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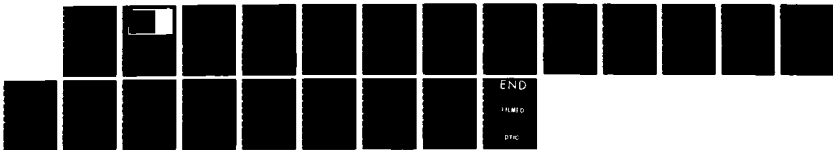
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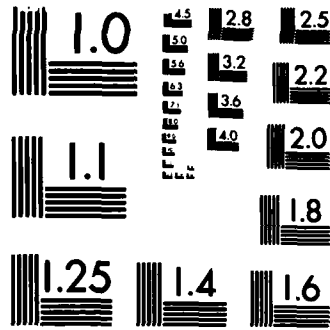
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A CLASS OF ONE-DIMENSIONAL DEGENERATE
PARABOLIC EQUATIONS

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A CLASS OF ONE-DIMENSIONAL DEGENERATE PARABOLIC EQUATIONS

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ABSTRACT

We use explicit self similar solutions of suitable model problems and comparison arguments to study the regularity of the free boundary near $t = 0$ for the one-dimensional degenerate Cauchy problem

$$\begin{aligned}v_t &= \phi(v)_{xx}, & x \in \mathbb{R}, t > 0, \\v(x, 0) &= g(x),\end{aligned}\tag{P}$$

where $\phi(v) = \max(v, 0)$. The datum g is assumed smooth on $\mathbb{R} \setminus \{0\}$ with at most exponential growth at infinity and satisfies

$$xg(x) > 0, \quad x \neq 0, \quad g(0) = 0,$$

the inequality being strict near $x = 0$.

AMS (MOS) Subject Classifications: 35K55, 34B30, 35R35

Key Words: Cauchy problem, degenerate, self-similar solutions, free boundary, regularity, comparison method

Work Unit Number 1 (Applied Analysis)

-E-

SIGNIFICANCE AND EXPLANATION

Degenerate parabolic equations arise in the description of melting processes, gas dynamics and certain biological models. The interfaces corresponding to degeneracies in the constitutive function usually separate different media in the physical problem.

Problem (P) stated in the abstract is related to nonlinear diffusion equations with nonmonotone constitutive functions as has been discussed in [HMT-3]. In this report we obtain explicit self-similar solutions for (P) corresponding to a class of model initial data and determine the free boundary explicitly. The qualitative behavior of these solutions, in particular of their interfaces, is typical of the situation in more general problems. For general initial data, ^{the author} we then use these self-similar solutions as comparison functions to study the regularity and the behavior of the free boundary for small time.

Keywords: one dimensional degenerate Cauchy problem.

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A CLASS OF ONE-DIMENSIONAL DEGENERATE PARABOLIC EQUATIONS

John A. Nohel

To Jaroslav Kurzweil on his sixtieth birthday

1. INTRODUCTION. In this paper we use self similar solutions to study the one-dimensional degenerate Cauchy problem

$$\begin{aligned}v_t &= \phi(v)_{xx}, & x \in \mathbb{R}, t > 0, \\v(x,0) &= g(x)\end{aligned}\tag{P}$$

for the constitutive function $\phi(v) = \max(v,0)$. We assume that the initial data g are smooth on $\mathbb{R} \setminus \{0\}$ with at most exponential growth at infinity and satisfy

$$xg(x) > 0, \quad x \neq 0, \quad g(0) = 0, \tag{g}$$

and the inequality is strict near $x = 0$. The principal issue is the regularity of the free boundary near $t = 0$.

Problems of this type arise as convexifications of diffusion equations with nonmonotone constitutive functions as has been discussed in [HN1,H]. The behavior of solutions for (P) is similar to those of the one phase Stefan problem in which $g(x) \equiv -1$ for $x < 0$, and g has a jump discontinuity at $x = 0$. However, (P) and the Stefan problem exhibit different regularity properties of the free boundary near $t = 0$.

