosen the present formulation of prescribing \( \gamma, b \) and \( K \) because it is technically the easiest: it lends itself more directly to a variational formulation. We hope to consider other formulations in a later work.

In the next section we rewrite the plasma problem with slightly normalized constants, and describe the main results and the structure of the paper. Many of the results of this paper are valid in \( n \)-dimensions. For this reason we shall assume that \( \Omega \) is \( n \)-dimensional where \( n \geq 2 \), unless the contrary is explicitly stated.
2. Mathematical formulation; the structure of the paper. Let \( \Omega \) be a bounded domain in \( \mathbb{R}^n \) with \( C^2 \) boundary \( \partial \Omega \), and let \( \gamma \) and \( \mu^2 \) be given positive constants. The *plasma problem* is to find a function \( u \), a closed surface \( \Gamma_p \) lying in \( \Omega \) and a positive constant \( \lambda \) such that

\[
\Delta u + \lambda u = 0 \quad \text{in} \; \Omega_p = \text{int}\{x \in \Omega, u(x) \leq 0\},
\]

\[
\Delta u = 0 \quad \text{in} \; \Omega_v = \{x \in \Omega, u(x) > 0\},
\]

\[
u = \gamma \quad \text{on} \; \partial \Omega,
\]

\[
u = 0 \quad \text{on} \; \Gamma_p \; \text{where} \; \Gamma_p = \partial \Omega_p,
\]

\[
|\nabla u_+|^2 - |\nabla u_-|^2 = \mu^2 \quad \text{on} \; \Gamma_p
\]

and

\[
\int_{\Omega} u_-^2 = 1;
\]

here \( \nabla u_- (\nabla u_+) \) denotes the limit of \( \nabla u \) from \( \Omega_p (\Omega_v) \).

In this paper we shall prove that for \( n = 2 \) there exists a solution to the plasma problem and that \( \Gamma_p \) is continuously differentiable and, in fact, analytic; the open set \( \Omega_v \) is connected, but \( \Omega_p \) may have several components \( G_1, \ldots, G_N \). There is however only one component, say \( G_1 \), in which \( u < 0 \) everywhere; in all the other components \( u \) vanishes identically. For the simpler plasma model with (1.17), it is known [19] (see also [13; pp. 529–531]) that for any variational solution \( \Omega_p \) has a single component.

For \( n \geq 3 \) there still exists a solution of the plasma problem and \( u \) is Lipschitz continuous, but the free boundary condition (2.5) is satisfied only in a weak sense. (We do not establish here the regularity of the free surface).

Our approach is based on variational methods of Alt and Caffarelli [2], and Alt, Caffarelli and Friedman [3], and the more recent papers of Caffarelli [5] [6] [7].

The structure of the paper is as follows:

In §3 we introduce a variational formulation of the plasma problem with a functional \( J(u) \) as in [3] but with the integral constraint (2.6). We establish several simple properties of the minimizers, such as subharmonicity, and a weak form of the free boundary condition. However the integral constraint does not allow us to adapt any of the deeper results from [3]. We can partially overcome this difficulty by introducing, in §4, another variational problem which does not have any constraints in the admissible classes but, instead, has a new and a bit more complicated functional, \( J_\eta(u) \), namely:

\[
J_\eta(u) = J(u) - \eta \left( \int_{\Omega} u_-^2 \right)
\]
where

\[ f_\eta(s) = \begin{cases} \frac{1}{\eta} (s - 1) & \text{if } s < 1 \\ \eta (s - 1) & \text{if } s \geq 1 \end{cases} \]

and \( \eta \ll 1 \). Any minimizer of \( J_\eta \) is shown to be also a minimizer of \( J \), and for the rest of the paper we study only minimizers of \( J_\eta \).

In §5 we derive \( C^\alpha \) regularity of any minimizer \( u \), and in §6 we prove nondegeneracy. These results are obtained by adapting methods of [3]. The next fundamental result, proved in §7, is the monotonicity theorem which asserts that

\[ r \to \frac{1}{r^4} \int_{B_r} \rho^{2-n} |\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n} |\nabla u_-|^2 \cdot e^{\alpha \lambda r^2 - \frac{1-\alpha}{\alpha} N} \]

is monotone increasing in \( r \). This is an extension of a monotonicity theorem proved in [3] in case \( \lambda = 0 \), and it can be used, precisely as in [3], to establish the Lipschitz continuity of \( u \).

In §8 we consider blow-up sequences and identify their limits. In §9 we begin the initial study of the free boundary, showing that \( \Delta u_+ \) and \( \Delta u_- + \lambda u_- \) are measures supported on the free boundary, absolutely continuous with respect to \( dH^{n-1} \). The results of §§8, 9 are similar to those in [3]; see also [2].

In establishing the regularity of the free boundary in [3] the following comparison result (Lemma 8.1 in [3]) was crucial: if \( u, \bar{u} \) are minimizers and \( u > \bar{u} \) on the boundary then \( u > \bar{u} \) in the entire domain. This lemma is no longer true in our case (where \( \lambda > 0 \)). We therefore proceed in entirely different way, adapting the recent Harnack inequality approach of Caffarelli [5] [6] for weak solutions.

We begin, in §10, by introducing weak solutions and subsolutions. In [5] Caffarelli constructed a large class of subsolutions which he used to establish the regularity of “flat” free boundaries. In our case, where \( \lambda > 0 \), we can only construct a much smaller class of subsolutions. However by exploiting additional ideas from [3] we shall be able, nevertheless, to establish (in subsequent sections) the regularity of the free boundary.

In §11 we introduce (as in [6]) the concept of \( \varepsilon \)-monotonicity and prove (Theorem 11.3) that

(i) \( \varepsilon \)-monotonicity,
(ii) flatness, and
(iii) full monotonicity at the boundary

imply Lipschitz continuity of the free boundary of a weak solution.

In §13 we improve Theorem 11.3 by showing that assumption (i) is always satisfied; this is Theorem 13.2. The proof which is an adaptation from Caffarelli’s paper [6] requires several auxiliary estimates, some of which are proved in §12. (In case \( \lambda = 0 \) the condition (iii) was not assumed in [6]; it was in fact verified by using the much larger family of subsolutions available in case \( \lambda = 0 \).)

In §14 it is shown that minimizers of \( J_\eta \) are weak solutions. At this point we go back to adapt some results from [3] in order to show that the assumption (iii) above is satisfied by any minimizer. Since for \( n = 2 \) assumption (ii) is also satisfied (as proved in §8 of [3]), we conclude that for \( n = 2 \) the free boundary is Lipschitz continuous and, in fact, it is also continuously differentiable and \( \nabla u_\pm \) is continuous up to the boundary. In §15 we establish the
$C^{1+\alpha}$ smoothness of the free boundary; the analyticity of the free boundary then follows by known techniques.

The sets $\Omega_+ \equiv \Omega_+(u) = \{ x \in \Omega, u(x) > 0 \}$, $\Omega_- \equiv \Omega_-(u) = \text{int} \{ x \in \Omega, u(x) \leq 0 \}$ are open and $\Omega_+(u)$ contains a neighborhood of $\partial \Omega$. In §16 we prove that $\Omega_+(u)$ is connected, whereas $\Omega_-(u)$ consists of a finite number of components $G_1, \ldots, G_N$. In just one component, say $G_1, u < 0$ throughout. In all other components $G_j, u \equiv 0$; such components do in fact exist for some domains $\Omega$.

3. A variational problem. We introduce the admissible class

$$K = \{ v \in H^1(\Omega), \ v = \gamma \text{ on } \partial \Omega, \int_\Omega v^2 = 1 \}$$

and the functional

$$(3.1) \quad J(v) = \int_\Omega \left[ |\nabla v|^2 + \mu_-^2 I_{\{v \leq 0\}} + \mu_+^2 I_{\{v > 0\}} \right]$$

where $\mu_-, \mu_+$ are positive constants satisfying

$$\mu_+^2 - \mu_-^2 = \mu^2$$

and $I_A$ denotes the characteristic function of a set $A$.

**Problem (J).** Find $u \in K$ such that

$$J(u) = \min_{v \in K} J(v).$$

This variational problem is a generalization of the one introduced by Temam [21] for the case $\mu_+ = \mu_- = 0$.

**Theorem 3.1.** There exists a solution of problem (J).

The proof is the same as for Theorem 1.1 of [3]. We denote a solution by $u$, and proceed to establish some basic properties.

**Theorem 3.2.** The solution $u$ is subharmonic in $\Omega$.

**Proof.** Take any $\xi \in C^1_0(\Omega), \xi \geq 0$ and $\varepsilon > 0$, and set

$$(3.2) \quad \tilde{u}_\varepsilon = u - \varepsilon \xi$$

and

$$(3.3) \quad u_\varepsilon = -\sqrt{a_\varepsilon} (\tilde{u}_\varepsilon)_- + (\tilde{u}_\varepsilon)_+, \ a_\varepsilon = 1/\int_\Omega (\tilde{u}_\varepsilon)_-^2.$$

Then $u_\varepsilon \in K$ and

$$0 \leq J(u_\varepsilon) - J(u)$$

$$= a_\varepsilon \int_\Omega \left[ |\nabla (\tilde{u}_\varepsilon)_-|^2 + |\nabla (\tilde{u}_\varepsilon)_+|^2 + \mu_-^2 I_{\{u_\varepsilon \leq 0\}} + \mu_+^2 I_{\{u_\varepsilon > 0\}} \right]$$

$$- \int_\Omega \left[ |\nabla u|^2 + \mu_-^2 I_{\{u \leq 0\}} + \mu_+^2 I_{\{u > 0\}} \right]$$

$$= a_\varepsilon \int_\Omega \left[ |\nabla \tilde{u}_\varepsilon|^2 - |\nabla u|^2 \right] + (a_\varepsilon - 1) \int_\Omega |\nabla u|^2 + \int_\Omega (|\nabla \tilde{u}_\varepsilon|^2 - |\nabla u|^2)$$

$$+ \int_\Omega \mu_-^2 I_{\{\tilde{u}_\varepsilon \leq 0\}} - \int_\Omega \mu_-^2 I_{\{u \leq 0\}} + \int_\Omega \mu_+^2 I_{\{\tilde{u}_\varepsilon > 0\}} - \int_\Omega \mu_+^2 I_{\{u > 0\}}.$$
where we have used the fact that $\text{sgn } u_\varepsilon = \text{sgn } \tilde{u}_\varepsilon$.

Since $a_\varepsilon = 1 + o(1)$ and

$$\frac{a_\varepsilon - 1}{\varepsilon} = \frac{1}{\varepsilon} \int_\Omega \frac{1}{(\tilde{u}_\varepsilon)^2_+} \left[ \int u_\varepsilon^2 - \int (\tilde{u}_\varepsilon)^2 \right]$$

$$= \frac{1}{\varepsilon} \int_\Omega (u_\varepsilon - (u - \varepsilon \xi)^2) \to -2 \int_\Omega u_\varepsilon \xi \leq 0 \text{ as } \varepsilon \to 0,$$

we have

$$0 \leq (1 + o(1))(-2\varepsilon) \int_{\{u_\varepsilon \leq 0\}} \nabla u \cdot \nabla \xi - 2\varepsilon \int_{\{u_\varepsilon > 0\}} \nabla u \cdot \nabla \xi$$

$$+ \int_{\{u \leq \varepsilon \xi\}} \mu_-^2 - \int_{\{u \geq \varepsilon \xi\}} \mu_+^2 + \int_{\{u > \varepsilon \xi\}} \mu_+^2 - \int_{\{u > 0\}} \mu_+^2 + o(\varepsilon)$$

$$= -2\varepsilon \int_\Omega \nabla u \cdot \nabla \xi - \int_{\{0 < u \leq \varepsilon \xi\}} \mu^2 + o(\varepsilon) \leq -2\varepsilon \int_\Omega \nabla u \cdot \nabla \xi + o(\varepsilon).$$

It follows that

$$\int_\Omega \nabla u \cdot \nabla \xi \leq 0 \quad \forall \xi \in C^1_0(\Omega), \xi \geq 0,$$

and the proof is complete.

For the next result we temporarily assume that $u$ is continuous in $\bar{\Omega}$. Then $\Omega_p = \text{int } \{x \in \Omega, u(x) \leq 0\}$, $\hat{\Omega}_p = \{x \in \Omega, u(x) < 0\}$, and $\Omega_v = \{x \in \Omega, u(x) > 0\}$ are nonempty open subsets of $\Omega$ and $\Omega_p \subset \Omega$.

**Theorem 3.3.** If $u$ is continuous in $\bar{\Omega}$ then

$$\Delta u + \lambda u = 0 \quad \text{in } \hat{\Omega}_p$$

where

$$\lambda = \int_\Omega |\nabla u_\varepsilon|^2,$$

and

$$\Delta u = 0 \quad \text{in } \Omega_v.$$

**Proof.** For any $\xi \in C^1_0(\hat{\Omega}_p)$ take $\varepsilon > 0$ with $|\xi|$ sufficiently small so that $u - \varepsilon \xi < 0$ in $\hat{\Omega}_p$, and define $u_\varepsilon$ as before, by (3.3), (3.2). Then $\text{sgn } u_\varepsilon = \text{sgn } u$ and $u_\varepsilon = u$ in $\Omega \setminus \hat{\Omega}_p$ and, since $u_\varepsilon \in K$,

$$0 \leq J(u_\varepsilon) - J(u) = a_\varepsilon \int_{\hat{\Omega}_p} [ |\nabla (u - \varepsilon \xi)|^2 - |\nabla u|^2 ] + (a_\varepsilon - 1) \int_{\hat{\Omega}_p} |\nabla u|^2$$

$$= -2\varepsilon a_\varepsilon \int_{\hat{\Omega}_p} \nabla u \cdot \nabla \xi + \lambda (a_\varepsilon - 1) + o(\varepsilon).$$
Recalling (3.4) we get

\[- \int_{\partial \Omega_p} \nabla u \cdot \nabla \xi + \lambda \int_{\partial \Omega_p} u \xi = 0 \quad \forall \xi \in C^1_0(\Omega_p),\]

i.e., (3.5) holds. The proof of (3.7) is similar.

The set \( \Gamma_p = \partial \Omega_p \cap \partial \Omega_u \) is called the strict free boundary. The next theorem shows that \( u \) satisfies, in a generalized sense, the equation

\[|\nabla u_+|^2 - |\nabla u_-|^2 = \mu_+^2 - \mu_-^2 = \mu^2 \quad \text{on} \quad \Gamma_p.\]

provided the set \( \{u = 0\} \) has zero measure.

**Theorem 3.4.** Let \( \Omega_0 \) be any open subset of \( \Omega \). If \( u \) is continuous in \( \Omega_0 \) and \( \text{meas}\{x \in \Omega_0, u(x) = 0\} = 0 \) then, for any \( \eta \in C^3(\Omega_0, \mathbb{R}^n) \),

\[
\lim_{\varepsilon \to 0} \int_{\partial\{u < \varepsilon\}} (|\nabla u|^2 - \mu_-^2) \eta \cdot \nu + \lim_{\delta \to 0} \int_{\partial\{u > \delta\}} (|\nabla u|^2 - \mu_+^2) \eta \cdot \nu = 0
\]

where \( \nu \) is the outward normal.

Here \( \varepsilon \) and \( \delta \) are such that \( \partial\{u < \varepsilon\} \) and \( \partial\{u > \delta\} \) are continuously differentiable; by Sard’s theorem this is true for a.a. \( \varepsilon \) and \( \delta \).

**Proof.** For simplicity of notation we take \( \Omega_0 = \Omega \). Following the proof of Theorem 2.4 in [3] we define, for any \( \varepsilon > 0 \) with small \( |\varepsilon| \), diffeomorphism

\[\tau_\varepsilon : \Omega \to \Omega \]

by \( \tau_\varepsilon(x) = x + \varepsilon \eta(x) \) and set \( \tilde{u}_\varepsilon(\tau_\varepsilon(x)) = u(x) \). Next we introduce a function

\[u_\varepsilon = -\sqrt{a_\varepsilon} (\tilde{u}_\varepsilon)_- + (\tilde{u}_\varepsilon)_+, \quad a_\varepsilon = 1/ \int_{\tilde{\Omega}} (\tilde{u}_\varepsilon)^2.\]

Then \( u_\varepsilon \in K \) and

\[0 \leq J(u_\varepsilon) - J(u) = a_\varepsilon \int_{\tilde{\Omega}} |\nabla u_-(D\tau_\varepsilon)^{-1}|^2 \det(D\tau_\varepsilon) + \int_{\tilde{\Omega}} |\nabla u_+(D\tau_\varepsilon)^{-1}|^2 \det(D\tau_\varepsilon)\]

\[+ \int_{\tilde{\Omega}} \mu_-^2 I_{\{u_-(x) \leq 0\}} \det(D\tau_\varepsilon) + \int_{\tilde{\Omega}} \mu_+^2 I_{\{u_+(x) > 0\}} \det(D\tau_\varepsilon)\]

\[\leq - \int_{\tilde{\Omega}} |\nabla u|^2 - \int_{\tilde{\Omega}} \mu_-^2 I_{\{u \leq 0\}} - \int_{\tilde{\Omega}} \mu_+^2 I_{\{u > 0\}}.\]

Since \((D\tau_\varepsilon)^{-1} = 1 - \varepsilon D\eta + o(\varepsilon), \det(D\tau_\varepsilon) = 1 + \varepsilon \nabla \cdot \eta + o(\varepsilon) \) and \( u_\varepsilon(\tau_\varepsilon(x)) = -\sqrt{a_\varepsilon} u_-(x) + u_+(x) \),

we obtain, after simple calculation,

\[0 \leq (a_\varepsilon - 1) \int_{\tilde{\Omega}} |\nabla u_-|^2 - 2\varepsilon a_\varepsilon \int_{\tilde{\Omega}} \nabla u_- D\eta \nabla u_- - 2\varepsilon \int_{\tilde{\Omega}} \nabla u_+ D\eta \nabla u_+\]

\[+ \varepsilon a_\varepsilon \int_{\tilde{\Omega}} |\nabla u_-|^2 \nabla \cdot \eta + \varepsilon \int_{\tilde{\Omega}} |\nabla u_+|^2 \nabla \cdot \eta + \varepsilon \mu_-^2 I_{\{u \leq 0\}} \nabla \cdot \eta + \varepsilon \mu_+^2 I_{\{u > 0\}} \nabla \cdot \eta + o(\varepsilon).\]
Noting (cf. (3.4)) that
\[
a_\varepsilon - 1 = \frac{1}{\tilde{\Omega}} \left[ \int_{\tilde{\Omega}} u_\varepsilon^2 - \int_{\tilde{\Omega}} u_\varepsilon^2 (1 + \varepsilon \nabla \cdot \eta + o(\varepsilon)) \right] = -\varepsilon \int_{\tilde{\Omega}} u_\varepsilon^2 \nabla \cdot \eta + o(\varepsilon)
\]
and that the linear term in \( \varepsilon \) in the preceding inequality must vanish, we get
\[
0 = \left( -\int_{\tilde{\Omega}} u_\varepsilon^2 \nabla \cdot \eta \right) \int_{\tilde{\Omega}} |\nabla u_\varepsilon|^2 - 2 \int_{\tilde{\Omega}} \nabla u D\eta \nabla u + \int_{\tilde{\Omega}} |\nabla u|^2 \nabla \cdot \eta + \int_{\tilde{\Omega}} \mu_+^2 I_{\{u \leq 0\}} \nabla \cdot \eta
\]
\[
+ \int_{\tilde{\Omega}} \mu_+^2 I_{\{u > 0\}} \nabla \cdot \eta
\]
\[
= \int_{\tilde{\Omega}} (|\nabla u|^2 - \lambda u_\varepsilon^2 + \mu_+^2 I_{\{u \leq 0\}} + \mu_+^2 I_{\{u > 0\}}) \nabla \cdot \eta - 2 \int_{\tilde{\Omega}} \nabla u D\eta \nabla u.
\]
We now use the assumption that meas \( \{u = 0\} = 0 \) to conclude from the last relation that
\[
0 = \lim_{\varepsilon \downarrow 0} \int_{\{u > \varepsilon\}} \left[ (|\nabla u|^2 + \mu_+^2) \nabla \cdot \eta - 2\nabla u D\eta \nabla u \right]
\]
\[
+ \lim_{\varepsilon \downarrow 0} \int_{\{u < -\varepsilon\}} \left[ (|\nabla u|^2 - \lambda u_\varepsilon^2 + \mu_+^2) \nabla \cdot \eta - 2\nabla u D\eta \nabla u \right].
\]
(3.9)
Notice that, in \( \{u > \varepsilon\}, \Delta u = 0 \) and
\[
\nabla \cdot \left[ (|\nabla u|^2 + \mu_+^2) \eta - 2(\eta \cdot \nabla u) \nabla u \right] = (|\nabla u|^2 + \mu_+^2) \nabla \cdot \eta + (\nabla(|\nabla u|^2)) \cdot \eta - 2(\nabla(\eta \cdot \nabla u)) \cdot \nabla u
\]
\[
= (|\nabla u|^2 + \mu_+^2) \nabla \cdot \eta - 2\nabla u D\eta \nabla u
\]
where in the last equation we made use of the identity
\[
\nabla u \cdot \nabla(\eta \cdot \nabla u) = \frac{1}{2} \eta \cdot \nabla(|\nabla u|^2) + \nabla u D\eta \nabla u.
\]
Similarly, in \( \{u < -\varepsilon\}, \Delta u + \lambda u = 0 \) and
\[
\nabla \cdot \left[ (|\nabla u|^2 + \mu_-^2 - \lambda u_\varepsilon^2) \eta - 2(\eta \cdot \nabla u) \nabla u \right] = (|\nabla u|^2 + \mu_-^2 - \lambda u_\varepsilon^2) \nabla \cdot \eta - 2\nabla u D\eta \nabla u.
\]
Therefore we deduce from (3.9) that
\[
0 = \lim_{\varepsilon \downarrow 0} \int_{\{u > \varepsilon\}} \nabla \cdot \left[ (|\nabla u|^2 + \mu_+^2) \eta - 2(\eta \cdot \nabla u) \nabla u \right]
\]
\[
+ \lim_{\varepsilon \downarrow 0} \int_{\{u < -\varepsilon\}} \nabla \cdot \left[ (|\nabla u|^2 + \mu_-^2 - \lambda u_\varepsilon^2) \eta - 2(\eta \cdot \nabla u) \nabla u \right]
\]
\[
= \lim_{\varepsilon \downarrow 0} \int_{\partial \{u > \varepsilon\}} (\mu_+^2 - |\nabla u|^2) \eta \cdot \nu + \lim_{\varepsilon \downarrow 0} \int_{\partial \{u < -\varepsilon\}} (\mu_-^2 - |\nabla u|^2) \eta \cdot \nu
\]
where in the last equality we made use of the fact that \( |\nabla u| = \mp \nabla u \cdot \nu \) on \( \{u = \delta\} \) and on \( \{u = -\varepsilon\} \) respectively; this is the assertion (3.8).

**Remark 3.1.** If \( u \geq 0 \) in \( \Omega_0 \) and meas\{ \( x \in \Omega_0, u(x) \neq 0 \} > 0 \) then we have \( |\nabla u_+|^2 = \mu_+^2 - \mu_-^2 = \mu^2 \) on \( \Gamma_p \cap \Omega_0 \) in the sense that
\[
\lim_{\varepsilon \downarrow 0} \int_{\partial \{u > \varepsilon\}} \left( |\nabla u|^2 - \mu^2 \right) \eta \cdot \nu = 0 \quad \forall \eta \in C_0^1(\Omega_0, \mathbb{R}^n).
\]
4. Another variational principle. The constraint $\int_{\Omega} u_+^2 = 1$ in the definition of the admissible functions poses serious difficulties to establishing further properties for any minimizer $u$ (by trying to extend the analysis of [3]). We need to have a more "flexible" class of admissible functions. This however will require a modification of the functional $J$.