Existence and uniqueness of weak solutions of (P) can be proved using nonlinear semigroup theory [BCPa,E]. Indeed, Benilan, Crandall, and Pierre [BCPi] have obtained optimal existence and uniqueness results for the porous medium equation (i.e. problem (P) with $\phi(v) = \max(v^m,0)$, $m > 1$) in \mathbb{R}^n . However, their results do not apply directly to the case $m = 1$. Details of

the proofs in the present context are given in Vázquez [V1] and the results (Theorems 3.1, 3.2) are stated in Section 3. Using standard approximation arguments and the comparison method discussed in [V1] (see Section 3) one establishes the existence of a continuous monotone decreasing free boundary $t \rightarrow s(t)$, $s(0) = 0$ and $v(s(t)^+, t) = 0$. Moreover, the pair (v, s) satisfies the free boundary problem

$$\begin{aligned} v_t &= v_{xx}, & x > s(t), & t > 0, \\ v(x, 0) &= g(x), & x > 0, \\ v(s(t)^+, t) &= 0, \\ g(s(t))s'(t) &= v_x(s(t)^+, t), & t > 0, \\ s(0) &= 0. \end{aligned} \tag{P}$$

Conversely, the solution v of (P) extended by $v(x, t) = g(x)$ for $x < s(t)$ is a weak solution of (P).

In the special case of (P), (g) with the function g satisfying the additional assumption: $g'(0^+), g'(0^-) \neq 0$, we have shown by solving a singular integral equation [HN2,3] that the problem (P) has a unique solution (v, s) . Moreover,

$$s(t) = -\kappa\sqrt{t} + O(t^{\alpha+1/2}) \quad (t \rightarrow 0^+), \tag{1.1}$$

for any $0 < \alpha < 1/2$, where κ is the uniquely defined monotone function of $p := g'(0^+)/g'(0^-)$ determined implicitly by the equation

$$p = \frac{\kappa^2}{2} + \frac{\kappa^3}{4} e^{\kappa^2/4} \int_{-\kappa}^{\infty} e^{-y^2/4} dy. \tag{1.2}$$

For $t > \varepsilon > 0$ the free boundary is smooth. It should be observed that a formal expansion of the ODE $g(s(t))s'(t) = v_x(s(t)^+, t)$ yields

$$(p_-)s(t)s'(t) = (p_+) + \dots,$$

so that

$$s(t) = -\sqrt{2p} t + \dots,$$

where \dots denote terms of higher degree powers of t . However, if $p = 1$, then (1.2) implies $\kappa = .9034 \dots \neq \sqrt{2}$. The reason for this apparent inconsistency is that all derivatives of v become singular at (x,t) at $(0,0)$ and in particular, v_x is discontinuous at $(0,0)$. By contrast, for the one phase Stefan problem [FP1,2; KN; S] the solution is smooth on the set $\{(x,t) : x > s(t), t \in [0,T]\}$.

The purpose of this note is to discuss the regularity and qualitative behavior for small t of the free boundary of (P) for more general initial data g . Of particular interest is the model datum

$$g(x) = \begin{cases} p_+ x^\gamma, & x > 0, \\ -p_- |x|^\gamma, & x < 0, \end{cases} \quad (D)$$

where $p_\pm, \gamma > 0$ are given constants, for which the integral equation method of [HN2,3] breaks down if $\gamma \neq 1$, i.e. if the datum g is not piecewise linear. It will be shown in Section 2 that (P) with the model initial datum (D) can be solved explicitly for all $\gamma > 0$ using self similar solutions, and the free boundary is determined explicitly for all $t > 0$ by proving the following result.