Let $\eta$ be a positive real number and let

\begin{equation}
(4.1) \quad f_\eta(s) = \begin{cases} \frac{1}{\eta}(s-1) & \text{if } s < 1 \\ \eta(s-1) & \text{if } s \geq 1. \end{cases}
\end{equation}

We introduce the admissible class

\begin{equation}
(4.2) \quad K_0 = \{ v \in H^1(\Omega), v = \gamma \text{ on } \partial \Omega \},
\end{equation}

and a new functional

\begin{align}
J_\eta(v) &= \int_{\Omega} \left[ |\nabla v|^2 + \mu_-^2 I_{\{v \leq 0\}} + \mu_+^2 I_{\{v > 0\}} \right] - f_\eta(\int_{\Omega} v^2) \\
(4.3) &= J(v) - f_\eta(\int_{\Omega} v_+^2).
\end{align}

Problem $(J_\eta)$. Find $u \in K_0$ such that

\begin{equation}
J_\eta(u) = \min_{v \in K_0} J_\eta(v).
\end{equation}

Theorem 4.1. If $\eta$ is small enough then any continuous function $u$ in $\overline{\Omega}$ which is a solution to problem $(J_\eta)$, is also a solution to problem $(J)$.

Proof. All we need to prove is that any solution to problem $(J_\eta)$ satisfies

\begin{equation}
(4.4) \quad \int_{\Omega} u_+^2 = 1.
\end{equation}

Suppose

\begin{equation}
(4.5) \quad \int_{\Omega} u_+^2 > 1.
\end{equation}

Then $\hat{\Omega}_p \neq \emptyset$ and, since $u$ is continuous, $\hat{\Omega}_p$ is open. Take $u_\varepsilon = u - \varepsilon \xi$ where $\xi \in C_0^1(\hat{\Omega}_p)$. If $|\varepsilon|$ is small enough D then $\text{sgn } u_\varepsilon = \text{sgn } u$, $\int_{\Omega} (u_\varepsilon)^2 > 1$, and we easily get

\begin{equation}
0 \leq J_\eta(u_\varepsilon) - J_\eta(u) = -2\varepsilon \int_{\Omega} (\nabla u \cdot \nabla \xi + \eta u_\varepsilon \xi) + o(\varepsilon).
\end{equation}

It follows that $\int_{\Omega} (\nabla u \cdot \nabla \xi + \eta u_\varepsilon \xi) = 0$ and, therefore,

\begin{equation}
(4.6) \quad \Delta u + \eta u = 0 \text{ and } u < 0 \text{ in } \hat{\Omega}_p.
\end{equation}

Since $\hat{\Omega}_p \subset \Omega$ we conclude that $\eta > \lambda_1(\Omega)$ where $\lambda_1(\Omega)$ is the first eigenvalue of $\Delta$ in $\Omega$. Thus if we choose $\eta \leq \lambda_1(\Omega)$ then (4.5) cannot hold.
Suppose next that

\[(4.7) \quad \int_{\Omega} u_-^2 < 1.\]

Observe that

\[\inf_{v \in K_0} J_\eta(v) \leq C, \quad C \text{ independent of } \eta.\]

Therefore

\[(4.8) \quad J(u) - \frac{1}{\eta} \left( \int_{\Omega} u_-^2 - 1 \right) = J_\eta(u) \leq \inf_{v \in K_0} J_\eta(v) \leq C.\]

Since \(J(u) > 0\), we conclude that

\[(4.9) \quad \int_{\Omega} u_-^2 \geq 1 - C \eta > \frac{1}{2} \quad \text{if } C \eta < \frac{1}{2};\]

consequently \(\Omega_p \neq \phi\). Proceeding as before we derive, analogously to (4.6),

\[\Delta u + \frac{1}{\eta} u = 0 \quad \text{in } \Omega_p.\]

Multiplying by \(u\) and integrating over \(\Omega_p\) results in

\[\frac{1}{\eta} \int_{\Omega} |\nabla u_-|^2 \leq \frac{1}{\eta} \int_{\Omega} u_-^2 \leq \int_{\Omega} u_-^2 \leq J_\eta(u), \quad \text{since } -f_\eta(\int_{\Omega} u_-^2) > 0.\]

Recalling (4.8),(4.9), we obtain

\[\frac{1}{\eta} < 2C\]

which is a contradiction if \(\eta < 1/(2C)\).

From now on we study only the minimizers of \(J_\eta\), and assume that \(\eta\) is small enough so that any continuous minimizer is also a solution to problem \((J)\).

5. \(C^\alpha\) regularity.

**Theorem 5.1.** There exists a solution to problem \((J_\eta)\).

Indeed, the proof is the same as for Theorem 1.1 of [3].

**Theorem 5.2.** Any solution \(u\) to problem \((J_\eta)\) is subharmonic in \(\Omega\).

The proof is the same as for Theorem 3.2 since

\[\int_{\Omega} (u_-)_e^2 = \int_{\Omega} u_-^2 = 1.\]
so that

\[ J_\eta(u_\varepsilon) \geq J_\eta(u) \quad \text{implies that} \quad J(u_\varepsilon) \geq J(u). \]

By Lemma 10.1 in [13; p. 90] there is a version of the subharmonic function \( u \) such that

\[ \int_{B_r(x)} u \downarrow u(x) \quad \text{if} \ r \to 0, \quad \forall x \in \Omega, \]

and this implies that \( u \) is upper semicontinuous. It follows that the set \( \partial^0 \Omega_\rho = \{ u < 0 \} \) is open and, by the proof of Theorem 3.3,

\[ \Delta u + \lambda u = 0 \quad \text{in} \ \partial^0 \Omega_\rho. \]

By the isoperimetric inequality for the principal eigenvalue, the volume of each component \( D_i \) of \( \partial^0 \Omega_\rho \) is bounded from below by a constant depending only on \( \lambda \). Hence there is only a finite number of such components \( D_i \). Since \( \int_{D_i} u^2 \leq 1 \), by elliptic estimates

\[ u_- \leq c_i \quad \text{in} \ D_i \cap \{ u_- > 1 \} \]

where \( c_i > 1 \). It follows that

\[ u_- \leq C_1 \quad \text{in} \ \partial^0 \Omega_\rho \quad \text{where} \ C_1 = \max_i c_i. \]

Since \( u \) is subharmonic, by the maximum principle \( u \leq \gamma \) in \( \Omega \). Thus, altogether,

(5.1)

\[ -C_1 \leq u \leq \gamma \quad \text{in} \ \Omega. \]

**Theorem 5.3.** Any solution \( u \) to problem \( (J_\eta) \) is in \( C^\alpha(\overline{\Omega}) \) for any \( 0 < \alpha < 1 \).

**Proof.** Let \( B_r \subset \Omega \) be any ball of radius \( r \) and denote by \( v_r \) the solution to

\[ \Delta v_r = 0 \quad \text{in} \ B_r, \quad v_r = u \quad \text{on} \ \partial B_r. \]

Extend \( v_r \) by \( u \) to \( \Omega \setminus B_r \). Then, by the minimality of \( u \),

\[
\int_{B_r} [ |\nabla u|^2 + \mu_- I_{\{u \leq 0\}} + \mu_+ I_{\{u > 0\}} ] - f_\eta(\int_{\Omega} u^2) \\
\leq \int_{B_r} [ |\nabla v_r|^2 + \mu_- I_{\{v_r \leq 0\}} + \mu_+ I_{\{v_r > 0\}} ] - f_\eta(\int_{\Omega} (v_r)^2).
\]

It follows that

\[
\int_{B_r} (u - v_r)^2 = \int_{B_r} [ |\nabla u|^2 - |\nabla v_r|^2 ] \leq Cr^n + f'_\eta(\delta) [ \int_{B_r} u^2 - \int_{B_r} (v_r)^2 ] \\
\leq Cr^n + C \int_{B_r} u_-^2 \leq Cr^n
\]

where we have used (5.1).
Proceeding as in [20; Th. 5.3.6] (cf. [2]) one can use the last estimate to establish the bound

$$\int_{B_r} |\nabla (u - v_R)|^2 \leq C(R)r^n(\log \frac{R}{r} + 1) \quad \text{if } 0 < r < R$$

so that

$$\int_{B_r} |\nabla u|^2 \leq C(R)r^n(\log \frac{R}{r} + 1)$$

and then, by [20; Th. 3.5.2], $u$ is in $C^\alpha(\Omega)$.

To prove that $u \in C^\alpha$ near the boundary, we flatten the boundary, i.e., for a given $x_0 \in \partial \Omega$ and a small ball $B_\rho(x_0)$ we introduce a $C^2$ diffeomorphism $y = \Phi(y)$ from $B_\rho(x_0) \cap \Omega$ onto the half ball $B^+_1(0)$. Let $v_r$ be harmonic function in $\Phi^{-1}(B^+_1(0))$ with $v_r = u$ on $\partial \Phi^{-1}(B^+_1(0))$. Consider the function $\tilde{v}_r = v_r \circ \Phi$ in $B^+_1(0)$ and extend it to $B^+_r(0)$ by

$$2\gamma - \tilde{v}_r(y_1, \ldots, y_{n-1}, -y_n).$$

Similarly define $\tilde{u} = u \circ \Phi$ and extend it in the same way to $B^+_r(0)$. As before we have

$$\int [ |\nabla u|^2 - |\nabla v_r|^2] \leq C r^n$$

($v_r$ has been extended into $\Omega$ by $u$), and this leads to

$$\tilde{J}(\tilde{u}) \leq \tilde{J}(\tilde{v}_r) + C r^n$$

where

$$\tilde{J}(w) = \int_{B^+_1(0)} \sum a_{ij}(y)w_y, w_y, dy$$

where $(a_{ij})$ is a positive definite matrix with bounded measurable coefficients. The technique of [20] can then again be used to deduce that $\tilde{u} \in C^\alpha(B_{r_1}(0))$ for some $0 < r_1 < 1$, and therefore $u \in C^\alpha(B_{\rho_1}(x_0) \cap \Omega)$ for some $\rho_1 > 0$.

**Remark 5.1.** The $C^\alpha$ norm of $u$ in any compact subset $G$ of $\Omega$ depends only on $M, \delta$ and $\mu^2$ where $M = \sup_{\Omega} |u|$ and $\delta = \text{dist}(G, \partial \Omega)$.

From Theorems 5.3 and 4.1 we have:

**Corollary 5.4.** Any minimizer of $(J_u)$ is also a minimizer of $(J)$.

**Notation.** In order to indicate the dependence of $\Omega_u$ and $\Omega_p$ on $u$, we introduce the notation:

$$\Omega^+(u) = \{x \in \Omega; u(x) > 0\},$$

$$\Omega^-(u) = \text{int}\{x \in \Omega; u(x) \leq 0\}.$$

**Definition.** The free boundary $F(u)$ is defined by

(5.2) \hspace{1cm} F(u) = \partial \Omega^+(u) \cap \Omega.
Remark 5.2. We claim:

\begin{equation}
\partial \Omega^-(u) \subset F(u).
\end{equation}

Indeed, if \( x_0 \notin F(u) \) while \( x_0 \in \Omega \setminus \Omega^+(u) \), then there is a neighborhood \( N \) of \( x_0 \) such that \( u \leq 0 \) in \( N \). Since \( u \) is subharmonic, either \( u < 0 \) in \( N \) or \( u \equiv 0 \) in \( N \). In either case \( N \subset \Omega^-(u) \) so that \( x_0 \notin \partial \Omega^-(u) \). Finally if \( x_0 \in \partial \Omega \) then \( u(x_0) > 0 \) and again \( x_0 \notin \partial \Omega^-(u) \).

Remark 5.3. In §15 it will be shown that for some domains \( \Omega \) the set \( \{ u = 0 \} \) has nonempty interior. This situation does not occur if \( \mu^2 = 0 \) and \( n = 2 \); see [19].

6. Lower and upper estimates on averages. The results of this section are similar to results obtained in [3] in case the admissible class is \( K_0 \) (defined in (4.2)) and the variational functional is \( J(v) \); the fact that we are dealing here with \( J_\eta(v) \) instead of \( J(v) \) causes just minor changes. We shall refer to [3] whenever the changes are obvious.

Theorem 6.1 (Nondegeneracy). For any \( 0 < \kappa < 1 \) there exists a positive constant \( c \) depending only on \( \kappa \) and \( \mu^2 \) such that if \( B_r \subset \Omega \) and

\[ \frac{1}{r} \int_{\partial B_r} u_+ < c \]

then \( u_+ = 0 \) in \( B_{\kappa r} \).

The proof is similar to the proof of Theorem 3.1 in [3]; the term \( f_\eta(\int u^2_+) \) cancels out the term \( f_\eta(\int v^2_+) \), where \( v \) is the modification of \( u \), as defined in [3].

Corollary 6.2. If \( B_r \subset \Omega \) with center in the free boundary \( \partial \{ u > 0 \} \cap \Omega \), then

\begin{equation}
\frac{1}{r} \int_{\partial B_r} u_+ \geq c \quad (c > 0)
\end{equation}

where \( c \) depends only on \( \mu^2 \).

Theorem 6.3. There exists a positive constant \( c \) depending only on \( \mu^2_- \) and \( \mu^2_+ \) such that if \( B_r \subset \Omega \) with center in \( \{ u = 0 \} \) then

\[ \frac{1}{r} \int_{\partial B_r} |u| \leq c. \]

Proof. The proof is similar to the proof of Theorem 4.1 in [3]; the only difference occurs in the proof of Lemma 4.2 of [3], which asserts that

\begin{equation}
\Delta u(B_{r/2}) \leq cr^{n-1}.
\end{equation}

To prove (6.2) define \( v \) by \( v = u \) in \( \Omega \setminus B_r \) and

\[ \Delta v = 0 \quad \text{in } B_r, \quad v = u \quad \text{on } \partial B_r. \]

From \( J_\eta(u) \leq J_\eta(v) \) and the uniform bound on \( u \) (see (5.1)) we obtain

\[ \int_{B_r} |\nabla u|^2 - \int_{B_r} |\nabla v|^2 \leq cr^n. \]
The left-hand side is equal to

\[ \int_{B_r} \nabla (u - v) \cdot \nabla (u + v) = \int_{B_r} \nabla (u - v) \cdot \nabla u = \int_{B_r} (v - u) \Delta u \]

where \( \Delta u \) is a measure supported in \( \{ u \leq 0 \} \). Hence

\[ \int_{B_r \cap \{ u = 0 \}} (v - u) \Delta u \leq c r^n - \int_{B_r \cap \{ u < 0 \}} (v - u) \Delta u \]

\[ = c r^n + \lambda \int_{B_r \cap \{ u < 0 \}} (v - u) u \leq C r^n, \]

where we have again used the uniform bound (5.1). We can now complete the proof of (6.2) precisely as in Lemma 4.2 of [3].

7. The monotonicity theorem.

**THEOREM 7.1. (THE MONOTONICITY THEOREM).** Set \( N = \max \{ n - 1, 2 \} \) and let \( \frac{N}{2 + N} < \alpha < 1 \). Suppose \( u \) is a minimizer of \((J_\rho)\). Take any point \( x_0 \) in the free boundary \( \partial \{ u > 0 \} \cap \Omega \) and denote by \( B_r \) the ball in \( \Omega \) with center \( x_0 \) and radius \( r \). Then there exists a positive constant \( \kappa_\alpha \) depending only on \( \mu^2, \alpha \) and the \( C^{\alpha}(\Omega) \)-norm of \( u \) such that the function

\[ \varphi(r) = \frac{1}{r^4} \int_{B_r} \rho^{2-n} |\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n} |\nabla u_-|^2 \cdot e^{\kappa_\alpha \rho^{2-\frac{1}{\alpha} N}} \]

where \( \lambda = \int_{\Omega} |\nabla u_-|^2 \), is monotone increasing in \( r \).

In the special case where \( u_\pm \) are both harmonic, this result is due to Alt, Caffarelli and Friedman [3]; in their case, \( \kappa_\alpha = 0 \). The main part of the proof of Theorem 7.1 follows closely the proof in [3]; however we shall also need, for the present case, the additional lemma:

**LEMMA 7.2.** Under the assumptions of Theorem 7.1, there exists a constant \( \kappa'_\alpha \), depending only on \( \alpha, \mu^2 \) and the \( \alpha \)-Hölder norm of \( u \), such that

\[ \int_{B_r} \rho^{2-n} (u_-)^2 \leq \kappa'_\alpha r^{2-\frac{1}{\alpha} N} \int_{B_r} \rho^{2-n} |\nabla u_-|^2. \]

**Proof.** Denote by \( S_r^\pm \) the support of \( u_\pm \) on \( S_r = \partial B_r \). By Corollary 6.2,

\[ H^{n-1}(S_r^\pm) \neq 0 \]

where \( H^{n-1}(S_r^{\pm}) \) denotes the Hausdorff measure of \( S_r^{\pm} \).

By nondegeneracy there exists a point \( y_r \in S_r \) with \( u(y_r) > cr \) \( (c > 0) \). Since \( u \in C^\alpha \) we then have, for any \( x \in B_{\kappa r^{1/\alpha}}(y_r) \) \((0 < \kappa < 1)\)

\[ u(x) \geq u(y_r) - C_\alpha |x - y_r|^\alpha > cr - C_\alpha \kappa^\alpha r \geq 0 \quad \text{if} \quad \kappa^\alpha \leq \frac{c}{C_\alpha}. \]

Therefore

\[ H^{n-1}(S_r^\pm) \geq \kappa_{n-1}(\kappa r^{1/\alpha})^{n-1} \]
where $\kappa_m$ is the volume of the $m$-dimensional unit ball.

It follows that

\begin{equation}
\frac{H^{n-1}(S_r^-)}{H^{n-1}(S_r)} = 1 - \frac{H^{n-1}(S_r^+)}{H^{n-1}(S_r)} \leq 1 - \frac{\kappa_{n-1} \kappa_{n-1}^{n-1}}{n\kappa_n} r^{(\frac{1}{n}-1)(n-1)}.
\end{equation}

Denote by $\nabla_v v$ the gradient of a function $v$ on $S_r$ and introduce constants (which depend on $r$)

\begin{equation}
\frac{1}{\alpha_r^\pm} = \inf_{v \in H_0^1(S_r^\pm)} \frac{\int_{S_r^\pm} |\nabla v|^2}{\int_{S_r^\pm} v^2},
\end{equation}

and $\beta_r^\pm \in (0,1]$,

\begin{equation}
\frac{1 - (\beta_r^\pm)^2}{\alpha_r^\pm} = (n - 2) \frac{\beta_r^\pm}{\sqrt{\alpha_r^\pm}}.
\end{equation}

Then, (cf. [3; p.441])

\begin{equation}
\frac{\beta_r^\pm}{\sqrt{\alpha_r^\pm}} = \gamma_r^\pm \quad \text{where} \quad \gamma_r^\pm (\gamma_r^\pm + n - 2) = \frac{1}{\alpha_r^\pm}, \quad \gamma_r^\pm > 0
\end{equation}

and, by an estimate of Friedland and Hayman [12] on the functions $\gamma_r^\pm$,

\begin{equation}
\frac{\beta_r^\pm}{\sqrt{\alpha_r^\pm}} \geq \psi \left( \frac{H(S_r^\pm)}{H(S_r)} \right) \quad \text{if} \quad H(S_r^\pm) \neq 0
\end{equation}

where

\begin{equation}
\psi(s) = \begin{cases} 
\frac{1}{2} \log \frac{1}{4s} + \frac{3}{2} & \text{if} \quad s \leq \frac{1}{4} \\
2(1 - s) & \text{if} \quad \frac{1}{4} < s < 1.
\end{cases}
\end{equation}

Hence, by (7.3),

\begin{equation}
\frac{\beta_r^-}{\sqrt{\alpha_r^-}} \geq \psi \left( 1 - \frac{\kappa_{n-1} \kappa_{n-1}^{n-1}}{n\kappa_n} r^{(\frac{1}{n}-1)(n-1)} \right) = \frac{2\kappa_{n-1} \kappa_{n-1}^{n-1}}{n\kappa_n} r^{(\frac{1}{n}-1)(n-1)}.
\end{equation}

By the definition of $\alpha_r^\pm$ and of $\beta_r^\pm$ (in (7.4)),

\begin{equation}
\int_{S_r} |\nabla u_-|^2 \geq \frac{1}{r^2} \int_{S_r} |\nabla u_-|^2 \geq \frac{1 - (\beta_r^-)^2}{\alpha_r^-} \frac{1}{r^2} \int_{S_r} u_-^2 = \frac{(n - 2)\beta_r^-}{\sqrt{\alpha_r^-}} \frac{1}{r^2} \int_{S_r} u_-^2 \quad \text{if} \quad n > 2
\end{equation}

so that, by (6.6),

\begin{equation}
\int_{S_r} u_-^2 \leq \kappa'_a r^{2-(\frac{1}{n}-1)N} \int_{S_r} |\nabla u_-|^2 \quad \text{if} \quad H(S_r^-) \neq 0.
\end{equation}
If $n = 2$ then, since $\beta_r^- = 1$, we have

$$\int_{S_r} |\nabla u_-|^2 \geq \frac{(\beta_r^-)^2}{\alpha_r^-} \frac{1}{r^2} \int_{S_r} u_-^2 \cdot \int_{S_r} u_-^2$$

where we have again used (7.6); hence (7.8) is valid also if $n = 2$. Finally if $H(S_r^-) = 0$ then (7.8) is trivially true.

Multiplying (7.8) by $r^{2-n}$ and integrating from 0 to $\rho$, the assertion (7.2) follows.

**Proof of Theorem 7.1.** Consider the function

$$g(r) = \frac{1}{r^4} \int_{B_r} \rho^{2-n}|\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n}|\nabla u_-|^2.$$ 

Then a.e.

$$g'(r) = -\frac{4}{r^5} \int_{B_r} \rho^{2-n}|\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n}|\nabla u_-|^2 + \frac{1}{r^4} \int_{S_r} r^{2-n}|\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n}|\nabla u_-|^2$$

(7.9)

$$+ \frac{1}{r^4} \int_{B_r} \rho^{2-n}|\nabla u_-|^2 \cdot \int_{S_r} r^{2-n}|\nabla u_-|^2.$$ 

We first wish to prove that

(7.10) 

$$g'(r) \geq -\frac{4\lambda}{r^5} \int_{B_r} \rho^{2-n}u_-^2 \cdot \int_{B_r} \rho^{2-n}|\nabla u_+|^2 \quad \text{where } \lambda = \int_{\Omega} |\nabla u_-|^2.$$ 

Without loss of generality we may assume that

(7.11) 

$$\int_{B_r} \rho^{2-n}(|\nabla u_-|^2 - \lambda u_-^2) > 0$$

since, otherwise, (7.10) follows immediately from (7.9).

Proceeding as in the proof of (5.2) in [3] we get

$$2 \int_{B_r} \rho^{2-n}|\nabla u_+|^2 \leq r^{2-n} \int_{S_r} 2u_+(u_+)_r + (n-2)r^{1-n} \int_{S_r} u_+^2,$$

$$2 \int_{B_r} \rho^{2-n}|\nabla u_-|^2 \leq r^{2-n} \int_{S_r} 2u_-(u_-)_r + (n-2)r^{1-n} \int_{S_r} u_-^2 + 2\lambda \int_{B_r} \rho^{2-n}u_-^2.$$ 

(Actually a careful look at the proof shows that equalities hold.) Also, as in [3; (5.6)],

$$\int_{S_r} |\nabla u_+|^2 \geq \frac{\beta_r^\pm}{\sqrt{\alpha_r^\pm}} \frac{1}{r} \left\{ \int_{S_r} 2|u_+(u_+)_r| + \frac{n-2}{r} \int_{S_r} u_+^2 \right\}$$

so that

(7.12) 

$$r^{2-n} \int_{S_r} |\nabla u_+|^2 \geq \frac{2}{r} \frac{\beta_r^+}{\sqrt{\alpha_r^+}} \int_{B_r} \rho^{2-n}|\nabla u_+|^2,$$

$$17$$
and

\[ (7.13) \quad r^{2-n} \int_{B_r} |\nabla u_+|^2 \geq \frac{2}{r} \frac{\beta_+}{\sqrt{\alpha_r}} \int_{B_r} \rho^{2-n} (|\nabla u_-|^2 - \lambda u_-^2). \]

Substituting (7.12) and (7.13) into (7.9) results in

\[ g'(r) \geq -\frac{4}{r^5} \int_{B_r} \rho^{2-n} |\nabla u_+|^2 \cdot \int_{B_r} \rho^{2-n} |\nabla u_-|^2 + \frac{2}{r^5} \left( \frac{\beta_+}{\sqrt{\alpha_r}} + \frac{\beta_-}{\sqrt{\alpha_r}} \right) \int_{B_r} \rho^{2-n} (|\nabla u_-|^2 - \lambda u_-^2) \cdot \int_{B_r} \rho^{2-n} |\nabla u_+|^2. \]

Since, by [3; (5.7)],

\[ \frac{\beta_+}{\sqrt{\alpha_r}} + \frac{\beta_-}{\sqrt{\alpha_r}} \geq 2 \]

and since we have assumed that (7.11) holds, the assertion (7.10) follows.