Proposition 1.1. For the model datum (D) problem (\bar{P}) has the unique self similar solution

$$v(x,t) = t^{\gamma/2} \psi\left(\frac{x}{\sqrt{t}}\right), \quad x > s(t), \quad t > 0$$

where $\psi(\cdot)$ is the unique solution of the ordinary differential equation

$$2\psi''(\xi) + \xi\psi'(\xi) - \gamma\psi(\xi) = 0, \quad \xi > -\kappa \quad (1.3)$$

subject to the initial conditions

$$\psi(-\kappa) = 0, \quad \psi'(-\kappa) = (p_-) \frac{\kappa^{\gamma+1}}{2}, \quad (1.4)$$

and κ is related to p_{\pm} via the condition

$$\lim_{\xi \rightarrow +\infty} \xi^{-\gamma} \psi(\xi) = p_{+} . \quad (1.5)$$

The free boundary is $s(t) = -\kappa\sqrt{t}$, $t > 0$. Moreover, given $p = p_{+}/p_{-} > 0$,

$\kappa > 0$ is the unique solution of the equation

$$p = \left(\frac{\kappa}{\sqrt{2}}\right)^{\gamma+1} D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) \exp\left(\frac{\kappa^2}{8}\right) , \quad (1.6)$$

where $D_{-\gamma-1}(\cdot)$ is the parabolic cylinder function of index $(-\gamma - 1)$

[B, p. 119].

It is readily verified that (1.6) reduces to (1.2) if $\gamma = 1$. The regularity of the free boundary for problem (P) with initial data (g) more general data than (D) can then be discussed using the above explicit solutions as comparison functions. This will be done briefly in Section 3 using ideas of Vázquez [V1,2]. The principal result is

Theorem 1.2. Let v be the solution of (P), where the smooth datum g satisfies assumptions (g), $xg(x) > 0$ for x near zero, and there exists $\gamma > 0$ such that

$$-\lim_{x \rightarrow 0^{-}} g(x) |x|^{-\gamma} = a > 0 \quad (1.7)$$

$$\lim_{x \rightarrow 0^{+}} G(x) x^{-(\gamma+1)} = b > 0 ,$$

where $G(x) = \int_0^x g(\xi) d\xi$, $x > 0$. Let $p := b(\gamma + 1)/a$. Then

$$s(t) = -\kappa t^{1/2} (1 + o(1)) \quad (t \rightarrow 0^{+}) , \quad (1.8)$$

where $\kappa = \kappa(p) > 0$ is the uniquely defined inverse of the function p defined by equation (1.6); for $t > \varepsilon > 0$ the free boundary is smooth for as long as it exists.

As already remarked in the special case $\gamma = 1$ the integral equation approach yields the stronger result (1.1). The proof of Theorem 1.2 is sketched in Section 3.

Proposition 1.1 and the comparison method used in the proof of Theorem 1.2 can be used to discuss the regularity of the free boundary near $t = 0$ for initial data more general than those satisfying (1.7). For example, if, in place of (D),

$$g(x) = \begin{cases} ax^\alpha, & x > 0 \\ -|x|^\beta, & x < 0, \end{cases} \quad (1.9)$$

where $a, \alpha > 0, \beta > 0$, and $\alpha > \beta$, then there exist constants $c_1, c_2 > 0$ which depend on α, β such that

$$c_1 a^{\frac{1}{\beta+1}} t^\lambda < -s(t) < c_2 a^{\frac{1}{\beta+1}} t^\lambda, \quad (1.10)$$

where $\lambda = \frac{\alpha + 1}{2(\beta + 1)}$, for $t > 0$ sufficiently small. On the other hand, if $\beta > \alpha$ in (1.9),

$$\lim_{t \rightarrow 0^+} \frac{-s(t)}{t^{1/2} |\log t|^{1/2}} = (2(\beta - \alpha))^{1/2}.$$

If $\beta = \alpha$ in (1.9), $\lambda = \frac{1}{2}$ and the situation is covered by Proposition 1.1.

The constitutive function $\phi(v) = \max(v, 0)$ in (P) is piecewise linear. However, self similar solutions of (P,D) exist for more general constitutive functions ϕ , but they cannot in general be found explicitly. We expect to investigate the regularity of the free boundary near $t = 0$ for such problems in future work. This question is not discussed in [BMPe] where other qualitative aspects of several such problems are investigated.

Valuable discussions during the preparation of this paper with colleagues and friends including R. Askey, M. G. Crandall, K. Höllig, and J. L. Vázquez are gratefully acknowledged.

2. SELF SIMILAR SOLUTIONS. In this section we consider the Cauchy problem (P) for the model datum (D). Let $\bar{v} = \bar{v}(x,t;\gamma,p_+,p_-)$ be the solution of (P), (D), and define the transformation $v \rightarrow Tv$ by

$$Tv(x,t) = \mu v(\lambda x, \lambda^2 t), \quad (2.1)$$

where $\mu, \lambda > 0$ are constants. T transforms solutions into solutions and in particular, it is clear that $(p_-)\bar{v}(x,t;\gamma,p,1)$, where $p = p_+/p_-$, is a solution of (P), (D). Denoting $\bar{v}(x,t,\gamma;p,1) := \bar{v}(x,t;\gamma,p)$, uniqueness (Theorem 3.2) implies that

$$\bar{v}(x,t;\gamma,p_+,p_-) = (p_-)\bar{v}(x,t;\gamma,p). \quad (2.2)$$

Since $T\bar{v}(x,0;\gamma,p) = \bar{v}(x,0;\gamma,p)$ if and only if $\mu\lambda^\gamma = 1$, uniqueness of solutions of (P), (D) further implies that

$$\bar{v}(x,t;\gamma,p) = (\lambda^{-\gamma})\bar{v}(\lambda x, \lambda^2 t; \gamma, p) \quad (2.3)$$

for any $\lambda > 0$. Fixing the point (x,t) and choosing $\lambda = t^{-1/2}$ in (2.3) implies that \bar{v} is the self similar solution

$$\bar{v}(x,t;\gamma,p) := t^{\gamma/2} \psi(xt^{-1/2}) \quad (2.4)$$

of the Cauchy problem (P), (D) for any $\gamma > 0$. By the comparison method (Section 3) the free boundary s of (P), (D) is monotone decreasing and $s'(t) < 0$ for $t > 0$, $s(0) = 0$. Moreover, by the equivalence of problems (P), (D) and (\bar{P}) , (D) the free boundary $s = \{(x,t) : xt^{-1/2} = -\kappa, t > 0\}$, where $\kappa > 0$ is the constant uniquely determined in Proposition 1.1, and by Proposition 3.3

$$\bar{v}(x,t;\gamma,p) > 0, \quad x > s(t), \quad t > 0.$$

Proof of Proposition 1.1. Substituting \bar{v} defined by (2.4) in (\bar{P}) one sees that ψ must satisfy the linear differential equation (1.3), and conditions (1.4) and (1.5).

Equation (1.3) can be solved explicitly. Put $x = \xi/\sqrt{2}$ and $w(\xi) = \psi(x)$. Then (1.3) becomes

$$w''(x) + xw'(x) - \gamma w(x) = 0. \quad (2.5)$$

Setting $w(x) =: y(x)\exp(-x^2/4)$ we obtain

$$y''(x) - \left(\frac{1}{2} + \gamma + \frac{x^2}{4}\right)y(x) = 0. \quad (2.6)$$