We now substitute the inequality (7.2) of Lemma 7.2 into (7.10) to deduce that

\[ g'(r) \geq -4\lambda \kappa_r r^{1-\frac{1}{a\alpha N}} g(r), \]

from which the assertion of Theorem 7.1 follows.

**Theorem 7.3.** Any solution \( u \) of problem \( (J_\eta) \) is Lipschitz continuous in \( \overline{\Omega} \).

The proof, based on Theorems 7.1 and 6.3, is similar to the second proof of Theorem 5.3 in [3]. (The fact that Theorem 7.1 differs somewhat from the monotonicity formula in [3] causes only minor changes.) In that proof the Harnack inequality and a scaling argument were used. Note that the Harnack inequality for positive solutions of \( \Delta u + cu = 0 \) \( (c > 0) \) is valid [14] and the constant in the inequality depends only on the sup-norm of \( c \) (and the compact subdomain). Since the scaling changes the equation \( \Delta u + \lambda u = 0 \) into an equation \( \Delta v + \rho^2 \lambda v = 0 \) with \( \rho \) small, we can use the Harnack inequality (as in [3]) with a constant independent of the scaling, and this allows the proof of Theorem 7.3 to proceed as in [3].

8. **Blow-up limits.** Suppose \( u \) is a solution to problem \( (J_\eta) \) and \( x_k \to x_0 \in \Omega, \rho_k \downarrow 0, u(x_k) = 0 \). The sequence

\[ u_k(x) = \frac{1}{\rho_k} u(x_k + \rho_k x) \]

is called a **blow-up** sequence with respect to \( B_{\rho_k}(x_k) \). Since \( |\nabla u_k(x)| \leq C \) in any bounded set and \( u_k(0) = 0 \), any blow-up sequence has a subsequence for which

\[ u_k(x) \to u_0(x) \text{ uniformly in bounded sets,} \]

\[ \nabla u_k \to \nabla u_0 \text{ weakly star in } L^\infty_{\text{loc}}(\mathbb{R}^n); \]

\( u_0 \) is called a **blow-up limit**.

**Lemma 8.1.** As \( k \to \infty \),

\[ \partial \{u_k > 0\} \to \partial \{u_0 > 0\} \text{ locally in the Hausdorff metric,} \]

\[ \nabla u_k \to \nabla u_0 \text{ a.e. in } \mathbb{R}^n. \]
The proof is the same as for [3; Lemma 6.1].

Set
\[ J_B^0(v) = \int_B \left[ |\nabla v|^2 + \mu_+^2 I_{\{v \leq 0\}} + \mu_-^2 I_{\{v > 0\}} \right]. \]

**Definition 8.1.** A function \( u \) is called a minimizer of \((J^0)\) in \( \mathbb{R}^n \), or a *global minimizer*, if for any \( B_r \subset \mathbb{R}^n \) and for any \( v \in H^1(B_r) \) with \( v = u \) on \( \partial B_r \),

\[ J_{B_r}^0(u) \leq J_{B_r}^0(v). \]

**Lemma 8.2.** Any blow up limit \( u_0 \) is a minimizer of \((J^0)\) in \( \mathbb{R}^n \).

Proof. Since \( u \) is a minimizer of \((J_\eta)\), \( \int_\Omega u_\eta^2 = 1 \); further, for any \( \hat{v} \) such that \( \hat{v} = u \) outside \( B_{\rho_k} \),

\[ J_{B_{\rho_k}}^0(u) \leq J_{B_{\rho_k}}^0(\hat{v}) + \frac{1}{\eta} \left| \int_\Omega \hat{v}_\eta^2 \right| = J_{B_{\rho_k}}^0(\hat{v}) + \frac{1}{\eta} \left| \int_{B_{\rho_k}} (u_\eta^2 - \hat{v}_\eta^2) \right|, \]

or, by the change of variables \( x = x_k + \rho_k y \),

\[ J_{B_1}^0(u_k) \leq J_{B_1}^0(\hat{v}) + \frac{1}{\rho_k^2} \left| \int_{B_1} ((u_k)_\eta^2 - \hat{v}_\eta^2) \right| (\hat{v}(y) = \hat{v}(x)). \]

Choosing, as in the proof of Lemma 5.4 of [2], \( \hat{v} = v + (1 - \eta)(u_k - u_0) \) where \( \eta \in C_0^\infty(B_1) \) and letting \( k \to \infty \) in (8.2) we then obtain (cf. [2]) the assertion (8.1) for \( B = B_1 \). The proof for any \( B_r \) is the same.

**Theorem 8.3** Suppose \( D \Subset \Omega, B_r(x^0) \subset D \) with center \( x^0 \) in \( \partial\{u > 0\} \cap \Omega \). Then

\[ \frac{1}{r} \int_{\partial B_r(x^0)} u \geq c, \quad c > 0 \]

where \( c \) is a constant depending on the Lipschitz coefficient of \( u \) in \( D \).

The proof is the same as for [3; Theorem 6.3].

Consider a blow-up family

\[ u_\epsilon(x) = \frac{1}{\epsilon} u(x^0 + \epsilon x), \quad x^0 \in \partial\{u > 0\} \cap \Omega \]

and let

\[ I_\epsilon(r) = \frac{1}{r^4} \left( \int_{B_r(0)} \rho^{2-n} |\nabla(u_\epsilon)_+|^2 \cdot \int_{B_r(0)} \rho^{2-n} |\nabla(u_\epsilon)_-|^2 \right) e^{\kappa_\epsilon \lambda(\epsilon r)^{2-\frac{1-\alpha}{N}}} \]

\[ = \frac{1}{(\epsilon r)^4} \left( \int_{B_{\epsilon r}(x^0)} \rho^{2-n} |\nabla u_+|^2 \cdot \int_{B_{\epsilon r}(x^0)} \rho^{2-n} |\nabla u_-|^2 \right) e^{\kappa_\epsilon \lambda(\epsilon r)^{2-\frac{1-\alpha}{N}}} \equiv I_{\epsilon r}. \]
Note that the \( u_e \) satisfy a uniform Lipschitz bound and therefore \( \kappa_\alpha \) is independent of \( \varepsilon \). By monotonicity, \( \tilde{I}_\rho \) is increasing function of \( \rho \). Consequently there exists a nonnegative constant \( \sigma \) such that

(8.3) \[ I_\varepsilon(r) \downarrow \sigma \text{ if } \varepsilon \downarrow 0. \]

For any converging blow-up sequence \( u_{\varepsilon_k} \to u_0 \) we have that \( u_{\varepsilon_k}(x) \to u_0(x) \) uniformly in bounded subsets, \( \nabla u_{\varepsilon_k}(x) \to \nabla u_0(x) \) a.e., and by the Lebesgue bounded convergence theorem,

\[ I_{\varepsilon_k}(r) \to \frac{1}{r^4} \int_{B_r} \rho^{2-n} |\nabla u_0|^2 \cdot \int_{\partial B_r} \rho^{2-n} |\nabla u_0|^2 \]

where \( B_r = B_r(0) \). Combining this with (8.3) we conclude:

**Lemma 8.4.** For any blow-up limit \( u_0 \) of \( \{ u_\varepsilon \} \) there holds:

(8.4) \[ \frac{1}{r^4} \int_{B_r} \rho^{2-n} |\nabla u_0|^2 \cdot \int_{\partial B_r} \rho^{2-n} |\nabla u_0|^2 = \sigma \text{ for all } r > 0. \]

Since \( u_0 \) is a minimizer of \( (J_0^n) \), Lemma 6.6 of [3] is then valid, namely:

**Lemma 8.5.** In Lemma 8.4,

(i) if \( \sigma = 0 \) then \( u_0 \geq 0 \) in \( \mathbb{R}^n \);

(ii) if \( \sigma > 0 \) and \( n = 2 \) then \( u_0(x) = \mu_2(x \cdot e)_+ - \mu_1(x \cdot e)_- \) in \( \mathbb{R}^2 \) where \( e \) is a constant unit vector, \( \mu_i \) are positive constants, and \( \mu_2 - \mu_1^2 = \mu_2 = \mu_4^2 - \mu_2^- \).

**9. Properties of the free boundary.**

**Theorem 9.1.** There exists a positive constant \( c \in (0,1) \) such that, for any ball \( B_r \subset \Omega \) with center in \( \partial \{ u > 0 \} \cap \Omega \),

(9.1) \[ c \leq \frac{\mathcal{L}^n(B_r \cap \{ u > 0 \})}{\mathcal{L}^n(B_r)} \leq 1 - c. \]

**Proof.** The left-hand inequality can be established, as in [3], by the nondegeneracy and Lipschitz continuity of the solution. To obtain the right-hand inequality let \( v \) be the solution of

\[ \Delta v = 0 \text{ in } B_r, \]

\[ v = u \text{ on } \partial B_r. \]

Then \( v \geq u \) in \( B_r \) and

\[ \frac{1}{r^2} \int_{B_r} |\nabla (u - v)|^2 \leq \mu^2 \int_{B_r} I_{\{ u \leq 0 < v \}} + \frac{1}{\eta} \int_{B_r} (u_-^2 - v_-^2). \]

By Poincaré's inequality

\[ \frac{c}{r^2} \int_{B_r} |u - v|^2 \leq \int_{B_r} |\nabla (u - v)|^2 \leq \mu^2 \mathcal{L}^n(B_r \cap \{ u \leq 0 \}) + \frac{1}{\eta} \int_{B_r} (u_-^2 - v_-^2)(u_- + v_-). \]
Since \( u \leq v \), the inequalities \( 0 \leq u_- - v_- \leq |u - v| \) and \( u_+ + v_- \leq 2u_- \) hold, so that
\[
\frac{c}{r^2} \int_{B_r} |u - v|^2 \leq \mu^2 \mathcal{L}^n(B_r \cap \{u \leq 0\}) + \frac{\delta}{r^2} \int_{B_r} |u - v|^2 + C_\delta r^2 \int_{B_r} u_-^2.
\]
Choosing \( \delta = \frac{c}{2} \) and using the fact that \( u_- \) is bounded, we get
\[
\frac{c}{r^2} \int_{B_r} |u - v|^2 \leq \mathcal{L}^n(B_r \cap \{u \leq 0\})
\]
with another constant \( c > 0 \). The remaining part of proof is the same as for Theorem 7.1 in [3].

We introduce the distributions
\[
d\Lambda_+ = \Delta u_+ \quad \text{and} \quad d\Lambda_- = \Delta u_- + \lambda u_-.
\]

**Lemma 9.2.** \( \Lambda_+ (\Lambda_-) \) is a Radon measure supported in \( \partial\{u > 0\} \cap \Omega \) \( (\partial\{u < 0\} \cap \Omega) \).

**Proof.** Proceeding similarly to [2; Remark 4.2] we have for any \( \zeta \in C^\infty_0(\Omega) \), \( \zeta \geq 0 \) and \( \varepsilon > 0 \),
\[
- \int_{\Omega \cap \{u < -\varepsilon\}} \nabla \zeta \cdot \nabla u + \lambda \int_{\Omega \cap \{u < -\varepsilon\}} \zeta u = - \int_{\Omega \cap \{u < -\varepsilon\}} \zeta \frac{\partial u}{\partial \nu} dH^{n-1}.
\]
A similar relation holds for the test function
\[
\eta \equiv \zeta \max\{\min(2 + \frac{u}{\varepsilon}, 1), 0\}.
\]
Since \( \eta = \zeta \) on \( \Omega \cap \partial\{u < -\varepsilon\} \), we obtain
\[
- \int_{\Omega \cap \{u < -\varepsilon\}} \nabla \zeta \cdot \nabla u + \lambda \int_{\Omega \cap \{u < -\varepsilon\}} \zeta u = - \int_{\Omega \cap \{u < -\varepsilon\}} \nabla \left( \zeta \max\left(\min(2 + \frac{u}{\varepsilon}, 1), 0\right) \right) \cdot \nabla u + \lambda \int_{\Omega \cap \{u < -\varepsilon\}} \zeta \max\left(\min(2 + \frac{u}{\varepsilon}, 1), 0\right) u.
\]
Noting that
\[
\max(\min(2 + \frac{u}{\varepsilon}, 1), 0) \equiv 1 \quad \text{if} \quad u \geq -\varepsilon, \quad \equiv 0 \quad \text{if} \quad u \leq -2\varepsilon,
\]
it follows that
\[
\int_{\Omega} \nabla \zeta \cdot \nabla u_- - \lambda \int_{\Omega} \zeta u_- = \int_{\Omega} \nabla \left( \zeta \max\left(\min(2 - \frac{u_-}{\varepsilon}, 1), 0\right) \right) \cdot \nabla u_- - \lambda \int_{\Omega} \zeta \max\left(\min(2 - \frac{u_-}{\varepsilon}, 1), 0\right) u_-
\]
\[
\leq \int_{\Omega \cap \{u \geq -2\varepsilon\}} |\nabla \zeta \cdot \nabla u_-| = \int_{\Omega \cap \{-2\varepsilon < u < 0\}} |\nabla \zeta \cdot \nabla u| \to 0 \quad \text{if} \quad \varepsilon \to 0,
\]

by the continuity of $u$. Hence $\Delta u + \lambda u \geq 0$ in the sense of distributions. Similarly $\Delta u_+ \geq 0$ in the sense of distributions. Since $u_\pm$ are continuous, the lemma follows (cf. [2]).

**Theorem 9.3.** For any open set $D \subset \Omega$ there exist positive constants $C, c$ such that for any $B_r \subset D$ with center in $\partial \{u > 0\}$

\begin{equation}
0 \leq \int_{B_r} d\Lambda_- \leq C r^{n-1},
\end{equation}

\begin{equation}
c r^{n-1} \leq \int_{B_r} d\Lambda_+ \leq C r^{n-1}.
\end{equation}

**Proof.** We proceed as in [2; Theorem 4.3]. To prove the upper bound in (9.2) we first deduce from the proof of Lemma 9.2 with suitable $\zeta$'s that

\[ \int_{B_r} d\Lambda_- \leq \int_{\partial B_r} \nabla u_- \cdot \nu \, dH^{n-1} + \lambda \int_{B_r} u_- \]

for $\nu$. Using the Lipschitz continuity of $u$, it follows that $\int_{B_r} d\Lambda_- \leq C r^{n-1}$. The proof of (9.3) is precisely as in [2; Theorem 4.3]; for the lower bound we need to use Corollary 6.2.

**Theorem 9.4. (Representation Theorem).**

(i) If $D \subset \Omega$ then $H^{n-1}(D \cap \partial \{u > 0\}) < \infty$;

(ii) There exist Borel functions $q_u^\pm$ such that

\[ d\Lambda_\pm = q_u^\pm H^{n-1} L \partial \{u > 0\}, \]

that is, for any $\zeta \in C^\infty_0(\Omega)$,

\[ -\int_{\Omega} \nabla u_- \cdot \nabla \zeta + \lambda \int_{\Omega} u_- \zeta = \int_{\Omega \cap \partial \{u < 0\}} \zeta q_u^- \, dH^{n-1}, \]

\[ -\int_{\Omega} \nabla u_+ \cdot \nabla \zeta = \int_{\Omega \cap \partial \{u > 0\}} \zeta q_u^+ \, dH^{n-1}; \]

(iii) For any open set $D \subset \Omega$ there exist positive constants $c, C$ depending on $D$ and the Lipschitz constant of $u$ such that for any ball $B_r(x) \subset D$ with $x \in \partial \{u > 0\} \cap \Omega$,

\begin{equation}
c \leq q_u^+ \leq C, \quad 0 \leq q_u^- \leq C,
\end{equation}

\begin{equation}
c r^{n-1} \leq H^{n-1}(B_r(x) \cap \partial \{u > 0\}) \leq C r^{n-1}.
\end{equation}

Indeed this follows as in [3; Th. 7.3]; we use here Theorem 9.3.

Since $\partial \{u > 0\} \cap \Omega$ has finite $H^{n-1}$ measure, the set $A = \Omega \cap \{u > 0\}$ has finite perimeter locally in $\Omega$, that is, $\mu_u \equiv -\nabla I_A$ is a Borel measure and the total variation $|\mu_u|$ is a Radon measure; see [2] and the references therein to [11; 4.5.11, 4.5.5.]. We denote by $\partial_{\text{red}} \{u > 0\}$ the reduced boundary of $\partial \{u > 0\} \cap \Omega$, that is, the set of points for which there exists a unique unit normal. Then [2] [11; 4.5.6]

\[ \mu_u = \nu_u H^{n-1} L \partial_{\text{red}} \{u > 0\}. \]
Theorem 9.5 (Identification Theorem). Let \( x_0 \in \partial_{\text{red}} \{ u > 0 \} \) with

\[
\phi^{n-1}(H^{n-1} \mathcal{L} \{ u > 0 \}, x_0) \leq 1,
\]

\[
\int_{B_r(x_0) \cap \partial \{ u > 0 \}} |q^\pm_u - q^\pm_u(x_0)| = o(1) \text{ as } r \to 0.
\]

(i) If, in Lemma 8.5, \( \sigma > 0 \) and \( n = 2 \), then

\[
u(x_0 + x) = \mu_2(x \cdot e(x))_+ - \mu_1(x \cdot e(x))_+ + o(|x|) \text{ as } |x| \to 0
\]

where \( e(x) \) is a unit vector, \( \mu_i \) are positive constants, and \( \mu_2^2 - \mu_1^2 = \mu^2, \quad (\mu_2 - \mu_1)e(x_0) = (q^+_u(x_0) - q^-_u(x_0))\nu_u(x_0) \);

(ii) If, in Lemma 8.5, \( \sigma = 0 \) then

\[
u(x_0 + x) = q^+_u \max\{ -x \cdot \nu_u(x_0), 0 \} + o(|x|) \text{ as } |x| \to 0
\]

and

\[
q^+_u(x_0) = \mu_2^2 - \mu_1^2 = \mu^2.
\]

Here \( \nu_u(x_0) \) is the outward normal to \( \partial \{ u > 0 \} \) at \( x_0 \).

The proof is the same as for Theorem 7.4 in [3].

As in [2], Theorem 9.1 implies that

\[
H^{n-1}(\partial \{ u > 0 \} \setminus \partial_{\text{red}} \{ u > 0 \}) = 0
\]

and then, for \( H^{n-1} \) a.a. \( x_0 \in \partial_{\text{red}} \{ u > 0 \}, \) the assumptions (9.6), (9.7) are satisfied. Therefore for \( H^{n-1} \) a.a. \( x \in \partial \{ u > 0 \} \) the free boundary in a neighborhood of \( x_0 \) is approximately a straight line if \( n = 2 \).

10. Weak solutions and subsolutions. In order to study the regularity of the free boundary for solutions \( u \) of problem \((J_n)\), we need to introduce the concept of weak solutions and weak subsolutions.

In the sequel we shall denote the dot product \( x \cdot y \) also by \( < x, y > \).

Definition 10.1 Let \( G(s) \) be a continuous strictly monotone increasing function of \( s \in \mathbb{R} \) with \( G(s) \geq s \) if \( s \geq 0 \), and let \( \Omega \) be a bounded open set in \( \mathbb{R}^n \). Consider a function \( u \) continuous in \( \Omega \) and satisfying:

(i) \( \Delta u = 0 \) in \( \Omega^+(u) = \{ x \in \Omega; u(x) > 0 \} \),

(ii) \( \Delta u + \lambda u = 0 \) in \( \Omega^-(u) = \{ x \in \Omega; u(x) \leq 0 \} \) where \( \lambda \) is a positive constant.

Then we say that \( u \) satisfies the weak free boundary condition

\[
u^+_u = G(u^-_u) \text{ along } F(u) = \partial \{ u > 0 \} \cap \Omega
\]

if for any \( x_0 \in F(u) \) for which \( F(u) \) has a one-sided tangent ball at \( x_0 \) (i.e., there exists a ball \( B_\rho(y) \) such that \( x_0 \in \partial B_\rho(y) \) and \( B_\rho(y) \) is contained either in \( \Omega^+(u) \) or in \( \Omega^-(u) \)),

\[
u(x) = \alpha < x - x_0, \nu > + \beta < x - x_0, \nu > + o(|x - x_0|)
\]

and \( \beta \geq 0, \quad \alpha = G(\beta), \) where \( \nu \) is the unit radial direction of \( \partial B_\rho(y) \) at \( x_0 \) pointing into \( \Omega^+(u) \).

The function \( u \) is called a weak solution. We shall often write \( u^+_u = \alpha, \ u^-_u = \beta. \)

Definition 10.2. A function \( v \) continuous in \( \Omega \) is called a subsolution if instead of (i), (ii) and (10.1) it satisfies:
\[(i') \Delta v \geq 0 \text{ in } \Omega^+(v) = \{v > 0\},\]
\[(i'') \Delta v + \lambda v \geq 0 \text{ in } \Omega^-(v) = \operatorname{int}\{v \leq 0\},\]
and, for any \(x_0 \in F(v)\) at which \(F(v)\) has a tangent ball \(B_p(y)\) from \(\Omega^+(v)\) or from \(\Omega^-(v)\),
\[(10.2) \quad v(x) \geq \alpha < x - x_0, \nu > + \beta < x - x_0, \nu > - o(|x - x_0|)\]
for some \(\beta \geq 0\) and \(\alpha \geq G(\beta)\).

**Definition 10.3.** A point \(x_0 \in F(v)\) at which \(F(v)\) has a tangent ball from \(\Omega^+(v)\) (see Definition 10.2) will be called a regular point.

**Lemma 10.1.** Let \(v \leq u\) be two continuous functions in \(\Omega\), \(v < u\) in \(\Omega^+(v)\), \(v\) a subsolution and \(u\) a weak solution. If every point in \(F(v)\) is regular, then \(F(v) \cap F(u) = \emptyset\).

The proof, which easily follows from Definitions 10.1–10.3 and the strong maximum principle, is the same as that of Lemma 6 in [5].

**Lemma 10.2** Let \(\Omega\) be a bounded domain and let \(\varphi_i \in C^0(\Omega) \cap L^\infty(\Omega)\) \((i = 1, 2)\) satisfy:
\[
\Delta \varphi_1 + \lambda \varphi_1 \geq 0 \quad \text{in } \mathcal{D}'(\Omega),
\]
\[
\Delta \varphi_2 + \lambda \varphi_2 \geq -\varepsilon \quad \text{in } \mathcal{D}'(\Omega)
\]
for some \(\lambda \geq 0\), \(\varepsilon > 0\). Then the function \(\varphi = \max\{\varphi_1, \varphi_2\}\) satisfies:
\[
\Delta \varphi + \lambda \varphi \geq -\varepsilon \quad \text{in } \mathcal{D}'(\Omega).
\]

**Proof.** Introduce the solution \(w\) to
\[
\Delta w = -\lambda \varphi - \varepsilon \quad \text{in } \Omega, \quad w = 0 \quad \text{on } \partial \Omega.
\]
Then \(\Delta (\varphi_i - w) \geq 0\) for \(i = 1, 2\), i.e., \(\varphi_i - w\) is subharmonic. For any ball \(B \subset \Omega\) let \(h\) be the harmonic function in \(B\) with boundary values \(\varphi_i - w\) on \(\partial B\). Then \(h \geq \varphi_i - w\) on \(\partial B\) and, since \(\varphi_i - w\) is subharmonic, \(h \geq \varphi_i - w\) in \(B\); hence \(h \geq \varphi - w\). We conclude that \(\varphi - w\) is subharmonic, and consequently,
\[
\Delta \varphi + \lambda \varphi + \varepsilon = \Delta (\varphi - w) \geq 0 \quad \text{in } \mathcal{D}'(\Omega).
\]

We next state a comparison principle for a family of subsolutions.

**Lemma 10.3.** Let \(\lambda \leq \lambda_0\) where \(\lambda_0\) is the principal eigenvalue of \(\Delta\) for the Dirichlet problem in a bounded domain \(\Omega\). Let \(v_t, 0 \leq t \leq 1\), be a family of subsolutions in \(\Omega\), continuous in \(\overline{\Omega} \times [0, 1]\), and let \(u\) be a weak solution continuous in \(\overline{\Omega}\). Assume that
\[(a) \ \nu_0 \leq u \text{ in } \Omega;\]
\[(b) \ \overline{\Omega}^+(v_t) \cap \partial \Omega \text{ is nonempty, } v_t \leq u \text{ on } \partial \Omega, \text{ and } v_t < u \text{ on } \overline{\Omega}^+(v_t) \cap \partial \Omega, \text{ for } 0 \leq t \leq 1;\]
\[(c) \ \text{every point } x_0 \in F(v_t) \text{ is regular};\]
\[(d) \ \text{the family } \Omega^+(v_t) \text{ is continuous, that is, for any } \varepsilon > 0, \ \Omega^+(v_t) \subset N_\varepsilon(\Omega^+(v_{t_0})) \text{ if } |t_1 - t_2| < \delta(\varepsilon), \text{ where } \delta(\varepsilon) \text{ is positive and } N_\varepsilon(A) \text{ denotes the } \varepsilon\text{-neighborhood of the set } A.\]
Then \(v_t \leq u \text{ in } \Omega \text{ for } 0 \leq t \leq 1\).

The case \(\lambda = 0\) is Lemma 7 in [5]. The present case of \(\lambda > 0\) requires additional analysis.

**Proof.** Set \(T = \{t; v_t \leq u \text{ in } \Omega\}\). By (a) and the continuity of \(v_t\), \(T\) is nonempty and closed, and it remains to show that \(T\) is open. Let \(t_0 \in T\). By (b) and the strong maximum principle we have that \(v_{t_0} < u \text{ in } \Omega^+(v_{t_0})\). Since every point of \(F(v_{t_0})\) is regular, it follows by Lemma
10.1 that $\overline{\Omega^+(v_{t_0})}$ is compactly contained in $\Omega^+(u) \cup \{x \in \partial \Omega, u(x) > v_{t_0}(x)\} \equiv \Omega_0^+(u)$ (we used here assumption (b)). We can therefore choose $\varepsilon > 0$ small enough such that

$$\overline{\Omega} \cap N_\varepsilon(\Omega^+(v_{t_0})) \subset \Omega_0^+(u).$$

By assumption (d), there is then a $\delta > 0$ such that

$$\Omega^+(v_t) \subset \Omega \cap N_\varepsilon(\Omega^+(v_{t_0})) \subset \Omega^+(u) \text{ if } |t - t_0| \leq \delta.$$  

(10.3)

Thus $u$ is harmonic in $\Omega^+(v_t)$ while $v_t$ is subharmonic, and, by the maximum principle (using (b)), $v_t < u$ in $\Omega^+(v_t)$ if $|t - t_0| \leq \delta$. Since obviously $v_t \leq u$ in $\Omega^-(v_t) \setminus \Omega^-(u)$, it remains to show that

$$v_t \leq u \text{ in } \Omega^-(u).$$

(10.4)

Observe that (10.3) implies that

$$\Omega^- (u) \subset \Omega \setminus \overline{\Omega^+(u)} \subset \Omega \setminus \overline{\Omega^+(v_t)} = \Omega^-(v_t)$$

(10.5)

if $|t - t_0| \leq \delta$. For such $t$'s we introduce the function

$$w_t^\tau = v_t - u - \tau \text{ for any small } \tau > 0.$$  

It satisfies (by (10.5))

$$\Delta w_t^\tau + \lambda w_t^\tau \geq -\lambda \tau \text{ in } \Omega^-(u).$$

(10.6)

It will be convenient to work with the functions

$$W_t^\tau = \max\{w_t^\tau, 0\}.$$  

(10.6)

By Lemma 10.2

$$\Delta W_t^\tau + \lambda W_t^\tau \geq -\lambda \tau \text{ in } \Omega^-(u).$$

(10.7)

Also, $v_t \leq u$ on $\partial \Omega^-(u)$ so that $w_t^\tau \leq -\tau$ on $\partial \Omega^-(u)$, and consequently $W_t^\tau = 0$ in some $\eta$-neighborhood of $\partial \Omega^-(u)$; hence

$$\text{supp } W_t^\tau \subset \Omega^-(u).$$

(10.8)

Without loss of generality we may assume that $\Omega^-(u)$ is connected (otherwise we restrict $W_t^\tau$ to each component of $\Omega^-(u)$). Extending $W_t^\tau$ by 0 into $\mathbb{R}^n \setminus \Omega^-(u)$ we then have, by (10.7),

$$\Delta W_t^\tau + \lambda W_t^\tau \geq -\lambda \tau \text{ in } \mathcal{D}'(\mathbb{R}^n).$$

Since $\lambda < \lambda_G$, we can choose a subdomain $G$ of $\Omega$ such that $\overline{\Omega^-(u)} \subset G$ and $\lambda < \lambda_G$. Denote by $W_t^{\tau, \sigma}$ $\sigma$-mollifiers of $W_t^\tau$. Then

$$\Delta W_t^{\tau, \sigma} + \lambda W_t^{\tau, \sigma} \geq -\lambda \tau \text{ in } \mathbb{R}^n$$

(10.9)
and, for small enough $\sigma$,

$$\text{supp } W_i^{r,\sigma} \subseteq G.$$ 

Consider the principal eigenfunction $\varphi$ of $\Delta$ in $G$:

\begin{equation}
\varphi > 0, \Delta \varphi + \lambda_G \varphi = 0 \text{ in } G, \quad \varphi = 0 \text{ on } \partial G.
\end{equation}

By Sard’s theorem, $\partial\{\varphi > \rho\}$ is smooth for almost every $\rho > 0$. We choose $\rho$ small enough so that also

$$\text{supp } W_i^{r,\sigma} \subset \{\varphi > \rho\}.$$ 

Then, by Green’s formula and (10.9), (10.10),

$$0 = \int_{\partial(\varphi > \rho)} (\varphi \frac{\partial W_i^{r,\sigma}}{\partial \nu} - W_i^{r,\sigma} \frac{\partial \varphi}{\partial \nu}) \quad = \quad \int_{\{\varphi > \rho\}} (\varphi \Delta W_i^{r,\sigma} - W_i^{r,\sigma} \Delta \varphi)$$

$$\geq (\lambda_G - \lambda \int \varphi W_i^{r,\sigma} - \lambda \tau \int \varphi.$$ 

Taking $\rho \to 0$ and then $\sigma \to 0$, we obtain

$$\lambda \tau \int \varphi \geq (\lambda_G - \lambda \int \varphi W_i^{r} = (\lambda_G - \lambda \int \varphi W_i^{r}.$$ 

Letting, finally, $\tau \to 0$ we get

$$0 \geq (\lambda_G - \lambda \int \varphi(v_t-u)_+$$

and, since $\lambda_G - \lambda > 0$, $(v_t-u)^+ = 0$ in $\Omega^-(u)$, which completes the proof of (10.4).

We shall need later on to work with specific families of subsolutions. A very general construction was given in [5; Lemma 10] in case $\lambda = 0$. However this construction does not extend to the case $\lambda > 0$. We shall therefore have to be content with a much smaller family:

**Lemma 10.4** Let $u$ be a weak solution (as in Definition 10.1), and let

\begin{equation}
v_\sigma(x) = \sup_{B_\sigma(x)} u, \quad \sigma > 0.
\end{equation}

Then $v_\sigma$ is a subsolution in the open set $\Omega_\sigma = \{x \in \Omega, \text{dist}(x,\partial \Omega) > \sigma\}$, and every point of $F(v_\sigma)$ is regular.

This is a generalization of Lemma 8 of [5], where the case $\lambda = 0$ was considered.

**Proof.** Since $u$ is continuous in $\Omega$, $v_\sigma$ is obviously continuous in $\Omega_\sigma$. In the open set $\Omega^+(v_\sigma)$, $v_\sigma$ is locally the supremum of an equicontinuous family of translations of harmonic functions $u(x+\epsilon)$; hence $v_\sigma$ is subharmonic in $\Omega^+(v_\sigma)$, and it vanishes on $\partial \Omega^+(v_\sigma) \cap \Omega$.

Next we proceed analogously to Lemma 10.2 to prove that

\begin{equation}
\Delta v_\sigma + \lambda v_\sigma \geq 0 \text{ in } \Omega^-(v_\sigma).
\end{equation}
Let $w$ be the solution to

$$\Delta w = -\lambda v_\sigma \text{ in } B, \quad w = 0 \text{ on } \partial B$$

where $B$ is a ball in $\Omega^-(v_\sigma)$. For any $e \in B_\sigma(0)$, we have

$$\Delta(u_e - w) \geq 0 \text{ in } B, \quad \text{where } u_e(x) = u(x + e).$$

Take any ball $B_0 \subseteq B$ and let $h$ be the harmonic function in $B_0$ with boundary values $v_\sigma - w$. Then $h \geq u_e - w$ on $\partial B_0$ and, since $u_e - w$ is subharmonic, $h \geq u_e - w$ in $B_0$. It follows that $h \geq v_\sigma - w$ in $B_0$. Hence $v_\sigma - w$ is subharmonic in $B$, and

$$\Delta v_\sigma + \lambda v_\sigma = \Delta(v_\sigma - w) \geq 0 \text{ in } B,$$

and the proof of (10.12) is complete. To show that $v_\sigma$ is a weak subsolution we next need to verify the free boundary condition for subsolutions.

Let $x_0 \in F(v_\sigma)$. We claim that there exists a point $y_0 \in F(u)$ such that $y_0 \in \partial B_\sigma(x_0)$. Indeed, there is sequence $x_m \in \Omega^+(v_\sigma)$ such that $x_m \to x_0$ (and then $v_\sigma(x_m) \to v_\sigma(x_0) = 0$). By definition of $v_\sigma$,

$$B_\sigma(x_m) \cap \Omega^+(u) \neq \emptyset \quad \text{(since } x_m \in \Omega^+(v_\sigma)).$$

Now, $u$ is harmonic in $B_\sigma(x_m) \cap \Omega^+(u)$, so that by the maximum principle,

$$u > 0 \text{ at some points on } \partial(B_\sigma(x_m) \cap \Omega^+(u))$$

Consequently $\partial B_\sigma(x_m) \cap \Omega^+(u) \neq \emptyset$. It follows that there exists a sequence $y_m \in \partial B_\sigma(x_m) \cap \Omega^+(u)$ such that $u(y_m) > 0$, $y_m \to y_0$ and, therefore,

$$0 < u(y_m) \leq \sup_{B_\sigma(x_m)} u = v_\sigma(x_m).$$

Letting $m \to \infty$ we see that $u(y_0) = 0$. Hence $y_0 \in F(u) \cap \partial B_\sigma(x_0)$ and the claim is proven.

Since $u(y) \leq \sup_{B_\sigma(x_0)} u = v_\sigma(x_0) = 0$ for all $y \in B_\sigma(x_0)$, it follows that $B_\sigma(x_0)$ is tangent to $F(u)$ at $y_0$, from $\Omega^-(u)$. By definition of the weak solution $u$ we then have

$$u(y) = \alpha < y - y_0, \nu >_+ -\beta < y - y_0, \nu >_+ + o(|y - y_0|)$$

with $\alpha = G(\beta)$, where $\nu$ is the outer normal to $\partial B_\sigma(x_0)$ at $y_0$.

For $x$ near $x_0$ the point $y = y_0 + x - x_0$ is near $y_0$ and $|y - x| = |y_0 - x_0| = \sigma$, $y \in \overline{B_\sigma(x)}$.

By definition of $v_\sigma$ and (10.13) we then have

$$v_\sigma(x) \geq u(y) = \alpha < x - x_0, \nu >_+ -\beta < x - x_0, \nu >_+ + o(|x - x_0|).$$

Hence $v_\sigma$ satisfies the free boundary condition (10.2).

Finally it remains to prove that all points of $F(v_\sigma)$ are regular. Let $x_0 \in F(v_\sigma)$, and choose $y_0 \in F(u)$ with $y_0 \in \partial B_\sigma(x_0)$, as above. For any $x \in B_\sigma(y_0)$ we have $y_0 \in B_\sigma(x)$, and since $y_0 \in F(u) = \partial \Omega^+(u)$, $B_\sigma(x) \cap \Omega^+(u) \neq \emptyset$. It follows that $v_\sigma(x) > 0$. Hence $B_\sigma(y_0) \subset \Omega^+(v_\sigma)$ and, since $x_0 \in \partial B_\sigma(y_0)$, $B_\sigma(y_0)$ is tangent to $F(v_\sigma)$ at $x_0$ from $\Omega^+(v_\sigma)$. 27
11. \( \varepsilon \)-monotonicity and flatness imply Lipschitz.

**Definition 11.1** A function \( u \) defined in an open set \( \Omega \) is said to be \( \varepsilon \)-monotone in the direction \( \tau \) (\( \tau \) is a unit vector) if \( u(x + h\tau) \geq u(x) \) for all \( h \geq \varepsilon \) and \( x, x + h\tau \) in \( \Omega \).

**Lemma 11.1.** Let \( u \) be \( 1 \)-monotone function in a direction \( e \), in the ball \( B_M \) of \( \mathbb{R}^n \), satisfying

\[ \Delta u + \lambda u = 0 \text{ with } \lambda \geq 0. \]

If \( M = M(n) \) is large enough then \( D_e u(0) \geq 0 \), where \( D_e \) is the directional derivative.

The case \( \lambda = 0 \) coincides with Lemma 1 in [6].

**Proof.** For any \( 1 < \mu < \frac{1}{2} M \) the function

\[ w_\mu(x) = u(x + \mu e) - u(x) \]

is nonnegative and

\[ \Delta w_\mu + \lambda w_\mu = 0 \text{ in } B_{M/2}. \]

We claim that

\[ \lambda \leq \frac{C}{M^2}. \]

Indeed, if \( (\lambda_1, \varphi) \) is the principal eigenvalue for \( \Delta \) in \( B_{M/2} \) with \( \varphi > 0 \) in \( B_{M/2} \), \( \varphi = 0 \) on \( \partial B_{M/2} \), then

\[ 0 \leq -\int_{\partial B_{M/2}} w_\mu \frac{\partial \varphi}{\partial \nu} = \int_{B_{M/2}} (\varphi \Delta w_\mu - w_\mu \Delta \varphi) = (\lambda_1 - \lambda) \int_{B_{M/2}} \varphi w_\mu. \]

Since the last integral is positive, we get \( \lambda \leq \lambda_1 \leq C/M^2 \).

Making use of the estimate (11.1), we can apply Harnack’s inequality [14; p.199] to \( w_\mu(Mx) \) in \( B_{1/2} \). We then conclude that

\[ \frac{1}{c_0} \leq \frac{w_\mu(x)}{w_\mu(y)} \leq c_0 \quad \forall x, y \in B_{M/4}, \]

where \( c_0 = c_0(n) > 1 \).

Set

\[ \tilde{w}_\mu(x) = u(x + \mu e) - u(x + (\mu - 1)e). \]

By the same argument as before,

\[ \frac{1}{c_0} \leq \frac{\tilde{w}_\mu(x)}{\tilde{w}_\mu(y)} \leq c_0 \quad \forall x, y \in B_{M/4}. \]

Taking, in particular, \( 0 < \mu < \frac{1}{8} M \), \( x = y - (\mu - 1)e \) and \( y \in B_{M/8} \), we get

\[ \frac{1}{c_0} \leq \frac{\tilde{w}_\mu(y)}{w_1(y)} \leq c_0. \]
Now take \( \mu \) to be an integer and write
\[
    w_{\mu}(y) = \tilde{w}_{\mu}(y) + \tilde{w}_{\mu-1}(y) + \ldots + \tilde{w}_2(y) + w_1(y).
\]

Then, by the previous inequality,
\[
    \frac{\mu}{c_0} w_1(y) \leq w_{\mu}(y) \leq \mu c_0 w_1(y) \quad \forall y \text{ in } B_{M/8}
\]

and, by (11.2),
\[
    (11.3) \quad \frac{1}{c_0^2} \leq \frac{w_{\mu}(x)}{\mu w_1(y)} \leq c_0^2 \quad \text{if } x, y \in B_{M/8}.
\]

Because of the 1-monotonicity, if \( \mu \geq 2 \) then
\[
    w_{[\mu]-1} \leq w_{\mu} \leq w_{[\mu]+2}
\]

and, consequently, (11.3) holds for any \( \mu \) with \( 2 \leq \mu \leq \frac{1}{8} M \).

By the gradient estimates for the Poisson equation [14; p.37] and Harnack’s inequality (11.2), we have, in \( B_{M/8} \),
\[
    |D_\varepsilon w_{\mu}| \leq \frac{C_1}{M} w_{\mu}(0) + \lambda C_1 M w_{\mu}(0) \leq \frac{C}{M} w_{\mu}(0)
\]

where \( C, C_1 \) are positive constants independent of \( M \).

We can now estimate, by (11.2),
\[
    \frac{1}{c_0} w_1(0) \leq w_1(2\varepsilon) = u(3\varepsilon) - u(2\varepsilon) = \int_2^3 D_\varepsilon u(\mu\varepsilon)d\mu
\]
\[
    = \int_2^3 D_\varepsilon w_{\mu}(0)d\mu + D_\varepsilon u(0) \quad \text{(since } D_\varepsilon w_{\mu}(0) = D_\varepsilon u(\mu\varepsilon) - D_\varepsilon u(0))
\]
\[
    \leq \frac{C}{M} \int_2^3 w_{\mu}(0)d\mu + D_\varepsilon u(0) \quad \text{(by (11.4))}
\]
\[
    \leq \frac{C}{M} w_1(0) + D_\varepsilon u(0) \quad \text{(by (11.3)).}
\]

Hence
\[
    D_\varepsilon u(0) \geq \left( \frac{1}{c_0} - \frac{C}{M} \right) w_1(0) > 0 \quad \text{if } M \text{ is large enough},
\]

and the lemma follows.

Denote by \( \Gamma(\theta, \varepsilon) \) the cone with axis in the direction of the unit vector \( \varepsilon \) and opening \( \theta, 0 < \theta < \pi/2 \).

**Definition 11.2.** Let \( \varepsilon_0 > 0 \). A function \( u \) defined in an open set \( \Omega \) is said to be \( \varepsilon_0 \)-**monotone** in a subset \( G \) (of \( \Omega \)) in the direction \( \Gamma(\theta, \varepsilon) \) if
\[
    u(x) \geq \sup_{|y| \leq \sin \theta} u(x - \varepsilon(e + y)) \quad \forall x \in G,
\]
for any $\varepsilon \geq \varepsilon_0$ such that the cone with vertex $x$ and base \( \{ x - \varepsilon(e + y), \ |y| \leq \sin \theta \} \) is contained in $\Omega$. If in the above definition $\varepsilon_0 = 0$ then we say that $u$ is fully monotone in the direction $\Gamma(\theta, \varepsilon)$.

In case $\theta = 0$ and $G = \Omega$, this definition coincides with Definition 11.1 when $\tau = e$.

Lemma 11.1 yields:

**Corollary 11.2.** Let $u$ be a weak solution of the free boundary problem, as in Definition 10.1. Then there exists a positive constant $M(n)$ such that if $u$ is $\varepsilon_0$-monotone in $\Omega$ in the direction $\Gamma(\theta, \varepsilon)$ then $u$ is monotone in the direction $\Gamma(\theta, \varepsilon)$ outside $M\varepsilon_0$-neighborhood of the free boundary $F(u)$.

Indeed, this follows by working with the scaled function $\tilde{u}(x) = u(x_0 + \varepsilon_0 x)$, where $\text{dist}(x_0, F(u)) > M\varepsilon_0$.

In the next theorem we show that if $u$ is $\varepsilon$-monotone then "flat" free boundaries are Lipschitz. In the case $\lambda = 0$ (where $u_\pm$ are both harmonic) a more general result was established in Theorem 1 of [6]; that result was based on the construction of subsolutions in Lemma 4 of [6]. Such a construction however does not seem possible in the case $\lambda > 0$ (cf. the remark preceding Lemma 10.4).

We denote by $e_n$ the unit vector in the $x_n$-direction.

**Theorem 11.3** Let $u$ be a weak solution, as in Definition 10.1, in the cylinder $C_2 = B_2(0) \times (-2, 2)$ in $\mathbb{R}^n$. Assume that $\lambda < \lambda c_2$ and that

(i) the free boundary $F(u)$ lies in the strip $\{|x_n| < \varepsilon\}$;

(ii) $u$ is $\varepsilon$-monotone in $C_2$ in the direction $\Gamma(\theta, e_n)$;

(iii) $u$ is fully monotone on $\partial C^\varepsilon$ in the direction $\Gamma(\theta, e_n)$, where

\[ C^\varepsilon = C_1 \cap \{|x_n| < \sqrt{\varepsilon}\}, \quad C_1 = B_1(0) \times (-1, 1). \]

Then $u$ is fully monotone in $C_1$ in the direction $\Gamma(\theta, e_n)$; in particular, $F(u)$ is a Lipschitz graph in $C_1$ with respect to any direction in $\Gamma(\theta, e_n)$.

In Section 13 we shall improve Theorem 11.3, by removing the $\varepsilon$-monotonicity assumption.

**Proof.** Note that (i) and (ii) imply that $u > 0$ in \( \{ x_n > \varepsilon \} \) and $u < 0$ in \( \{ x_n < -\varepsilon \} \). For any $0 < \sigma < \varepsilon$ let $u_\sigma(x) = u(x - \sigma e_n)$ and introduce

\[ v_\sigma(x) = \sup_{B_\sigma \sin \theta(x)} u_1(y). \]

By Lemma 10.4 $v_\sigma$ is a subsolution and every point of $F(v_\sigma)$ is regular.

To show that $u$ is fully monotone in the direction $\Gamma(\theta, e_n)$ in the set $C_1$ we have to prove that

\[ u(x) \geq v_\sigma(x) \text{ in } C_1, \text{ for any } 0 < \sigma < \varepsilon. \]

Now, by Corollary 11.2, $u$ is fully monotone in the direction $\Gamma(\theta, e_n)$ in \( \{ x_n > M\varepsilon \} \) and in \( \{ x_n < -M\varepsilon \} \), so that

\[ u(x) \geq v_\sigma(x) \text{ if } |x_n| \geq M\varepsilon. \]

Hence to prove (11.5) it suffices to show that for $\varepsilon$ sufficiently small

\[ u(x) \geq v_\sigma(x) \text{ in } C^\varepsilon, \text{ for any } 0 < \sigma < \varepsilon. \]
We claim that

(11.8) \[ F(v_\sigma) \text{ lies above } F(u) \text{ in } C^\varepsilon, \]

that is, if \( u(x', x_n) = 0, v(x', \bar{x}_n) = 0 \) and both points lie in \( C^\varepsilon \) then \( \bar{x}_n \leq x_n \). To prove this we note that, by assumption (iii),

(11.9) \[ u(x) \geq v_\sigma(x) \text{ on } \partial C^\varepsilon \]

so that

(11.10) \[ F(v_\sigma) \text{ lies above } F(u) \text{ on } \partial C^\varepsilon. \]

By the proof of Lemma 10.4, the distance from every point of \( F(v_\sigma) \) to \( F(u_1) \) is \( \leq \sigma \). Hence \( F(v_\sigma) \cap C^\varepsilon \) lies in \( |x_n| < 2\varepsilon \).

Suppose now that (11.8) is not true, and introduce translates of \( u \),

\[ u_\tau(x) = u(x + \tau e_n) \text{ in } C^\varepsilon_\tau = C_2 - \tau e_n, \tau \geq 0. \]

Then \( F(u_\tau) = F(u) - \tau e_n \) and there exists a smallest \( \tau > 0 \) such that

(11.11) \[ F(v_\sigma) \text{ lies above } F(u_\tau) \text{ in } C^\varepsilon \]

and the two sets intersect at some point \( x_0 \in \overline{C_\varepsilon} \). By (11.10), \( x_0 \in C^\varepsilon_\tau \). Since \( F(v_\sigma) \cap C^\varepsilon \) lies in \( \{|x_n| \leq 2\varepsilon\} \), we also have

\[ 0 < \tau < 3\varepsilon, \quad x_0 \in \{|x_n| \leq 2\varepsilon\}. \]

Recalling (11.6), it follows that if \( \varepsilon \) is small enough then in the \( \tau \)-neighborhood of \( B_1(0) \times \{\frac{1}{2\sqrt{\varepsilon}} < |x_n| < 2\sqrt{\varepsilon}\} \) \( u \) is fully monotone in the direction \( \Gamma(\theta, e_n) \). Hence

(11.12) \[ u_\tau(x) \geq u(x) \geq v_\sigma(x) \text{ on } \partial C^\varepsilon_\tau \cup \{B_1(0) \times \{\frac{1}{2\sqrt{\varepsilon}} < |x_n| < 2\sqrt{\varepsilon}\}\}, \]

where \( C^\varepsilon_\tau = C^\varepsilon - \tau e_n \). In particular \( u_\tau \geq v_\sigma \) on \( \partial C^\varepsilon_\tau \) and, by (11.11),

(11.13) \[ u_\tau(x) \geq v_\sigma(x) \text{ on } \partial(C^\varepsilon_\tau \cap \{v_\sigma > 0\}). \]

Since \( u_\tau \) is harmonic in \( C^\varepsilon_\tau \cap \{v_\sigma > 0\} \) while \( v \) is subharmonic, the maximum principle yields

(11.14) \[ u_\tau(x) > v_\sigma(x) \text{ in } C^\varepsilon_\tau \cap \{v_\sigma > 0\}. \]

Indeed, otherwise we have \( u_\tau \equiv v_\sigma \) in this set and, by (11.12), \( u_\tau \equiv u > 0 \) in the same set. By analytic continuation \( u_\tau \equiv u > 0 \) everywhere in \( \left( B_1(0) \times \{-\sqrt{\varepsilon} < x_n < 2\sqrt{\varepsilon}\}\right) \cap \{u > 0\} \), which is a contradiction.

From (11.12) we infer that

\[ u_\tau(x) \geq v_\sigma(x) \text{ on } \partial(C^\varepsilon \cap \{u_\tau < 0\}). \]

We can then proceed precisely as in the proof of (10.4) and establish that

\[ u_\tau(x) \geq v_\sigma(x) \text{ in } C^\varepsilon \cap \{u_\tau < 0\}. \]
Combining this with (11.14) we deduce that

\[ u_\tau(x) \geq v_\sigma(x) \quad \text{in } C_\tau^\varepsilon \cap C_\varepsilon. \]

Since every point of \( F(v_\sigma) \) is regular, Lemma 10.1 can then be applied to conclude that \( F(v_\sigma) \cap F(u_\tau) \cap (C_\tau^\varepsilon \cap C_\varepsilon) = \emptyset \), a contradiction since \( x_0 \) belongs to this set.

Having proved (11.8) we can now apply the maximum principle (as in the proof of (11.14)) to conclude that

\[ (11.15) \quad u > v_\sigma \quad \text{in } \Omega^+(v_\sigma) \cap C_\varepsilon. \]

Since \( u \) is fully monotone on \( \partial C_\varepsilon \) in the direction \( \Gamma'(\theta, e_n) \), we have that \( u \geq v_\sigma \) on \( \partial C_\varepsilon \). Using this inequality and (11.15), we can argue as in the proof of Lemma 10.3 and show that \( v_\sigma - u - \tau \leq 0 \) in \( C_\varepsilon \setminus \Omega^+(v_\sigma) \), for any \( \tau > 0 \). (Here we need the assumption that \( \lambda < \lambda_{c_2} \).) Hence \( u \geq v_\sigma \) in all of \( C_\varepsilon \), i.e., (11.7) is satisfied.

The assertion about the Lipschitz continuity of \( F(u) \) is an immediate consequence of the full monotonicity of \( u \) in the direction \( \Gamma'(\theta, e_n) \).

**12. Auxiliary estimates.** In the next section we shall improve Theorem 11.3 by dropping the assumption (ii) of \( \varepsilon \)-monotonicity. To accomplish this we need some auxiliary results. The first lemma shows that “flatness” implies \( \varepsilon \)-monotonicity for \( u_+ \); more precisely:

**Lemma 12.1.** Suppose \( u \) is a weak solution (as in Definition 10.1) in \( C_2 = B_2(0) \times (-2, 2) \) satisfying:

(i) the free boundary \( F(u) \) lies in the strip \( |x_n| < \varepsilon \),
(ii) there exists positive constants \( \alpha_0 \) and \( \alpha_1 \) such that

\[ \alpha_0 d(x, F) \leq u_+(x) \leq \alpha_1 d(x, F) \quad \text{in } \Omega^+(u) \]

where \( d(x, F) \) is the distance from \( x \) to \( F(u) \). Then for any \( 0 < \theta < \frac{\pi}{2} \) there exist \( \delta = \delta(\theta) > 0 \) and \( c = c(\theta) > 0 \) such that \( u_+ \) is \( \varepsilon \varepsilon \)-monotone in \( C_1 \cap \{ |x_n| < \frac{\varepsilon}{2} \} \) in the direction \( \Gamma'(\theta, e_n) \).

**Proof.** Although the proof is contained in the arguments developed in the proof of Theorem 2’ in [6; p.73], we shall present it here in detail in order to make it clear, later on (in the proof of Lemma 12.2), how the result can be extended to \( u_- \) which satisfies \( \Delta u_- + \lambda u_- = 0 \).

Let \( A = \{ x_n = -\varepsilon \} \). Denote by \( v \) the harmonic function in \( C_3 \cap \{ x_n > -\varepsilon \} \) with boundary values \( u_+ \). Observe that \( v = 0 \) on \( \{ x_n = -\varepsilon \} \). By the maximum principle and assumption (ii),

\[ (12.1) \quad v(x) \geq u_+(x) \geq \alpha_0 (d(x, A) - \varepsilon). \]

By Lemma 5 in [5], for any \( 0 < \theta < \frac{\pi}{2} \) there exists a \( \delta = \delta(\theta) \) such that \( v \) is fully monotone in the direction \( \Gamma'(\theta, e_n) \) in a \( \delta \)-neighborhood of \( A \) which lies in \( C_1 \). In particular, if \( \delta \geq d(x, A) \geq c_1 \varepsilon \) then \( D_\tau v \geq 0 \) for any \( \tau \in \Gamma'(\theta, e_n) \). It then follows by Lemma 4 of [5], properly scaled, that

\[ (12.2) \quad \frac{D_\tau v(x)}{v(x)} d(x, A) \geq c_2(\theta) > 0. \]

Hence, by (12.1),

\[ (12.3) \quad D_\tau v(x) \geq \alpha_0 c_2 - \frac{\alpha_0 \varepsilon}{d(x, A)} \geq \alpha_0 (c_2 - \frac{1}{c_1}) \equiv c_3 > 0. \]
if $c_1$ is large enough.

On the other hand, by the maximum principle and assumption (ii),

\begin{equation}
    v(x) \leq \alpha_1 d(x, A) = \alpha_1 (x_n + \varepsilon) \text{ in } C_1 \cap \{x_n \geq -\varepsilon\}
\end{equation}

so that $v(x) \leq 2\alpha_1\varepsilon$ if $x_n = \varepsilon$. Using the maximum principle, we get

\begin{equation}
    v(x) \leq u_+(x) + 2\alpha_1\varepsilon
\end{equation}

in $C_1 \cap \{x_n \geq \varepsilon\}$; by (12.4), the inequality (12.5) holds also if $\{-\varepsilon \leq x_n \leq \varepsilon\}$.

We can now complete the proof of the lemma as follows:

If $\varepsilon$ is small enough then for all $x \in C_1 \cap \{-\varepsilon < x_n < \delta\}$ and $\tau \in \Gamma(\theta, e_n)$,

\begin{align*}
    u_+(x + c_4\varepsilon \tau) - u_+(x) &\geq v(x + c_4\varepsilon \tau) - 2\alpha_1\varepsilon - v(x) \quad \text{(by (12.1), (12.5))} \\
    &= \int_0^{c_4\varepsilon \cos \theta} D_\tau v(x + t\tau) dt - 2\alpha_1\varepsilon \geq \int_0^{c_4\varepsilon \cos \theta} D_\tau v(x + t\tau) dt - 2\alpha_1\varepsilon \\
    &\geq c_3(c_4 - c_1/\cos \theta)\varepsilon - 2\alpha_1\varepsilon \quad \text{(by (12.3))}
\end{align*}

and the right-hand side is positive if $c_4$ is sufficiently large. If $x \in C_1 \cap \{x_n < -\varepsilon\}$ then $u_+(x + c_4\varepsilon \tau) - u_+(x) = u_+(x + c_4\varepsilon \tau) \geq 0$ for any $c_4 > 0$.

**Lemma 12.2.** Let $u$ be a weak solution in $C_2 = B_2(0) \times (-2, 2)$ satisfying assumption (i), of Lemma 12.1, and suppose that

(ii) $u_-(x) \leq \alpha_1 d(x, F)$ in $\Omega^- (u)$, and

(iii) there exist positive constants $\gamma, \eta$ (independent of $\varepsilon$) such that

$$u_-(\gamma e_n) > \eta.$$ 

If $\lambda < \lambda c_2$ then for any $0 < \theta < \pi/2$ there exist $\delta = \delta(\theta) > 0$ and $c = c(\theta) > 0$ such that $u_-$ is $c\varepsilon$-monotone in $C_1 \times \{|x_n| < \delta/2\}$ in the direction $\Gamma(\theta, e_n)$.

**Proof.** Proceeding analogously to the proof of Lemma 12.1, we introduce a function $v$ satisfying

$$\Delta v + \lambda v = 0 \text{ in } C_2 \cap \{x_n < \varepsilon\},$$

$$v = u_- \text{ on } \partial(C_2 \cap \{x_n < \varepsilon\}).$$

Since $\lambda < \lambda c_2$ such a $v$ exists and is unique.

In trying to extend the proof of Lemma 12.1 we shall need the following comparison theorem:

\begin{equation}
    \text{If } \Delta w + \lambda w \leq 0 \text{ in } D, \ w \geq 0 \ \text{on } \partial D \text{ then } w \geq 0 \text{ in } D,
\end{equation}

provided $D \subset C_2$. This is a well known result since $\lambda < \lambda c_2 < \lambda D$. We shall also need the Harnack inequality for nonnegative solutions of $\Delta w + \lambda w = 0$; this, in fact, is true for any real $\lambda$ (see [14]). From Harnack’s inequality and assumption (iii) it follows that

$$u_-(x) \geq c\eta d(x, \{x_n = -\varepsilon\}) \text{ in } C_1 \cap \{x_n < -\varepsilon\}$$

so that, together with assumption (ii), $u_-$ satisfies the same conditions as does $u_+$ in Lemma 12.1, (ii).
We finally need extensions of Lemma 4 and 5 of [5] to the equation \( \Delta w + \lambda w = 0 \). These lemmas follow directly from Lemmas 1–3 of [5], so that it only remains to extend these three lemmas to solutions of \( \Delta w + \lambda w = 0 \). Lemma 1 is a boundary Harnack principle for harmonic functions; it is concerned with estimating the quotient \( u_1/u_2 \) of two positive harmonic functions from above and from below near the boundary [10] [8]. Its extension to solution of \( \Delta u_1 + \lambda u_1 = 0 \) was established in [9] [24]. Lemma 2 establishes the Hölder continuity for the quotient \( u_1/u_2 \) [16] [4] and the proof (as given in [16]) extends to solution of \( \Delta u_1 + \lambda u_1 = 0 \); see also [9; p.192]. Finally Lemma 3 shows how \( u_1 \), near the boundary, is dominated by values of \( u_1 \) away from the boundary [10] [8]; the proof follows by taking \( u_2 = y + \varepsilon \) in Lemma 1 (the bottom boundary is assumed to be \( y = -\varepsilon \)). To get the extension of Lemma 3 to the case of \( \Delta u + \lambda u = 0 \) we again take \( u_2 = y + \varepsilon \) but use an extension of Lemma 1 (given in [9] [24]) to estimate \( u_1/u_2 \) in the case where \( u_1 \) is a solution of \( \Delta u_1 + \lambda u_1 = 0 \).

We next need some gradient estimates.

**Lemma 12.3.** Let \( u \) be a nonnegative function in \( \Omega \cap B_1 \) satisfying

\[
\Delta u + \lambda u = 0 \text{ in } \Omega \cap B_1, \quad \lambda \geq 0.
\]

Assume that

(i) \( u \) vanishes on \( (\partial \Omega) \cap B_1 \), and

(ii) for any point \( x_0 \in (\partial \Omega) \cap B_1 \) for which there is a tangent ball from inside \( \Omega \),

\[
\liminf_{\varepsilon \downarrow 0} \frac{u(x_0 + \varepsilon \nu)}{\varepsilon} \leq c_0,
\]

where \( \nu \) is the inner normal. Then \( u \) is Lipschitz continuous in \( \Omega \cap B_{1/2} \) and

\[
|\nabla u|_{L^\infty(\Omega \cap B_{1/2})} \leq Cc_0.
\]

For \( \lambda = 0 \) this result is Lemma A2 in [6]. The proof given below is similar except for minor changes.

**Proof.** We may assume that \( c_0 = 1 \). It is enough to prove that \( u(x) \leq C d(x, \partial \Omega) \), for (12.7) then follows from interior gradient estimates, properly scaled. Set \( h = d(x, \partial \Omega) \) \((0 < h < \frac{1}{2})\). Then the ball \( B_h(x) \) is tangent to \( \partial \Omega \) at some point \( x_0 \). By Harnack's inequality

\[
\inf_{B_{h/2}} u \geq c_0 u(x).
\]

If \( v \) is the harmonic function in \( B_h(x) \setminus \overline{B_{h/2}(x)} \) with \( v = 0 \) on \( \partial B_h(x) \) and \( v = c_0 u(x) \) on \( \partial B_{h/2}(x) \) then, by comparison, \( v \leq u \) (since \( u \) is supersolution). It follows that

\[
\liminf_{\varepsilon \downarrow 0} \frac{v(x_0 + \varepsilon \nu)}{\varepsilon} \leq \liminf_{\varepsilon \downarrow 0} \frac{u(x_0 + \varepsilon \nu)}{\varepsilon} \leq 1.
\]

Since \( v(y) = v_0(|y - x|) \) (a radially symmetric function), we can easily compute that

\[
\lim_{\varepsilon \downarrow 0} \frac{v(x_0 + \varepsilon \nu)}{\varepsilon} = c_1 \frac{u(x)}{h}.
\]

Consequently \( u(x) \leq h/C_1 = C \operatorname{dist}(x, \partial \Omega) \).

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COROLLARY 12.4. If in Definition 10.1 of weak solution the parameters $\alpha, \beta$ are uniformly bounded, then the weak solution is Lipschitz continuous.

In the next two lemmas we shall use the monotonicity theorem and its proof.

**Lemma 12.5.** Let $u$ be a weak solution in $C_1 = B_1(0) \times (-1, 1)$ and let $0 \in F(u)$. Denote points in $C_1$ by $(x', y)$ where $x' \in B_1$, $-1 < y < 1$. If near 0

\begin{align*}
(12.8) \quad & u_+(x', y) \geq \alpha y_+ + o(|x|), \\
(12.9) \quad & u_-(x', y) \geq \beta y_- + o(|x|),
\end{align*}

where $\alpha \geq 0$, $\beta \geq 0$, then

\begin{equation}
(12.10) \quad c(n)\alpha^2\beta^2 \leq \lim\inf_{R \to 0} \phi(R)
\end{equation}

where $c(n) > 0$ and

\begin{equation}
(12.11) \quad \phi(R) = \frac{1}{R^n} \int_{B_R} \frac{\rho^{2-n} |
abla u_+|^2}{R} \cdot \int_{B_R} \rho^{2-n} |
abla u_-|^2 \quad (B_R = B_R(0)).
\end{equation}

This result is stated without proof in [6; A3].

**Proof.** We may assume that $\alpha > 0$, $\beta > 0$. Denote by $S_r^\pm$ the support of $u_\pm$ on $S_r = \partial B_r$.

From (12.8), (12.9) we have

\begin{equation}
H^{n-1}(S_r^\pm) > \frac{1}{4} H^{n-1}(S_r) \quad \text{for all } r \text{ small},
\end{equation}

so that

\begin{equation}
H^{n-1}(S_r^\pm) \leq \frac{3}{4} H^{n-1}(S_r).
\end{equation}

Hence, by (7.5),

\begin{equation}
\frac{\beta_r^\pm}{\sqrt{\alpha_r^\pm}} \geq \psi(\frac{3}{4}) = \frac{1}{2}.
\end{equation}

By the proof of (7.7) it then follows that

\begin{equation}
(12.12) \quad \int_{S_r} |
abla u_\pm|^2 \geq c(n) \int_{S_r} \left( \frac{u_\pm}{r} \right)^2 \quad (r = |x| = \sqrt{|x'|^2 + y^2})
\end{equation}

where $c(n) = \frac{n-2}{2}$ if $n \geq 3$, $= \frac{1}{4}$ if $n = 2$. Substituting (12.8) into the right-hand side of (12.12) (for $u_+$) yields

\begin{equation}
\int_{S_r} |
abla u_+|^2 \geq c(n)\alpha^2 \int_{S_r} \left( \frac{y_+}{r} \right)^2 + o(r^{n-1}).
\end{equation}

If we multiply by $r^{2-n}$ and integrate over $r$, $0 < r < R$, we get

\begin{equation}
\int_{B_R} r^{2-n} |
abla u_+|^2 \geq c(n)\alpha^2 R^2 + o(R^2)
\end{equation}

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with another constant \( c(n) \). A similar inequality holds for \( u_- \) and, taking the product, the assertion (12.10) follows.

**Lemma 12.6.** Let \( u \) be a weak solution as in Definition 10.1, with uniformly bounded parameters \( \alpha, \beta \). Let the assumptions of Lemma 12.5 hold for some nonnegative numbers \( \alpha, \beta \). Then

\[
\alpha^2 \beta^2 \leq \frac{C}{R^4} (\sup_{B_{2R}} u_+)^2 (\sup_{B_{2R}} u_-)^2.
\]

**Proof.** By Corollary 12.4 \( u \) is Lipschitz continuous and therefore the monotonicity theorem (which requires \( u \) to be Hölder continuous) can be applied. Combining it with the estimate (12.10) we get

\[
\alpha^2 \beta^2 \leq \frac{C}{R^4} \int_{B_R} \rho^{2-n} |\nabla u_+|^2 \cdot \int_{B_R} \rho^{2-n} |\nabla u_-|^2, \quad 0 < R < 1.
\]

Denote by \( u_\varepsilon \) the \( \varepsilon \)-mollifier of \( u_- \). Since \( \Delta u_- + \lambda u_- \geq 0 \) in the distribution sense, we have \( \Delta u_\varepsilon + \lambda u_\varepsilon \geq 0 \) and

\[
\Delta u_\varepsilon^2 = 2|\nabla u_\varepsilon|^2 + 2u_\varepsilon \Delta u_\varepsilon \geq 2|\nabla u_\varepsilon|^2 - 2\lambda u_\varepsilon^2.
\]

Suppose \( n \geq 3 \) and introduce Green’s function in \( B_{2R} \) with pole at the origin:

\[
G(x) = \frac{1}{(n-2)\omega_n} (|x|^{2-n} - (2R)^{2-n})
\]

By Green’s formula and (12.15),

\[
- \int_{\partial B_{2R}} u_\varepsilon \frac{\partial G}{\partial \nu} + u_\varepsilon^2(0) = \int_{B_{2R}} (\Delta u_\varepsilon^2)G
\]

\[
\geq 2 \int_{B_{2R}} |\nabla u_\varepsilon|^2 G - 2\lambda \int_{B_{2R}} u_\varepsilon^2 G \geq c \int_{B_{2R}} \rho^{2-n} |\nabla u_\varepsilon|^2 - 2\lambda \int_{B_{2R}} u_\varepsilon^2 G
\]

where \( c > 0 \). Letting \( \varepsilon \to 0 \) and noting that \( u_-(0) = 0 \), we get

\[
\int_{B_{2R}} \rho^{2-n} |\nabla u_-|^2 \leq \frac{1}{c} \left[ 2\lambda \int_{B_{2R}} (u_-)^2 G - \int_{\partial B_{2R}} (u_-)^2 \frac{\partial G}{\partial \nu} \right] \leq C (\sup_{B_{2R}} u_-)^2.
\]

Similarly

\[
\int_{B_{2R}} \rho^{2-n} |\nabla u_+|^2 \leq C (\sup_{B_{2R}} u_+)^2.
\]

The same estimates hold for \( n = 2 \) if we take \( G = \frac{1}{2\pi} \log \frac{2R}{|x|} \). Substituting these estimates into (12.14), the assertion (12.13) follows.
13. Flat free boundaries are Lipschitz. The purpose of this section is to improve Theorem 11.3 by relaxing the condition (ii) of \( \varepsilon \)-monotonicity. From Lemma 12.1 we already know that \( u_+ \) is \( \varepsilon \)-monotone if \( u \) is Lipschitz continuous and nondegenerate; since we shall later on apply the results for weak solutions to the variational solution of problem (\( J_n \)), \( u_+ \) will indeed be Lipschitz continuous (Theorem 7.3) as well as nondegenerate (Theorem 6.1). If \( u_- \) is also nondegenerate then Lemma 12.2 can be used to deduce that also \( u_- \) is \( \varepsilon \)-monotone, and the same is then true of \( u = u_+ - u_- \). The following lemma tells us that if \( u_- \) is degenerate then the monotonicity of \( u_+ \) can be improved:

**Lemma 13.1.** Let \( u \) be a weak solution (as in Definition 10.1) in \( C_2 = B_2 \times (-2,2) \) with uniformly bounded parameters \( \alpha, \beta \). Assume that

\[
\alpha_0 d(x,F) \leq u_+(x) \leq \alpha_1 d(x,F) \quad \text{in } \Omega^+(u) \quad (0 < \alpha_0 < \alpha_1 < \infty),
\]

and that \( u_- (x) \leq \alpha_2 d(x,F) \) in \( \Omega^-(u) \) \( (\alpha_2 > 0) \). Set \( u_0 = u(e_n) \). Then there exist \( \theta_0 \) close to \( \frac{\pi}{2} \), \( 0 \leq \theta_0 < \frac{\pi}{2}, \varepsilon_0 > 0, \delta_0 > 0 \) and \( 0 < \sigma < 1 \), all independent of \( \varepsilon \), such that if \( u_+ \) is \( \varepsilon \)-monotone in \( \Gamma(\theta_0, e_n) \) for \( \varepsilon < \varepsilon_0 \) then there is a large constant \( C \) (independent of \( \varepsilon \)) such that either \( u_- \) is \( C\varepsilon \)-monotone in \( C_1 \cap \{|x_n| < \delta_0\} \) in the direction \( \Gamma(\theta_0, e_n) \) or the following alternative holds:

(a) if \( u_- (-e_n) \geq C\varepsilon u_0 \) then \( u \) is \( C\varepsilon^{1/8} \)-monotone in \( C_1 \cap \{|x_n| < \delta_0\} \), in the direction \( \Gamma(\theta, e_n) \) for some \( 0 < \theta < \frac{1}{2} \theta_0 \);

(b) if \( u_- (-e_n) \leq C\varepsilon u_0 \) then \( u_+ \) is \( \sigma \varepsilon \)-monotone in the domain \( C_1 - \varepsilon\tau_2 \) in the direction \( \Gamma(\theta_0 - \varepsilon\tau_1, e_n) \), for some positive constants \( \tau_1, \tau_2 \) (independent of \( \varepsilon \)).

Lemma 13.1 for \( \lambda = 0 \) coincides with Lemma 6 of [6]. As in [6; p. 68] we can iterate the lemma by taking a decreasing sequence of \( \varepsilon \)'s, say \( \varepsilon \gamma^{-j} \) \( (\gamma \gg 1, j = 1, 2\ldots) \). This allows us to deduce that either \( u \) is \( C\varepsilon \)-monotone in the direction \( \Gamma(\theta, e_n) \) for some \( 0 < \theta < \theta_0 \), or the following dichotomy holds: either

(i) \( u_+ \) is fully monotone in \( C_1 \) in the direction \( \Gamma(\theta_1, e_n) \) for some \( 0 < \theta_1 < \frac{\pi}{2} \), or

(ii) \( u_- (-e_n) \geq \varepsilon c \) for some \( c > 0 \).

In case (i) it follows that \( F(u) \) is Lipschitz continuous. In case (ii), if \( u_- (x) \leq \alpha_2 d(x,F) \) then (by Lemma 12.2) \( u_- \) is \( \varepsilon \)-monotone and the assumption (ii) in Theorem 11.3 is satisfied. Observe that the assumptions

\[
u_+(x) \leq \alpha_1 d(x,F), \quad u_-(x) \leq \alpha_2 d(x,F)
\]

hold if the parameters \( \alpha, \beta \) in Definition 10.1 are uniformly bounded, whereas the inequality

\[
u_+(x) \geq \alpha_0 d(x,F) \quad (\alpha_0 > 0)
\]

is satisfied if \( G(0) > 0 \), since \( \beta \geq 0 \) and

\[
\alpha \geq G(\beta) \geq G(0) > 0.
\]

We thus have:

**Theorem 13.2.** Let \( u \) be a weak solution (as in Definition 10.1) in \( C_2 = B_2 \times (-2,2) \) with uniformly bounded parameters \( \alpha, \beta \), and assume that \( G(0) > 0 \) and \( \lambda < \lambda_{c_2} \). If

(i) \( F(u) \) lies in \( \{|x_n| < \varepsilon\} \), and

(ii) assumption (iii) in Theorem 11.3 holds,

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then \( F(u) \cap B_1(0) \) is Lipschitz graph in any direction \( 0 \leq \theta \leq \theta_1 \) for some \( 0 < \theta_1 < \frac{\pi}{2} \); here \( B_1(0) \) is the unit ball in \( \mathbb{R}^n \).

**Remark 13.1.** In case \( \lambda = 0 \) Caffarelli [6] established Theorem 13.2 without making the assumptions \((ii)\). The reason that our result requires the additional assumption \((ii)\) originated from the fact that, when \( \lambda > 0 \), we have a much smaller class of subsolutions to work with (cf. the remarks preceding Lemma 10.4 and Theorem 11.3). However, it will be shown later on that for variational solutions (i.e., for minimizers of problem \((J_n)\)) both assumptions \((i)\) and \((ii)\) of Theorem 13.2 are satisfied.

**Proof of Lemma 13.1.** By Lemma 12.6 we have, for \( \rho < \frac{1}{4} \),

\[
(\nu^+)^2(\nu^-)^2 \leq \frac{C}{\rho^4} (\sup_{B_\rho} u^-)(\sup_{B_\rho} u^+)^2
\]

at any point \( x_0 \) where \( F(u) \cap C_{2-2\rho} \) has a tangent ball from \( \Omega^-(u) \) (or from \( \Omega^+(u) \)); by Definition 10.1,

\[
u(x) = \nu^+ < x - x_0, \nu > -\nu^- < x - x_0, \nu > +o(|x - x_0|)
\]

as \( x \to x_0 \), and \( \nu^+ = G(\nu^-) \geq \nu^- \).

We may assume that

\[
sup_{B_\rho(x_0)} u^- \leq sup_{B_\rho(x_0)} u_+.
\]

Indeed, otherwise, by nondegeneracy of \( u_+ \) and Harnack's inequality (for \( u_- \)) there exists a point \( p = -\gamma e_n (\gamma > 0) \) such that \( u_-(p) \geq \eta > 0 \) where both \( \gamma \) and \( \eta \) are independent of \( \varepsilon \). Applying Lemma 12.2 we then conclude that \( u_- \) is \( C\varepsilon \)-monotone in the direction \( \Gamma(\theta, e_n) \) for any \( 0 < \theta < \frac{\pi}{2} \), and the lemma follows.

From (13.1), (13.2) and the inequality \( \nu^+ \geq \nu^- \) it follows that for any \( x_0 \) as above,

\[
u^- \leq \frac{C}{\rho} sup_{B_\rho(x_0)} u_+,
\]

and by the nondegeneracy and linear growth assumptions on \( u_+ \),

\[
u^- \leq \frac{C}{\rho} \frac{\alpha_1}{\alpha_0} u_n(\varepsilon) \leq \frac{C}{\rho} u_0
\]

where \( C \) is used to denote a generic constant. Applying Lemma 12.3 we conclude that

\[
\| Du_- \|_{L^\infty[C_{2-4\rho} \cap N_\rho(A)]} \leq \frac{C}{\rho} u_0
\]

where \( A = \{ x_n = f(x') - \varepsilon \} \) and \( F(u) \) lies in \( C\varepsilon \)-neighborhood of the graph \( x_n = f(x') \) (see Remark in Section 3 of [6]). Since \( u_- = 0 \) if \( x_n \geq f(x') + C\varepsilon \), we then have

\[
u^- \leq \frac{C\varepsilon u_0}{\rho} \text{ in } \{ x_n \geq f(x') - C\varepsilon \}.
\]

Introduce the solution \( v \) to

\[
\Delta v + \lambda v = 0 \text{ in } D,
\]

\[
v = 0 \text{ on } A,
\]

\[
v = u_- \text{ on } \partial D \setminus A
\]
where \( D = C_{2-\rho} \cap \{ x_n \leq f(x') - C\varepsilon \} \); since \( \lambda < \lambda_{c_2} \), \( v \) exists and is unique and, by comparison,

\[
(13.7) \quad v \leq u_- \text{ in } D.
\]

Introduce also the solution \( \tilde{v} \) to

\[
\begin{align*}
\Delta \tilde{v} + \lambda \tilde{v} &= 0 \quad \text{in } D, \\
\tilde{v} &= C \frac{\varepsilon u_0}{\rho} \quad \text{on } A, \\
\tilde{v} &= u_- \quad \text{on } \partial D \setminus A.
\end{align*}
\]

Using (13.5) we easily deduce, by comparison, that

\[
(13.8) \quad u_- \leq \tilde{v} \leq v + \frac{C\varepsilon u_0}{\rho} \text{ in } D.
\]

We next apply Harnack’s inequality ([9; Theorem 5.1] [24]) to \( v \in C_{2-4\rho} \cap \{ x_n < f(x') - C\varepsilon \} \) to get for some \( K \) large, depending only on \( \| f \|_{\text{Lip}} \),

\[
v|_{C_{2-4\rho}} \leq \frac{C}{\rho K} v(-e_n) \leq \frac{C}{\rho K} u_-(e_n) \quad (\text{by (13.7)}),
\]

so that, by (13.8),

\[
u_-|_{C_{2-4\rho}} \leq \frac{C\varepsilon u_0}{\rho} + \frac{C}{\rho K} u_-(e_n).
\]

Since \( u_+ \) grows like \( d(x, F) \),

\[
u_+|_{C_{2-4\rho}} \leq C u_0.
\]

Using these estimates in (13.1) and recalling that \( u_+ \leq u_- \), we obtain

\[
(u_-)^4 \leq \frac{C}{\rho^4} \sup_{B_{2\rho}}(u_+)^2 \cdot \sup_{B_{2\rho}}(u_-)^2 \leq \frac{C}{\rho^4} u_0^2 \left( \frac{\varepsilon u_0}{\rho} + \frac{u_-(e_n)}{\rho K} \right)^2,
\]

or

\[
(13.9) \quad u_- \leq \frac{C}{\rho} u_0^{1/2} \left( \frac{\varepsilon u_0}{\rho} + \frac{C}{\rho K} u_-(e_n) \right)^{1/2}.
\]

We now proceed to consider separately the cases (a), (b).

**Case (a).** Choose \( \rho = \frac{1}{45} \) so that \( C_{2-8\rho} = C_{9/5} \). Using (13.9) we obtain, by Lemma 12.3,

\[
|Du_-|_{L^\infty} \leq C u_0^{1/2} \left( u_-(e_n) \right)^{1/2}
\]

and, therefore,

\[
u_-(x) \leq C u_0^{1/2} \left( u_-(e_n) \right)^{1/2} d(x, F(u));
\]

in particular

\[
(13.10) \quad u_-(x) \leq C u_0^{1/2} \left( u_-(e_n) \right)^{1/2} \varepsilon \text{ on } A.
\]
By the arguments used in deriving (13.7) and (13.8) (whereupon we replace (13.5) by (13.10)) we get

\begin{equation}
(13.11) \quad v \leq u_- \leq v + Cu_0^{1/2}(u_-(e_n))^{1/2} \in C_{9/5};
\end{equation}

in particular, upon using the assumption in \((a)\),

\begin{align}
(13.12) \quad v(-e_n) & \geq u_-(e_n) - Cu_0^{1/2}(u_-(e_n))^{1/2} \varepsilon \\
& \geq u_-(e_n) - C\varepsilon^{1/2}u_-(e_n) \geq cu_-(e_n) \quad (c > 0)
\end{align}

provided \(\varepsilon\) is small.

By Lemma 2 of [12] for any \(0 < \theta_0 < \frac{\pi}{2}\) there exists a harmonic function

\[ h(z) = r^\alpha g(\sigma) \quad (\alpha > 1) \]

defined in the cone \(K\) with opening \(\theta_0\) such that \(h\) vanishes on \(\partial K\), and

\[ \alpha(\alpha + n - 2) = \frac{1}{\alpha_1} \]

where

\[ \frac{1}{\alpha_1} = \inf_{K_0} \frac{\int_{K_0} |\nabla f|^2}{\int_{K_0} |f|^2} ; \]

here the infimum is taken over all \(f \in H_0^1(K_0)\) where \(K_0\) is the spherical cap of opening \(\theta_0\).

Since \(\alpha = \gamma_1\), (7.5) becomes

\[ \alpha \geq \psi(s_0) \]

where \(s_0\) is the fraction of the surface area of \(K_0\) on \(S^{n-1}\). If \(\theta_0 \rightarrow \frac{\pi}{2}\) then \(\alpha \rightarrow 1\). Indeed suppose \(\alpha \rightarrow \alpha'\) for a sequence of \(\alpha\)'s. Then \(\alpha' \geq 1\). The function \(h = r^\alpha g(\sigma)\) (for the limiting \(g\)) is harmonic in \(\{x_n > 0\}\) and vanishes on \(x_n = 0\). It must then be regular up to \(x_n = 0\) and, since \(\partial h/\partial x_n \neq 0\) at the origin (by the maximum principle), \(\alpha' = 1\).

Since \(v\) is superharmonic in \(\{x_n < f(x') - C\varepsilon\}\), by (13.12), Harnack’s inequality (for \(v\)) and the maximum principle we have, for any \(x_0 \in A \cap C_{7/5}\) and \(x\) in the cone \(x_0 + \Gamma(\theta_0, -e_n)\),

\[ v(x) \geq cu_-(e_n)h(x - x_0). \]

In particular, for \(0 < \theta < \theta_0\),

\begin{equation}
(13.13) \quad v(x) \geq c|x - x_0|^\alpha u_-(e_n) \quad \text{for} \ x_0 \in A \cap C_{7/5}, \ x \in x_0 + \Gamma(\theta, -e_n)
\end{equation}

where \(c = c(\theta) > 0\).

Recall (see the proof of Lemma 12.2) that Lemma 5 of [5] extends to our case of \(\lambda > 0\), so that

\begin{equation}
(13.14) \quad D_\tau v \geq 0 \quad \text{in} \ N_{\delta_0}(A) \cap C_1, \ \text{for} \ \tau \in \Gamma\left(\frac{\theta_0}{2}, e_n\right), \ \delta_0 = \delta_0(\theta_0).
\end{equation}
Now take any two points $x_1, x_2$ in $N_{\delta_0}(A) \cap C_1$ such that
\begin{equation}
(13.15) \quad c_1 \varepsilon^{1/8} \leq |x_1 - x_2| \leq C_2 \varepsilon^{1/8} \quad (c_1 > 0, c_2 > 0)
\end{equation}
and
\[ x_2 - x_1 \in \Gamma(\theta, -e_n), \quad 0 < \theta < \frac{\theta_0}{2}. \]
If we prove that
\begin{equation}
(13.16) \quad u_-(x_2) \geq u_-(x_1),
\end{equation}
then the assertion (a) follows.

Without loss of generality we may assume that $x_1 \in \Omega^-(u)$. Set
\[ \tau = \frac{x_2 - x_1}{|x_2 - x_1|}. \]
By (13.14) and Lemma 4 of [5] extended to the case of $\lambda > 0$ (cf. the proof of Lemma 12.2),
\[ d_x D_\tau v(x) \geq cv(x) \text{ if } x \in N_{\delta_0}(A) \cap C_1 \]
where $d_x = d(x, A)$. Using also Harnack’s inequality we find that if $x - x_1 = \mu(x_2 - x_1)$ and $\frac{1}{2} < \mu < 1$ then
\begin{equation}
(13.17) \quad D_\tau v(x) \geq \frac{c}{\delta_0} v(x_2).
\end{equation}
Hence
\begin{equation}
(13.18) \quad v(x_2) - v(x_1) = \int_0^1 D_\tau v(x_1 + t(x_2 - x_1)) |x_2 - x_1| dt \\
\geq \int_{1/2}^1 D_\tau v(x_1 + t(x_2 - x_1)) |x_2 - x_1| dt \quad \text{(since } D_\tau v \geq 0) \\
\geq \frac{c}{\delta_0} \frac{v(x_2)}{\varepsilon^{1/8}} \quad \text{(by (13.15), (13.17))}.
\end{equation}

If $\varepsilon$ is small enough then $x_2 \in \{x_0 + \Gamma(\theta, -e_n)\}$ where $x_0 \in A \cap C_1$ and $|x_2 - x_0| \geq |x_2 - x_1|$. Hence, by (13.13) and (13.15),
\[ v(x_2) \geq c \varepsilon^{a/8} u_-(e_n). \]
Substituting this into the right-hand side of (13.18), we get
\[ v(x_2) - v(x_1) \geq \frac{c}{\delta_0} u_-(e_n) \varepsilon^{a+1}. \]

If we now recall (13.11), we deduce that
\begin{equation}
(13.19) \quad u_-(x_2) \geq v(x_2) \geq v(x_1) + \frac{c}{\delta_0} u_-(e_n) \varepsilon^{a+1} \\
\geq u_-(x_1) - c \frac{\frac{1}{2}}{\delta_0} \left[ u_-(e_n) \right]^{\frac{1}{2}} \varepsilon + \frac{c}{\delta_0} u_-(e_n) \varepsilon^{a+1} \geq u_-(x_1)
\end{equation}
provided
\[
\left[ u_\ast (-e_n) \right]^{1/2} \geq c u_0^{1/2} e^{-\frac{\varepsilon}{8}}.
\]

Recall that if \( \theta_0 \to \frac{\pi}{2} \) then \( \alpha \to 1 \); hence \( \alpha < 3 \) for some \( 0 < \theta_0 < \frac{\pi}{2} \), and the last inequality is then satisfied for \( \varepsilon \) small, by the assumption in \( (a) \). It follows that (13.16) holds.

**Case (b).** In this case we still have the estimate (13.9) and the proof of [6; p. 72] is valid since we need to work only with \( u_\ast \).

14. Minimizers are weak solutions. Let \( u \) be a minimizer of \( (J_n) \). We know that \( u \) is Lipschitz continuous and

\[
\Delta u = 0 \quad \text{in} \quad \Omega^+(u), \\
\Delta u + \lambda u = 0 \quad \text{in} \quad \Omega^-(u).
\]

To prove that \( u \) is a weak solution, with

\[ (14.1) \quad G(\beta) = (\mu^2 + \beta^2)^{1/2}, \]

it remains to prove (10.1) at any admissible point \( x_0 \) of \( F(u) = \partial \Omega^+(u) \), i.e., at any point for which there is a ball \( B_\rho(z_0) \) such that either \( B_\rho(z_0) \subset \Omega^+(u) \) or \( B_\rho(z_0) \subset \Omega^-(u) \), and \( x_0 \in \partial B_\rho(z_0) \); for simplicity we take \( x_0 = 0 \) and \( e_n \) in the direction \( \overrightarrow{x_0z_0} \). We shall need the following lemma:

**Lemma 14.1.** Let \( \Omega_i \ (i = 1, 2) \) be open sets such that

\[ \Omega_1 \cap B_1 \subset B_\rho(z_0) \cap B_1, \]
\[ \Omega_2 \cap B_1 \subset B_1 \setminus B_\rho(z_0) \]

(see Figure 2 (a), (b)). Assume that \( u \) is Lipschitz continuous in \( \overline{\Omega_i} \) and positive in \( \Omega_i \), for either \( i = 1 \) or \( i = 2 \), and that

\[ \Delta u + \lambda u = 0 \quad \text{in} \quad \Omega_i \quad (\lambda > 0), \]
\[ u = 0 \quad \text{on} \quad \partial \Omega_i. \]

Then, near 0, \( u \) has the asymptotic behavior

\[ (14.2) \quad u(x) = \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} y + o(|x|) \quad (x = (x', y)) \]

in \( y > 0 \); furthermore, \( \alpha > 0 \) for the case \( i = 1 \).
Figure 2

The case $\lambda = 0$ with $(\sin \sqrt{\lambda} y)/\sqrt{\lambda}$ replaced by $y$ coincides with Lemma A1 in [6].

**Proof.** Consider first the case $i = 1$ and define an increasing sequence

$$
\varepsilon_k = \inf_{B_{\rho}(z_0) \cap B_2^+} \frac{u}{\lambda^{\frac{1}{2}}} \sin \sqrt{\lambda} y \quad \left( B_\mu^+ = B_\mu \cap \{ y > 0 \} \right).
$$

Since $u$ is Lipschitz, $\alpha \equiv \lim \varepsilon_k$ is finite; further,

$$
(14.3) \quad u \geq \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} y + o(|x|) \quad \text{in } B_1 \cap B_\rho(z_0).
$$

We want to prove that equality holds in (14.3).

If this is not true then there is a sequence $x_k$ with $r_k = |x_k| \to 0$ such that

$$
u(x_k) - \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} y(x_k) > \delta_0 |x_k|
$$

for some $\delta_0 > 0$. Since $u$ is Lipschitz continuous,

$$
u(x) - \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} y \geq \frac{\delta_0}{2} |x_k| \quad \text{for } x \in B_{\delta_1 r_k}(x_k)
$$

where $\delta_1 > 0$ is independent of $k$, or

$$
(14.4) \quad \frac{u(r_k x)}{r_k} - \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} r_k y \geq \frac{1}{2} \delta_0 \quad \text{for } x \in B_{\delta_1 \left( \frac{x_k}{r_k} \right)}(x_k), \frac{x_k}{r_k} \in S^{n-1}.
$$

Consider the function

$$
v(x) = \frac{u(r_k x)}{r_k} - \frac{\alpha}{\sqrt{\lambda}} \sin \sqrt{\lambda} r_k y \frac{r_k}{r_k}.
$$
It satisfies
\[ \Delta v + \lambda r^2_k v = 0 \quad \text{in} \quad B_1 \cap B_\rho(z_0). \]

By Poisson’s formula (see [9])
\[ v(x) = \int_{\partial(B_1 \cap B_\rho(z_0))} v(y) dW^\xi_k(y) \]
where
\[ \frac{1}{C} \mathcal{P}^\xi(\xi) dS_\xi \leq dW^\xi_k \leq C \mathcal{P}^\xi(\xi) dS_\xi \]
and \( \mathcal{P}^\xi(y) \) is the normal derivative of Green’s function for the Laplacian. Using (14.4) and (14.3) we get
\[ v(x) \geq \frac{\delta_0}{C} \int_{S^{n-1} \cap B_{\delta_1}(\frac{e_k}{k})} \mathcal{P}^\xi(\xi) dS_\xi - C \delta_k \int_{(S^{n-1} \setminus B_{\delta_1}(\frac{e_k}{k})) \cup \partial B_\rho(z_0)} \mathcal{P}^\xi(\xi) dS_\xi \]
where \( \delta_k \to 0 \) if \( k \to \infty \). This yields
\[ v(x) \geq 2\delta \text{ dist} \left( x, \partial B_\rho(z_0) \right) \quad \text{for some} \quad \delta > 0, \]

and therefore also
\[ v(x) \geq \delta y \geq \frac{\delta}{2} \frac{1}{\sqrt{\lambda}} \sin \sqrt{\lambda} y \]
near the origin. Since this is a contradiction to the definition of \( \alpha \), the proof of (14.2) in \( B_\rho(z_0) \) is complete. If \( x \notin B_\rho(z_0) \) and \( y > 0 \), then \( y = o(|x|) \) and since \( u(x) \geq 0 \), (14.2) is again valid. Thus (14.2) holds for all \( y > 0 \). Finally, by the strong maximum principle, \( \alpha > 0 \).

Consider next the case \( i = 2 \), and extend \( u \) into \( \{ y > 0 \} \) by 0. The extended function, \( \hat{u} \), satisfies: \( \Delta \hat{u} + \lambda \hat{u} \geq 0 \). Define a decreasing sequence
\[ \varepsilon_k = \sup_{B_{2^{-k}} \setminus B_\rho(z_0)} \frac{\hat{u}_x}{\frac{1}{\sqrt{\lambda}} \sin \sqrt{\lambda} y}. \]

We can now proceed as before to establish the relation (14.2) in \( y > 0 \), where \( \alpha = \lim \varepsilon_k \geq 0 \).

**Lemma 14.2.** If \( u \) is a minimizer of \( (J_\eta) \) then \( u \) satisfies the weak free boundary condition along \( F(u) = \partial \Omega^+(u) \cap \Omega \).

**Proof.** Suppose \( x_0 \in F(u) \) and there is a tangent ball \( B_\rho(y_0) \) to \( F(u) \) at \( x_0 \), say from \( \Omega^+(u) \). By Lemma 14.1, near \( x_0 \),
\[ u_+(y) = \alpha < x - x_0, \nu > + o(|x - x_0|), \quad \alpha \geq 0 \]
(case 1 with \( \lambda = 0 \)), and
\[ u_-(x) = \beta \frac{1}{\sqrt{\lambda}} \sin \sqrt{\lambda} < x - x_0, \nu > + o(|x - x_0|) \]
\[ = \beta < x - x_0, \nu > + o(|x - x_0|) \quad (\beta \geq 0) \]
(case 2 with \( \lambda > 0 \)), since \( \sin t = t + o(t) \). Hence
\[
u(x) = u_+(x) - u_-(x) = \alpha < x - x_0, \nu >_+ - \beta < x - x_0, \nu >_+ + o(|x - x_0|).
\]
Furthermore, by taking a blow up limit we get
\[
U(x) = \alpha < x - x_0, \nu >_+ - \beta < x - x_0, \nu >_+,
\]
where \( U \) is a minimizer of the functional
\[
J^0(U) = \int \left( |\nabla U|^2 + \mu_+^2 I_{(U \leq 0)} + \mu_-^2 I_{(U > 0)} \right).
\]
in the sense Definition 8.1. Theorem 9.5 (or Theorem 3.4) yields
\[
\left( \frac{\partial U_+}{\partial \nu} \right)^2 - \left( \frac{\partial U_-}{\partial \nu} \right)^2 = \alpha^2 - \beta^2 = \mu_+^2 - \mu_-^2 = \mu^2,
\]
so that \( \alpha = G(\beta) \).

We now wish to apply Theorem 13.2. We have already proved that any variational solution (i.e., a solution \( u \) to problem \((J_\eta)\)) is a weak solution. Since \( u \) is also Lipschitz continuous, the parameters \( \alpha \) and \( \beta \) are uniformly bounded. By Lemma 8.5 and by Lemma 8.4 of [3], if \( n = 2 \) then the flatness condition holds. Corollary 11.2 tells us that \( u \) is fully monotone in the direction \( \Gamma(\theta, e_n) \) for \( x_n = \pm \sqrt{\varepsilon} \). Thus, if we prove that \( u \) is also fully monotone in the direction \( \Gamma(\theta, e_n) \) on \( \partial C_1 \cap \{|x_n| < \sqrt{\varepsilon}\} \) then the assumption (iii) of Theorem 11.3 (which is the assumption (ii) of Theorem 13.2) is completely satisfied. But this full monotonicity \( u \) is the same as the assertion (8.12) (or (8.29)) in [3]. The proof of this inequality in case \( \lambda = 0 \) is proved in Lemma 8.2 of [3] in case \( u(0, -\frac{1}{2}) < -\eta \) and in Lemma 8.11 of [3] if this nondegeneracy assumption is dropped. The proof of Lemma 8.11 is based on Lemmas 8.2 – 8.7, 8.9, 8.10 and Corollary 8.8 of [3]. The same proof can be given in case \( \lambda > 0 \), except for two changes:

(i) In pages 456 and 458 of [3] we need to take \( G \) to be Green’s function of \( \Delta + \lambda \) (not \( \Delta \)), and

(ii) instead of exploiting the subharmonicity of \( w \equiv |\nabla u_-| \) (in Lemma 8.10) we now use the fact that \( w^2 = |\nabla u_-|^2 \) is subsolution, i.e., \( \Delta w^2 + \lambda w^2 \geq 0 \). We then have, by elliptic estimates,
\[
W^2(x) \leq C \int_{B_R \setminus B_{R/2}} W^2 \text{ in } B_{R/4},
\]
where \( W^2 = \max \{|w^2, C_0 u_+(A) u_-(A_\ast)| \} \) in \( B_R \); observe that \( W^2 \) is a subsolution, by Lemma 10.2. The constant \( C \) depends on \( R \), but since \( R = \frac{1}{4} \delta (\gamma_0) \) (see Corollary 8.8 of [3]), \( C \) depends on \( \gamma_0 \), as in Lemma 8.10 of [3].

Finally, Theorem 13.2 requires that \( \lambda < \lambda_C \). However, all the assumptions of the theorem are valid in any smaller cylinder \( C_\rho \). We choose \( \rho \) so small that \( \lambda < \lambda_C \) (the principal eigenvalue of the Laplacian in \( C_\rho \)), and then Theorem 13.2 can be applied to \( C_\rho \) (after scaling). We conclude:

**Theorem 14.3.** If \( n = 2 \) then the free boundary of any minimizer of \((J_\eta)\) is Lipschitz continuous.

The proof that Lipschitz continuity implies \( C^1 \) continuity is given in [3; Th. 8.12]. That proof extends to the present case with some obvious changes. Hence

**Theorem 14.4.** If \( n = 2 \) then the free boundary of any minimizer of \((J_\eta)\) is continuously differentiable.

By the proof of Theorem 8.13 in [3], for any \( x_0 \in F(u) \), \( u \) is continuously differentiable as \( x \to x_0 \) from any angular region \( \{(x - x_0) \cdot \nu > c|x - x_0|\} \), \( c > 0 \).
15. $C^{1+\alpha}$ regularity of the free boundary. In Sections 10–14 we assumed that $G(s)$ is continuous and strictly monotone increasing function, and $G(s) \geq s$ if $s > 0$. In this section we shall also assume that $G(s)/s^c$ is monotone decreasing function in $s \in (0, \infty)$, for some $c > 0$.

In this section we prove:

**Theorem 15.1.** Let $u$ be a weak solution, as in Definition 10.1. If the free boundary is Lipschitz continuous then it is also in $C^{1+\alpha}$.

Combining this with Theorem 14.4 we conclude:

**Theorem 15.2.** If $n = 2$ then the free boundary of any minimizer $u$ of problem (Jn) is in $C^{1+\alpha}$.

We can use $C^{1+\alpha}$ transformation to flatten the free boundary and then apply to $u_-$ and the reflected $u_+$ the Schauder estimates for elliptic equations in divergence form [1]. This yields $C^{1+\alpha}$ regularity of $u_\pm$ up to the boundary. To obtain additional regularity we use the mapping $y = (x_1, \ldots, x_{n-1}, u(x))$ ([17]; see also [13; pp. 135–136]) and define functions $v_\pm(y) = (x_n)_\pm$. Then $v_-$ and the reflected $v_+$ across $y_n = 0$ satisfy a nonlinear elliptic system with coefficients as smooth as $\nabla v_\pm$, and with “good” nonlinear boundary conditions (cf. [17] [18]). Using elliptic regularity [1] we can derive $C^{2+\alpha}$ regularity and, by bootstrapping, establish $C^\infty$ and, in fact, analyticity. Thus we have:

**Corollary 15.3.** The assertions of Theorems 15.1, 15.2 can be strengthened: the free boundary is analytic.

Theorem 15.1 in the case $\lambda = 0$ is due to Caffarelli [5]. Our proof is based on his method; however several new arguments are needed.

Let $\varphi$ be a bounded, $C^2$ positive function in $\Omega$ satisfying:

$$\Delta \varphi \geq C \frac{\|\nabla \varphi\|^2}{\varphi} \quad \text{for } C \text{ sufficiently large } \quad (C > 1).$$

For any continuous function $u$ in $\Omega$, consider the function

$$v(x) = \sup_{B_{\rho}(x)} u$$

defined in $\Omega_{\delta} = \{x \in \Omega, d(x, \partial \Omega) > \delta\}$ where $\delta = \sup \varphi$ and $B_{\rho}(x)$ denotes the ball with center $x$ and radius $\rho$.

**Lemma 15.4.** Suppose $\|\nabla \varphi\|_{L^\infty} < 1$. If $u < 0$ and $\Delta u + \lambda u = 0$ in $\Omega$, where $\lambda \geq 0$, then

$$\Delta v + \lambda(1 - \|\nabla \varphi\|_{L^\infty})^2 v \geq 0 \quad \text{in } \Omega_{\delta}.$$

**Proof.** For $\lambda = 0$ this is Lemma 9 in [5]. To prove the lemma in case $\lambda > 0$, take any ball $B \subset \Omega_{\delta}$ and let $w$ be the solution to

$$\Delta w = -\lambda(1 - \|\nabla \varphi\|_{L^\infty}) v \quad \text{in } B, \quad w = v \quad \text{on } \partial B.$$

If we prove that the function $V = v - w$ is subharmonic in $B$ then $\Delta v = \Delta V + \Delta w \geq -\lambda(1 - \|\nabla \varphi\|_{L^\infty})^2 v$, and the lemma follows. But $V$ is subharmonic if and only if

$$\liminf_{r \to 0} \frac{1}{\int_{B_r(x_0)}} \int_{B_r(x_0)} [V(x) - V(x_0)] dx > 0 \quad \forall x_0 \in B,$$
so that it suffices to prove (15.5). For simplicity we take \( x_0 = 0 \).

The function \( u \) is subharmonic (\( \Delta u = -\lambda u > 0 \)) and therefore there exists a unit vector \( \nu_0 \) such that

\[
\nu(0) = u(\varphi(0)\nu_0).
\]

We choose a system of coordinates such that \( \nu_0 = e_n, \nabla\varphi(0) = \alpha e_1 + \beta e_n \). For any \( x \in B_r(0) \), set \( \nu(x) = \nu^*/|\nu^*| \) where

\[
\nu^* = e_n + \frac{\beta x_1 - \alpha x_n}{\varphi(0)} e_1 + \frac{\rho}{\varphi(0)} \sum_{i=2}^{n-1} x_i e_i,
\]

where \( \rho \) is chosen so that \( (1 + \rho)^2 = (1 + \beta)^2 + \alpha^2 \). Finally set

\[
y = y(x) = x + \varphi(x)\nu(x) = y^* + O(|x|^2).
\]

Proceeding as in [5] we write

\[
\int_{B_r(0)} [V(x) - V(0)] = \int_{B_r(0)} \left[ (V(x) - w(x)) - (V(0) - w(0)) \right]
\]

\[
\geq \int_{B_r(0)} \left[ (u(y(x)) - w(x)) - (u(y(0)) - w(0)) \right]
\]

\[
= \int_{B_r(0)} \left[ u(y(x)) - u(y^*(x)) \right] + \int_{B_r(0)} \left[ [u(y^*(x)) - w(x)] - [u(y(0)) - w(0)] \right]
\]

\[
\equiv I_1(r) + I_2(r)
\]

and

\[
(15.6) \quad \int_{B_r(0)} [u(y) - u(y^*)] = |\nabla u(y(0))| \left\{ \frac{r^2}{n+1} \left[ \frac{1}{2} \Delta \varphi - \frac{1}{\varphi(0)} (\beta^2 + \alpha^2 + (n-2)\rho^2) \right] + O(r^3) \right\}.
\]

It follows that

\[
\liminf_{r \to 0} \frac{1}{r^2} I_1(r) > 0,
\]

and in order to complete the proof of (15.5) it suffices to show that

\[
\liminf_{r \to 0} \frac{1}{r^2} I_2(r) \geq 0,
\]

that is,

\[
(15.7) \quad \liminf_{r \to 0} \frac{1}{r^2} \int_{B_r(0)} (u^*(x) - u^*(0)) \geq 0
\]

where \( u^*(x) = u(y^*(x)) - w(x) \).
As in [5] \( y^*(x) \) is a translation by \( \varphi(0) e_n \) plus a rotation followed by expansion by \( 1 + \rho \) of \( x \). Hence, by (15.4),

\[
\Delta u^* = -\lambda(1 + \rho)^2 u(y^*(x)) + \lambda \left( 1 - |\nabla \varphi|_{L^\infty} \right)^2 v \\
\geq -\lambda(1 + \rho)^2 u(y^*(x)) + \lambda \left( 1 - |\nabla \varphi|_{L^\infty} \right)^2 u(y(x)).
\]

Since \( u(y^*(x)) < 0 \) and

\[
(1 + \rho)^2 = (1 + \beta)^2 + \alpha^2 \geq 1 + |\nabla \varphi|_{L^\infty}^2 - 2|\nabla \varphi|_{L^\infty} = \left( 1 - |\nabla \varphi|_{L^\infty} \right)^2,
\]

it follows that

\[
\Delta u^*(x) \geq \lambda \left( 1 - |\nabla \varphi|_{L^\infty} \right)^2 [u(y) - u(y^*)].
\]

Recalling (15.6) we conclude that

\[
\int_{B_r(0)} \Delta u^* \geq O(r^{n+3}) \quad \text{or} \quad \int_{\partial B_r(0)} \frac{\partial u^*}{\partial r} \geq O(r^{n+3}).
\]

Multiplying the last inequality by \( r^{1-n} \) and integrating with respect to \( r \), then multiplying by \( r^n \), we get

\[
\int_{B_r(0)} [u^*(x) - u^*(0)] \geq O(r^{n+5}),
\]

from which (15.7) follows.

**Lemma 15.5.** Let \( u \) be a weak solution in \( \Omega \) and define \( \varphi \) and \( v \) as in Lemma 15.4. Then

(i) \( \Delta v \geq 0 \) in \( \Omega^+(v) \cap \Omega_\delta \) and \( \Delta v + \lambda (1 - |\nabla \varphi|_{L^\infty})^2 v \geq 0 \) in \( \Omega^-(v) \cap \Omega_\delta \);

(ii) every point of \( F(v) \) is regular;

(iii) at every point \( x_0 \) of \( F(v) \), \( v \) satisfies the inequality:

\[
v(x) \geq \alpha < x - x_0, \; v > + \beta < x - x_0, \; v > - o(|x - x_0|)
\]

with

\[
\frac{\alpha}{1 - |\nabla \varphi|} = G\left( \frac{\beta}{1 + |\nabla \varphi|} \right);
\]

(iv) if \( F(u) \) is Lipschitz graph with Lipschitz norm \( L \) and \( |\nabla \varphi| \) is small enough (depending on \( L \)), then \( F(v) \) is Lipschitz graph with Lipschitz norm \( L' \leq L + C|\nabla \varphi|_{L^\infty} \).

The assertion (i) follows from Lemma 15.4. The assertions (ii), (iii) and (iv) are included in Lemmas 11 and 10 of [5] in case \( \lambda = 0 \), and the proof for \( \lambda > 0 \) is precisely the same.

The function \( v \) satisfies (15.3) in \( \Omega^-(v) \cap \Omega_\delta \). However for the iterative argument to be carried out later on it is imperative that the inequality \( \Delta v + \lambda v \geq 0 \) be satisfied. Since we cannot establish this inequality, we shall try to remedy the situation by introducing a "corrective" function \( w \), defined by:

\[
\Delta w + \lambda w = 2\lambda |\nabla \varphi|_{L^\infty} v \quad \text{in} \; \Omega^-(v),
\]

\[
w = 0 \quad \text{on} \; \partial \Omega^-(v),
\]

\[
w = 0 \quad \text{in} \; \Omega \setminus \Omega^-(v).
\]

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Here we assume that $F(u)$ is Lipschitz and that $|\nabla \varphi|_{L^\infty}$ is small enough so that also $\partial \Omega^{-}(v)$ is Lipschitz. We further assume that $\lambda < \lambda_\Omega$ (which is not really a restriction, since we can study the $C^{1+\alpha}$ regularity in just a very small neighborhood $\Omega$ of a point). Notice that since every point of $F(v)$ is regular, every point of $\partial \Omega^{-}(v)$ has the outside ball property and therefore also a barrier. It follows that $w$ is continuous in $\Omega^{-}(v)$.

We claim:

$$0 \leq w \leq \frac{2C|\nabla \varphi|_{L^\infty}}{(1 - |\nabla \varphi|_{L^\infty})^2} v_- \text{ in } \Omega^{-}(v). \tag{15.9}$$

To prove it we use the representation

$$w = \int_{\Omega^{-}(v)} 2\lambda|\nabla \varphi|_{L^\infty} G_\lambda v_- \tag{15.10}$$

where $G_\lambda$ is Green’s function for $\Delta + \lambda$, and the pointwise estimate $G_\lambda \leq CG_0$, to get

$$0 \leq w \leq 2\lambda C|\nabla \varphi|_{L^\infty} V, \quad V = \int_{\Omega^{-}(v)} G_0 v_-.$$

Clearly $\Delta V = -v_-$ in $\Omega^{-}(v)$ and $V = 0$ on $\partial \Omega^{-}(v)$. On the other hand

$$\Delta \left( \frac{v_-}{\lambda(1 - |\nabla \varphi|_{L^\infty})^2} \right) \leq -v_- \text{ in } \Omega^{-}(v)$$

so that, by comparison,

$$V \leq \frac{v_-}{\lambda(1 - |\nabla \varphi|_{L^\infty})^2}.$$

Using this in (15.10), the assertion (15.9) follows.

We now define

$$\bar{v} = v - w \text{ in } \Omega \tag{15.11}$$

where $v$ is defined as in Lemma 15.5.

**Theorem 15.6.** The function $\bar{v}$ satisfies:

(i) $\Delta \bar{v} \geq 0$ in $\Omega^+(\bar{v})$, $\Delta \bar{v} + \lambda \bar{v} \geq 0$ in $\Omega^{-}(\bar{v})$;
(ii) every point of $F(\bar{v})$ is regular;
(iii) at every point $x_0$ of $F(\bar{v})$, $\bar{v}$ satisfies:

$$\bar{v}(x) \geq \alpha < x - x_0, \nu >_+ -\beta < x - x_0, \nu >_- + o(|x - x_0|)$$

with

$$\frac{\alpha}{1 - |\nabla \varphi|} = G \left( \frac{\beta}{(1 + |\nabla \varphi|) \cdot (1 + \frac{2C|\nabla \varphi|_{L^\infty}}{(1 - |\nabla \varphi|_{L^\infty})^2})} \right). \tag{15.12}$$

**Proof.** The proof follows from Lemma 15.5 and (15.8), (15.9), with

$$\frac{\alpha}{1 - |\nabla \varphi|} = G \left( \frac{\beta}{1 + |\nabla \varphi|} \right)$$
instead of (15.12); the relation between $\beta$ and $\bar{\beta}$ is given by $\beta = \left(1 + \frac{1 + 2C|\nabla \varphi|_{L^\infty}}{1 - |\nabla \varphi|_{L^\infty}}\right)\bar{\beta}$ and this easily gives the assertion (15.12).

We introduce the unit cylinder $C_1 = B_1(0) \times (-1, 1)$ in $\mathbb{R}^n$ and set $\partial C_1^0 = \partial C_1 \setminus \{x_n = 1\}$, $S_\eta = \{x \in C_1, d(x, \partial C_1^0) < \eta\}$ for any $0 < \eta < 1$.

**Lemma 15.7.** For any $\sigma > 0$, $\delta > 0$ and small $\eta > 0$ there exist $\tau = \tau(\eta) > 0$ and $C^2$ function $\varphi$ in $C_1$ such that

(i) $1 \leq \varphi \leq 1 + \delta \sigma$,

(ii) $\varphi \Delta \varphi \geq C|\nabla \varphi|^2$, $C$ as in (15.1) (which ensures that Lemma 15.1 is valid),

(iii) $\varphi = 1$ in $S_\eta$,

(iv) $\varphi|_{C_{1/2}} \geq 1 + \delta \sigma \tau$,

(v) $|\nabla \varphi| \leq \bar{C}\delta \sigma$ ($\bar{C}$ depends only on $\eta$),

(vi) $\frac{\partial}{\partial x_n} \varphi \geq 0$.

This lemma differs from Lemma 13 in [5] because we require here the additional condition (vi). Our construction of $\varphi$ is also different from the construction given in [5].

**Proof.** Let $\psi_0$ be a function satisfying:

$$
\begin{align*}
\Delta \psi_0 &= 0 \text{ in } C_1^\eta = B_{1-\eta}(0) \times (-1 + \eta, 2), \\
\psi_0 &= 1 \text{ on } \partial C_1^\eta \setminus \{x_n = 2\}, \\
\psi_0 &= a|x|^2 + b \text{ on } \{x_n = 2\}
\end{align*}
$$

(15.13)

where $a$, $b$ are positive constants chosen so that $\psi_0$ is continuous on $\partial C_1^\eta$.

By the maximum principle

$$
\frac{\partial \psi_0}{\partial x_n} \leq 0 \text{ in } C_1^\eta
$$

and

$$
0 < \psi_0 \leq \bar{\sigma} < 1 \text{ in } C_{2/3}.
$$

Extending $\psi_0$ by 1 into $\{x_n < 2\} \setminus C_1^\eta$, we have

$$
\Delta \psi_0 \leq 0, \quad \frac{\partial \psi_0}{\partial x_n} \leq 0 \text{ in } \{x_n < 2\}.
$$

Let $\psi_1 = \psi_0 \ast \rho_\eta$ be a mollifier of $\psi_0$, where supp $\rho_\eta \subset B_\eta(0)$. Then $\psi_1 \in C^2(C_1)$, and

$$
\Delta \psi_1 \leq 0 \text{ in } C_1, \quad \frac{\partial \psi_1}{\partial x_n} \leq 0 \text{ in } C_1,
$$

(15.14)

$$
0 < \psi_1 \leq \bar{\sigma} < 1 \text{ in } C_{1/2}.
$$

Let

$$
\psi_2 = \left(\frac{\psi_1 + 1}{2}\right)^{1/1-2C} \quad (C \text{ as in (15.1)}).
$$

(15.16)
Then
\[
0 \geq \Delta \psi_2^{1 - 2C} = \nabla (1 - 2C) \psi_2^{-2C} \nabla \psi_2 = (2C - 1)2C \psi_2^{-2C - 1} |\nabla \psi_2|^2 - (2C - 1) \psi_2^{-2C} \Delta \psi_2
\]
so that
\[
(15.17) \quad \psi_2 \cdot \Delta \psi_2 \geq 2C |\nabla \psi_2|^2.
\]
Also
\[
(15.18) \quad 1 \leq \psi_2 \leq 2^{1 - \frac{2C}{1 - 1}} \quad \text{(since } 0 \leq \psi_1 \leq 1),
\]
(15.19) \quad \psi_2 = 1 \text{ in } S_n,
(15.20) \quad \psi_2 \geq \left( \frac{1 + \delta}{2} \right)^{\frac{1}{1 - 2C}} \equiv \bar{\sigma} > 1 \text{ in } C_{1/2},
\]
and
\[
(15.21) \quad \frac{\partial \psi_2}{\partial x_n} = \frac{1}{1 - 2C} \left( \frac{\psi_1 + 1}{2} \right)^{\frac{1}{2C - 1}} \frac{\partial \psi_1}{\partial x_n} \geq 0 \text{ in } C_1.
\]
Now let
\[
(15.22) \quad \varphi = 1 + \delta \sigma \frac{\psi_2 - 1}{2^{1 - \frac{2C}{1 - 1}}}.
\]
Using (15.17)–(15.21) one can easily verify that \( \varphi \) satisfies the assertions (i)–(vi).

**Lemma 15.8.** Let \( u \) be a continuous function in \( C_1 \) satisfying \( u(x) \geq 0 \), and let \( \varphi, v \) be as in (15.1), (15.2). If \( \varphi_{x_n} \geq 0 \) then \( v_{x_n} \geq 0 \).

**Proof.** For any \( x \) in the domain of definition of \( v \) there exists a \( y \in \overline{B}_{\varphi(x)}(x) \) such that \( v(x) = u(y) \). For any small \( h > 0 \),
\[
| (y + he_n) - (x + he_n) | = |y - x| \leq \varphi(x) \leq \varphi(x + he_n)
\]
since \( \varphi_{x_n} \geq 0 \). Hence \( y + he_n \in \overline{B}_{\varphi(x + he_n)}(x + he_n) \) and therefore
\[
\frac{1}{h} \left( v(x + he_n) - v(x) \right) \geq \frac{1}{h} \left( u(y + he_n) - u(y) \right).
\]
Taking \( h \to 0 \) we get \( v_{x_n} \geq u_{x_n} \geq 0 \).

We shall need the following comparison result.

**Lemma 15.9.** Let \( C_1, S_n \) be as above and assume that \( \lambda < \lambda_{C_1} \). Let \( u \) be a weak solution in \( C_1 \), continuous in \( \overline{C}_1 \), with \( u_{x_n} \geq 0 \) in \( C_1 \). Let \( v \) be a continuous function in \( \overline{C}_1 \) satisfying:
(i) \( \Delta v \geq 0 \) in \( \{ v > 0 \} \), \( \Delta v + \lambda v \geq 0 \) in \( \text{int}\{ v \leq 0 \} \),
(ii) \( F(u) \cap S_n \neq \phi \) and \( F(v) \cap S_n \) lies above \( F(u) \cap S_n \),
(iii) every point of \( F(v) \) is regular,
(iv) at each point \(x_0 \in F(v) \setminus S_{\eta}\) \(v\) satisfies:

\[
v(x) \geq \alpha < x - x_0, \nu > -\beta < x - x_0, \nu > + o(|x - x_0|) \text{ with } \alpha \geq G(\beta),
\]

(v) \(v_{x_n} \geq 0\) in \(C_1 \cap \{v > 0\}\).

Assume also that \(v \leq u\) on \(\partial C_1\) and \(u \geq 0\) on \(\{x_n = 1\}\). Then \(v \leq u\) in \(C_1\).

**Remark 15.1.** This comparison result will play a crucial role in establishing the \(C^{1+\alpha}\) regularity of the free boundary. It replaces Lemma 10.3 (that is the extension of the comparison Lemma 7 in [5] to \(\lambda > 0\)) which is inadequate for our subsequent needs.

**Proof.** We first prove that

\[
F(v) \text{ lies above } F(u).
\]

Suppose this is not true. Then by (ii) there exists a \(\tau > 0\) such that \(F(u) - \tau e_n\) lies below \(F(v)\) and they touch at a point \(x_0 \in F(v) \setminus \overline{S}_{\eta}\). Set

\[
u(s) = u(x + \tau e_n), \ x \in C_1 - \tau e_n \equiv C_1^\tau.
\]

Then \(F(u_\tau) = F(u) - \tau e_n\). We claim that

\[
u(x) \geq u(x) \geq v(x).
\]

To prove it notice that \(C_1^\tau \cap C_1 = B_1(0) \times (-1, 1 - \tau)\), so that \(\partial(C_1^\tau \cap C_1) = \partial B_1 \times (-1, 1 - \tau) \cup B_1 \times (-1) \cup B_1 \times \{1 - \tau\}\) where \(B_1 = B_1(0)\). If \(x \in \partial B_1 \times (-1, 1 - \tau) \cup B_1 \times \{-1\} \subset \partial C_1\) then, since \(u_{x_n} \geq 0\) and \(u \geq v\) on \(\partial C_1\),

\[
u(x) \geq u(x) \geq v(x).
\]

On the other hand if \(x_0 \in B_1 \times \{1 - \tau\}\) then \(x_0 + \tau e_n \in \partial C_1\) so that, if also \(x_0 \in \{v > 0\}\),

\[
u(x_0) = u(x_0 + \tau e_n) \geq v(x_0 + \tau e_n) \geq v(x_0) \text{ by (v)}.
\]

If however \(x_0 \in \{v \leq 0\}\) then

\[
u(x_0) = u(x_0 + \tau e_n) \geq 0 \text{ (by assumption)}
\]

so that again \(u_\tau(x_0) \geq v(x_0)\).

From (15.25) and the fact that \(F(u_\tau)\) lies below \(F(v)\) we deduce that \(u_\tau \geq v\) on \(\partial(\{v > 0\} \cap C_1^\tau)\). Since \(u_\tau\) is harmonic and \(v\) is subharmonic in \(\{v > 0\} \cap C_1^\tau\), the maximum principle yields

\[
u \geq v \text{ in } \{v > 0\} \cap C_1^\tau.
\]

Furthermore, we have strict inequality:

\[
u > v \text{ in } \{v > 0\} \cap C_1^\tau;
\]

for otherwise \(u_\tau \equiv v\) in \(\{v > 0\} \cap C_1^\tau\), and this contradicts (ii), since \(\tau > 0\). Similarly we deduce from (15.25) and the fact that \(F(u_\tau)\) lies below \(F(v)\) that \(u_\tau \geq v\) in \(\{u_\tau \leq 0\} \cap C_1\).

Setting \(\Omega = C_1^\tau \cap C_1\) we then have:
(a) $u_\tau \geq v$ in $\Omega$,  
(b) $u_\tau > v$ in $\{v > 0\} \cap \Omega$,  
(c) $x_0 \in [F(u_\tau) \cap F(v)] \setminus S_\eta$.

By (iii) and (iv)

$$v(x) \geq \alpha < x - x_0, \nu \geq -\beta < x - x_0, \nu > +o\left(|x - x_0|\right), \quad \alpha \geq G(\beta).$$

Since $F(u_\tau)$ lies below $F(v)$ and they touch at $x_0$, there is a ball in $\Omega^+(u_\tau)$ tangent to $F(u_\tau)$ at $x_0$; therefore

$$u_\tau(x) = \bar{\alpha} < x - x_0, \nu > -\bar{\beta} < x - x_0, \nu > +o\left(|x - x_0|\right), \quad \bar{\alpha} = G(\bar{\beta}).$$

Comparing the two expansions and using (a), (b) we get $\alpha \leq \bar{\alpha}, \bar{\beta} \leq \beta$. Since $G$ is strictly monotone increasing, it follows that $\alpha = \bar{\alpha}, \beta = \bar{\beta}$. Hence

$$0 \leq u_\tau - v \leq o\left(|x - x_0|\right).$$

On the other hand, by (b) and the strong maximum principle,

$$u_\tau - v \geq \varepsilon_0|x - x_0|, \quad \varepsilon_0 > 0$$

in a small ball in $\Omega^+(v)$ tangent to $F(v)$ at $x_0$, which is a contradiction.

We have thus completed the proof of (15.23). Applying the maximum principle once more we get $v \leq u$ in $C_1$, and the assertion of the lemma follows.

We now state the final lemma of this section, which is crucial for the iterative procedure used in proving the $C^{1+\alpha}$ regularity of the free boundary.

**Lemma 15.10.** Let $u_1 \leq u_2$ be two weak solutions in $C_1$ with Lipschitz free boundaries $F_1 = F_1(u)$, and let $0 \in F_2$. Assume that $\lambda < \lambda_{C_1}$ and that

(i) $v_\varepsilon(x) \equiv \sup_{B_\varepsilon(x)} u_1(y) \leq u_2(x)$ in $C_{1-\varepsilon}$,

(ii) $v_\varepsilon(\frac{3}{4}e_n) \leq (1 - \sigma \varepsilon)u_2(\frac{3}{4}e_n)$ for some $\sigma > 0$,

(iii) $C_\rho(\frac{3}{4}e_n) \subset \Omega^+(u_1)$, $0 < \rho \leq \frac{1}{8}$ where $C_\rho(\frac{3}{4}e_n) = C_\rho + \frac{3}{4}e_n$.

Then for $\varepsilon$ small enough there exist $\delta > 0$ and $\tau > 0$ depending on $\rho$ such that, on $C_{\rho/4}$,

(15.26)

$$\left(v_{(1+\delta\tau)}\varepsilon(x)\right)_+ \leq \left(u_2(x)\right)_+.$$ 

**Proof.** Let $C^\rho = B_{\rho/2} \times (-\frac{3}{4}, \frac{3}{4})$, $\rho < \frac{1}{10}$. Define

$$v(x) = \sup_{B_{\rho/2} \times (-\frac{3}{4}, \frac{3}{4})} u_1$$

and $w$ by (15.8) with $\Omega = C^\rho$, $\varphi = \varepsilon \varphi_{\sigma, \tau}$, and set $\bar{v} = v - w$ and

$$\bar{w} = \bar{v} + \bar{\sigma}w^0 = v - w + \bar{\sigma}w^0.$$
here, $\varphi_{\sigma, \tau}^\delta$ is the function constructed in Lemma 15.7 in $C^\rho$ (instead of $C_1$) with $\eta < \frac{\rho}{16}$, $\bar{c}$ is still to be determined, and $w^0$ is the solution of

\[
\begin{align*}
\Delta w^0 &= 0 \quad \text{in} \quad \Omega^+(v) \cap C^\rho, \\
w^0 &= 0 \quad \text{on} \quad \partial \left( \Omega^+(v) \cap C^\rho \right) \setminus \left\{ x_n = \frac{3}{4} \right\}, \\
w^0 &= u_2 \left( \frac{3}{4} e_n \right) \quad \text{on} \quad x_n = \frac{3}{4}, \\
w^0 &= 0 \quad \text{in} \quad \Omega^-(v) \cap C^\rho.
\end{align*}
\]

We wish to apply the comparison lemma 15.9 to the pair $u_2, \bar{v}$. We therefore need to check the assumptions (i)-(v) for $\bar{v}$.

Assumption (i) follows from Theorem 15.6 (i). Notice that $\{ \bar{v} > 0 \} = \{ v > 0 \}$, $\{ \bar{v} \leq 0 \} = \{ v \leq 0 \}$, so that $F(\bar{v}) = F(v)$. By Theorem 15.6 (ii) we then conclude that the assumption (iii) holds for $\bar{v}$, i.e., every point of $F(\bar{v})$ is regular.

Proof of assumption (ii): If $\rho$ is small enough then $u_2 > 0$ on $x_n = \frac{3}{4}$, and it remains to prove that $F(\bar{v}) \cap \overline{S}_\eta$ lies above $F(u_2)$. Since $\varphi_{\sigma, \tau}^\delta = 1$ in $\overline{S}_\eta$, we have $\bar{v} = v_\epsilon - w + \bar{c}\sigma \epsilon w^0$ and $F(\bar{v}) = F(v_\epsilon)$, and, by assumption (i) of Lemma 15.10, $F(\bar{v}) \cap \overline{S}_\eta$ lies above $F(u_2)$.

Proof of assumption (iv): For each $x_0 \in F(\bar{v}) \setminus \overline{S}_\eta$, $\bar{v}$ satisfies

$$
\bar{v}(x) \geq \alpha \cdot \min(\bar{v} - x, 0) \geq \alpha \cdot \min(\bar{v} - x_0, 0) + o(|x - x_0|), \quad \alpha \geq G(\beta).
$$

By Dahlberg’s theorem (Lemma 1 in [5]) we have

$$
\frac{w^0}{v_+} \geq C > 0 \quad \text{in} \quad (C^\rho \setminus \overline{S}_\eta) \cap \Omega^+(v), \quad \text{near} \quad F(v) \setminus \overline{S}_\eta
$$

provided $\epsilon |\nabla \varphi_{\sigma, \epsilon}^\delta|$ is small enough so that $F(v)$ is Lipschitz; $C$ depends only on $\rho$ and on the Lipschitz norm of $F(u_1)$. Using also (15.9) we get

$$
\bar{v} \geq (1 + \bar{c}\sigma \epsilon) v_+ - \left( 1 + \frac{2c |\nabla \varphi|_{L^\infty}}{1 - |\nabla \varphi|_{L^\infty}^2} \right) v_- \quad \text{where} \quad \varphi = \epsilon \varphi_{\sigma, \tau}^\delta
$$

and by Lemma 15.5 (iii)

$$
\bar{v} \geq (1 + \sigma \epsilon) \bar{\alpha} \cdot \min(\bar{v} - x, 0) \geq \alpha \cdot \min(\bar{v} - x_0, 0) + o(|x - x_0|)
$$

with

$$
\frac{\bar{\alpha}}{1 - |\nabla \varphi|} = G\left( \frac{\beta}{1 + |\nabla \varphi|} \right).
$$

Setting

$$
\alpha = (1 + \sigma \epsilon) \bar{\alpha}, \quad \beta = \left( 1 + \frac{2c |\nabla \varphi|_{L^\infty}}{1 - |\nabla \varphi|_{L^\infty}^2} \right) \bar{\beta}
$$

and using the fact that $s^{-\epsilon} G(s)$ is decreasing for some positive constant $c$, we can deduce as in [5; p. 153] that $G(\beta) \leq \alpha$ if

$$
\frac{1 + C |\nabla \varphi|_{L^\infty}}{1 - |\nabla \varphi|_{L^\infty}} \frac{1}{1 + \sigma \epsilon} < 1, \quad \varphi = \epsilon \varphi_{\sigma, \tau}^\delta,
$$

where
which is indeed the case if $\delta$ is small (independent of $\varepsilon$), since $|\nabla \varphi|_{L^\infty} \leq c\varepsilon \delta$.

We next need to verify the assumption (v) of Lemma (15.9), i.e., that $\bar{v}_{x_n} \geq 0$ in $C^0 \cap \{\bar{v} > 0\}$. But in this set, $\bar{v} = v + \tilde{c} \varepsilon w^0$ and, as easily seen, $w^0_{x_n} \geq 0$, whereas by Lemma 15.8, $v_{x_n} \geq 0$.

In order to apply Lemma 15.9 we still need to check that $\bar{v} \leq u_2$ on $\partial C^\rho$.

On $\partial C^\rho \setminus \{x_n = \frac{3}{4}\}$, $\bar{v} = v_\varepsilon \leq u_2$ by assumption (i). On $\partial C^\rho \cap \{x_n = \frac{3}{4}\}$,

\[
\bar{v} \leq v_{(1+\delta\sigma)e_0} + \tilde{c} \varepsilon u_2 \left(\frac{3}{4} e_n\right) \quad \text{(since $\varphi^\delta_{\sigma, \tau} \leq 1 + \delta \sigma$)}
\]

\[
\leq u_2
\]

by Lemma 12 [5] provided $\delta \leq \delta(\rho)$.

We can now apply Lemma 15.9 and deduce that

$\bar{v} \leq u_2$ in $C^\rho$;

in particular, on $C_{\rho/4}$,

\[
\left(v_{(1+\delta\tau)e_0}\right)_+ \leq \bar{v}_+ \leq (u_2)_+.
\]

**Remark 15.2.** In the special case $\lambda = 0$ Caffarelli [5; Lemma 14] established a stronger result than Lemma 15.10, namely,

(15.27) \[v_{(1+\delta\tau)e}(x) \leq u_2(x).\]

Furthermore, his proof relies on the comparison lemma 10.3 (for $\lambda = 0$). In our case of $\lambda > 0$, we had to introduce a corrective term $w$ (so that $v - w$ becomes a subsolution, i.e., $\Delta (v - w) + \lambda (v - w) \geq 0$). This change (from $v$ to $v - w$) rendered Lemma 10.3 inadequate, and the new comparison lemma that we have used instead was Lemma 15.9.

**Proof of Theorem 15.1.** Although our result (15.26) is weaker than (15.27), it is still strong enough to establish the $C^{1+\alpha}$ regularity of the free boundary. We first use the proof of Lemma 17 of [5] to deduce from (15.26) that if $u$ is monotone in the direction $\Gamma(\theta, e_n)$ in $B_1$ then $u_+\gamma$ is monotone in a direction $\Gamma(\tilde{\theta}, e)$ with $\tilde{\theta} < \theta$ in $B_\rho$, for some $\rho > 0$, provided $\lambda < \lambda_{B_1}$. This implies that $F(u)$ is a Lipschitz graph in any direction in $\Gamma(\tilde{\theta}, e)$. We can therefore use Lemma 5 of [5] extended to the case $\lambda > 0$ (see the proof of Lemma 12.2) to deduce that $D_\tau u_- \geq 0$ for any direction $\tau$ in $\Gamma(\tilde{\theta}, e)$, in a smaller ball whose radius depends only on the Lipschitz coefficient of $F(u)$; this radius is invariant under similarity scaling $u(\mu x)/\mu$. We can now apply the iterative argument of [5; p. 157] to deduce that the free boundary is in $C^{1+\alpha}$ in a neighborhood of a free boundary point; finally, the assumption $\lambda < \lambda_{B_1}$ can be dropped, for we can start the iteration in a ball $B_{\rho_0}$ (instead of $B_1$) where $\rho_0$ is so small that $\lambda < \lambda_{B_{\rho_0}}$.

**16. Properties of $\Omega^+(u)$.** Let $u$ be a minimizer of $(J_\eta)$.

**Theorem 16.1.** $\Omega^+(u)$ is a connected open set.

**Proof.** Since $u \in C^1(\overline{\Omega})$ and $u = \gamma > 0$ on $\partial \Omega$, there is an $\Omega$-neighborhood of $\partial \Omega$ which belongs to $\Omega^+(u)$. If $\Omega^+(u)$ is not connected then it has a component $G$ such that $\overline{G} \subseteq \Omega$. But since $u = 0$ on $\partial G$, and $\Delta u = 0$ in $G$, $u$ is then identically zero in $G$, which is a contradiction.

From now on we consider only the case $n = 2$. Then $F(u) = \partial \Omega^+(u) \cap \Omega$ is locally continuously differentiable and, since $F(u) \cap \Omega$, $F(u)$ consists of a finite number of closed
smooth curves $F_i(u)$; each $F_i(u)$ encloses a domain $G_i$, and in each $G_i$ either $u < 0$ and
$\Delta u + \lambda u = 0$ everywhere, or else $u \equiv 0$.

**Theorem 16.2.** There cannot exist two components $G_i, G_j$ such that $u < 0$ in both $G_i$
and $G_j$.

*Proof.* Suppose the assertion is not true and take for simplicity $i = 1, j = 2$. Following
[19], consider the function

$$
\tilde{u} = \begin{cases}
    c_1 u & \text{in } G_1 \\
    c_2 u & \text{in } G_2
\end{cases}
$$

where

$$(16.1) \quad c_1^2 \int_{\overline{G_1}} u^2 + c_2^2 \int_{\overline{G_2}} u^2 = \int_{\overline{G_1}} u^2 + \int_{\overline{G_2}} u^2.$$

Then

$$
\int_{\overline{\Omega}} \tilde{u}_-^2 = \int_{\overline{\Omega}} u_-^2
$$

and, therefore, $J_\eta(u) \leq J_\eta(\tilde{u})$ is equivalent to

$$(16.2) \quad \int_{\overline{G_1}} |\nabla u|^2 + \int_{\overline{G_2}} |\nabla u|^2 \leq c_1 \int_{\overline{G_1}} |\nabla u|^2 + c_2 \int_{\overline{G_2}} |\nabla u|^2.$$

By integration by parts

$$
\int_{\overline{G_i}} |\nabla u|^2 = \lambda \int_{\overline{G_i}} u^2.
$$

Using this and (16.1) we conclude that equality holds in (16.2), so that $\tilde{u}$ is also a minimizer.
Consequently

$$|
\nabla \tilde{u}_+|^2 - |\nabla \tilde{u}_-|^2 = \mu^2 = |\nabla u_+|^2 - |\nabla u_-|^2 \quad \text{on } \partial G_i,$$

i.e.,

$$|\nabla u_+|^2 - c_1^2 |\nabla u_-|^2 = |\nabla u_+|^2 - |\nabla u_-|^2 \quad \text{on } \partial G_i.$$

By varying $c_1$ we deduce that $\nabla u_- = 0$ on $\partial G_1$, so that $u \equiv 0$ in $G_1$, which is a contradiction.

We shall now construct domains $\Omega$ for which $\Omega^-(u)$ has several components in which $u \equiv 0$.
We begin with a dumbell shaped domain consisting of two discs with a long narrow bridge connecting them:

$$
\Omega = B_r(0) \cup B_r(z_0) \cup T_\delta
$$

where

$$z_0 = (2L, 0), \ T_\delta = \{(x_1, x_2); \ 0 < x_1 < 2L, -\delta < x_2 < \delta\}$$

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and $L = 1/\sqrt{\delta}$, say.

**Theorem 16.3.** If $\mu_\pm$ are sufficiently large then, whenever $\delta$ is small enough, $\Omega^-(u)$ must have at least one component in which $u \equiv 0$.

**Proof.** Suppose the assertion is not true. Then $\Omega^-(u)$ is a domain in which $u < 0$. We claim:

(16.3) $\Omega^-(u)$ cannot contain points in both $B_r(0)$ and $B_r(z_0)$.

To prove (16.3) we suppose that it is not true. Since

$$\int \int |\nabla u_-|^2 \leq C_0, \quad C_0 \text{ independent of } \delta,$$

we must have

$$\int |\nabla u_-(\xi_1, x_2)|^2 dx_2 \leq C \delta^{1/2}$$

for some $\xi_1 \in \left( \frac{L}{8}, \frac{L}{4} \right)$ and $C > C_0$ (recall that $L = 1/\sqrt{\delta}$). Hence

(16.4) $|u_-(\xi_1, y)| \leq \int |\nabla u_-(\xi_1, x_2)| dx_2 \leq \left( 2\delta \int |\nabla u_-(\xi_1, x_2)|^2 \right)^{1/2} \leq C \delta^{3/4}$.

Similarly

(16.5) $|u_-(\xi_2, y)| \leq C \delta^{3/4}$

for some $(1 + \frac{\delta}{4})L < \xi_2 < (1 + \frac{\delta}{3})L$.

Now take half a disc $B_r^+(L, -\delta) = B_r(L, -\delta) \cap \{x_2 > -\delta\}$ and increase $\rho$ until it touches $\partial \Omega^-(u)$, say at a point $x_0$; we may assume that $\rho < \delta$, for otherwise we can work with half discs $B_r^-(L, \delta) \cap \{x_2 < \delta\}$.

We shall prove that

(16.6) $|\nabla u_+(x_0)| \geq \frac{c}{\rho} \quad (c > 0)$

and

(16.7) $|\nabla u_-(x_0)| \leq \frac{C \delta}{\rho}$.

To prove (16.6) we compare $u_+$ with the harmonic function $U$ in $B_r^+(L, -\delta)$ which takes the boundary value $\gamma$ on $\{(x_1, -\delta), |x_1 - L| < \frac{1}{2} \rho\}$ and zero elsewhere. Clearly $u_+ \geq U \geq 0$ in $B_r^+(L, -\delta)$ and $u_+ = U = 0$ at $x_0$, so that $|\nabla u_+| \geq |\nabla U|$ at $x_0$. On the other hand, by scaling $U$ and applying elliptic estimates, we find that $|\nabla U| \geq c/\rho$ at $x_0$, and therefore (16.6) holds.

To prove (16.7), consider the function

$$V = \frac{C_1}{\delta^{5/4}} (2\delta - x_2) (x_2 + 2\delta) \left( e^{\xi_1 - x_1} + e^{x_2 - \xi_2} \right)$$

in

$$S = \{ \xi_1 < x_1 < \xi_2, -\delta < x_2 < \delta \} \setminus B_r^+(L, -\delta).$$
Since $\lambda \leq C$ (C independent of $\rho$, $\delta$),

$$\Delta V + \lambda V = \frac{C_1}{\delta^{5/4}} \left[ -2 + (1 + \lambda)(2\delta - x_2)(x_2 + 2\delta) \right] \left( e^{x_1-x_2} + e^{x_2-x_1} \right) < 0$$

if $\delta$ is small. Further $V > 0 = u_-$ on $\partial \Omega^-(u) \cap S$ and (by (16.4), (16.5)) at $x_1 = \xi_1$ and $x_1 = \xi_2$ if $C_1$ is large enough. Since $\lambda$ is smaller than the principal eigenvalue of $\Delta$ in $\Omega^-(u) \cap S$, we can use a comparison theorem to deduce that $u_- \leq V$ in $S$; in particular

(16.8) $$u_-(x_1, x_2) \leq \frac{C_2}{\delta^{1/4}} \delta^{-1/\delta} \leq \delta \quad \text{if } |x_1 - L| < 1.$$

Let $W$ be the solution of $\Delta W + \lambda W = 0$ in

$$S_0 = \{|x_1 - L| < 2\delta, \ -\delta < x_2 < \delta\} \setminus B^+_{\rho}(L, -\delta)$$

with $W = u_-$ on $\partial S_0$. By (16.8) $0 \leq W \leq \delta$ on $\partial S_0$. Scaling $W$ by $1/\delta$ and using a version of the maximum principle, we easily find that if $\delta$ is small enough then

$$0 \leq W \leq C\delta \quad \text{in } S_0.$$

If we scale $W/\delta$ by $1/\rho$ and apply elliptic estimates, we get

$$|\nabla(W/\delta)| \leq \frac{C}{\rho} \quad \text{at } x_0.$$

Since also $W \geq u_-$ in $S_0$, $|\nabla W| \geq |\nabla u_-|$ at $x_0$, and (16.7) follows.

Having proved (16.6), (16.7) we see that the free boundary condition $|\nabla u_+|^2 - |\nabla u_-|^2 = \mu^2$ is contradicted if $\delta$ is small enough and this proves the assertion (16.3). It follows that $\Omega^-(u)$ does not intersect both $B_r(0)$ and $B_r(z_0)$; for definiteness we shall suppose that $\Omega^-(u)$ does not intersect $B_r(0)$.

We now take $\delta \to 0$ and obtain a limit function $u_0$ in $B_r(0)$, which minimizes

$$\bar{J}(v) \equiv \int_{B_r(0)} \left[ |\nabla v|^2 + \mu_+^2 I_{v>0} \right]$$

subject to $v = \gamma$ on $\partial B_r(0)$, and $u_0 > 0$ throughout $B_r(0)$. If however $\mu_+$ is sufficiently large, this is a contradiction since the minimizer must vanish on some disc.

Similarly one can show that for a domain $\Omega$ consisting of one disc connected to $m$ disjoint discs by “thin” and “long” bridges, $\Omega^-(u)$ must have at least $m$ components in which $u \equiv 0$ (provided $\mu_+\mu_-$ are large enough).

Actually the above analysis can be carried out if the length of a bridge is just $\gg \log \frac{1}{\delta}$.

**Remark 16.1.** The 3-dimensional radially symmetric plasma problem is to find $(u, \Gamma_\rho, \lambda)$ satisfying:

$$u_{rr} + u_{zz} - \frac{1}{r} u_r = 0 \quad \text{in } \Omega_v = \{(r, z) \in \Omega; u(r, z) > 0\},$$

$$u_{rr} + u_{zz} - \frac{1}{r} u_r + \lambda u = v \quad \text{in } \Omega_p = \Omega \setminus \Omega_v,$$

$$u = \gamma \quad \text{on } \partial \Omega,$$

$$u = 0 \quad \text{on } \Gamma_p,$$

$$\frac{|\nabla u_+|^2}{r^2} - \frac{|\nabla u_-|^2}{r^2} = \mu^2 \quad \text{on } \Gamma_p$$

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where $\Omega$ is a bounded domain in $\mathbb{R}^2$. If we set $\hat{\Omega} = \{ x = (x', z) \in \mathbb{R}^5, (|x'|, z) \in \Omega \}$ and define a function $w(x)$ by

$$|x'|^2 w(x) = u(|x'|, z),$$

then $w$ satisfies (2.1)-(2.4) in $\hat{\Omega}$ and

$$|\nabla w_+|^2 - |\nabla w_-|^2 = \frac{\mu^2}{|x'|^2}$$

on the free boundary. All the results of the paper extend to the present case with one serious exception: the verification of the full monotonicity condition in Theorem 11.3 (i.e., of assumption (iii)) for a minimizer of $J_\eta$. On one hand we cannot show that $\sup B_{\sigma}(x)$ subsolution in the $(r, z)$ variables. On the other hand if we use the mapping $(|x'|, z) \rightarrow (x', z)$ then a rectangle about a free boundary point goes into a shell between two concentric cylinders, and this does not allow us to prove monotonicity in the desired directions $e$. Since we are unable to verify assumption (iii) of Theorem 11.3, we cannot establish that the free boundary is a Lipschitz graph.
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