This differential equation has the general solution [B, p. 116-117]

$$y(x) = b_1 D_{-\gamma-1}(x) + b_2 D_{\gamma}(ix) \quad (-\infty < x < \infty, \gamma > 0),$$

where $D_{\nu}(\cdot)$ is the parabolic cylinder function of index ν . Thus the general solution of (1.3) is

$$\psi(\xi) = \left[b_1 D_{-\gamma-1}\left(\frac{\xi}{\sqrt{2}}\right) + b_2 D_{\gamma}\left(\frac{i\xi}{\sqrt{2}}\right) \right] \exp\left(\frac{-\xi^2}{8}\right) \quad (2.7)$$

for $-\infty < \xi < \infty$ and $\gamma > 0$. To impose the initial conditions (1.4) we need the formulae [B, p. 119]

$$\frac{d}{d\xi} \left[D_{-\gamma-1}\left(\frac{\xi}{\sqrt{2}}\right) \exp\left(\frac{-\xi^2}{8}\right) \right] = \frac{-1}{\sqrt{2}} D_{-\gamma}\left(\frac{\xi}{\sqrt{2}}\right) \exp\left(\frac{-\xi^2}{8}\right),$$

$$\frac{d}{d\xi} \left[D_{\gamma}\left(\frac{i\xi}{\sqrt{2}}\right) \exp\left(\frac{-\xi^2}{8}\right) \right] = \frac{i\gamma}{\sqrt{2}} D_{\gamma-1}\left(\frac{i\xi}{\sqrt{2}}\right) \exp\left(\frac{-\xi^2}{8}\right).$$

Then the initial conditions (1.4) yield the pair of equations

$$b_1 D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) + b_2 D_\gamma\left(-\frac{i\kappa}{\sqrt{2}}\right) = 0 \quad (2.8)$$

$$-b_1 D_\gamma\left(-\frac{\kappa}{\sqrt{2}}\right) + i\gamma b_2 D_{-\gamma-1}\left(-\frac{i\kappa}{\sqrt{2}}\right) = p_- \frac{\kappa^{\gamma+1}}{\sqrt{2}} \exp\left(\frac{\kappa^2}{8}\right).$$

Because (2.6) is of self-adjoint form the Wronskian of $D_\gamma(\cdot)$, $D_{-\gamma-1}(\cdot)$ is constant,

$$W(D_{-\gamma-1}(\cdot), D_\gamma(\cdot)) \equiv -i \exp\left[\left(\frac{\gamma+1}{2}\right)\pi i\right].$$

Thus

$$b_1(\kappa) = \frac{(p_-)\kappa^{\gamma+1} D_\gamma\left(-\frac{i\kappa}{\sqrt{2}}\right) \exp\left(\frac{\kappa^2}{8}\right)}{i\sqrt{2} \exp\left[\left(\frac{\gamma+1}{2}\right)\pi i\right]} \quad (2.9)$$

$$b_2(\kappa) = -\frac{(p_-)\kappa^{\gamma+1} D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) \exp\left(\frac{\kappa^2}{8}\right)}{i\sqrt{2} \exp\left[\left(\frac{\gamma+1}{2}\right)\pi i\right]},$$

and (2.7) with b_1, b_2 given by (2.9) is the solution of (1.3) satisfying the initial conditions (1.4). To compute the limit in (1.5) we use [B, p. 122]:

$$D_\nu(z) = z^\nu \exp\left(-\frac{z^2}{4}\right) [1 + O(|z|^{-2})] \quad \text{as } |z| \rightarrow \infty, \quad (2.10)$$

which is valid for $-\frac{3\pi}{4} < \arg z < \frac{3\pi}{4}$. Thus for $\xi \in \mathbb{R}$, $\gamma > 0$,

$$D_{-\gamma-1}\left(\frac{\xi}{\sqrt{2}}\right) = \exp\left(-\frac{\xi^2}{8}\right) \left(\frac{\xi}{\sqrt{2}}\right)^{-\gamma-1} [1 + O(|\xi|^{-2})], \quad \xi \rightarrow +\infty, \quad (2.11)$$

$$\left| D_\gamma\left(\frac{i\xi}{\sqrt{2}}\right) \right| = \exp\left(\frac{\xi^2}{8}\right) \left(\frac{\xi}{\sqrt{2}}\right)^\gamma \left| \exp\left(\frac{i\gamma\pi}{2}\right) \right| [1 + O(|\xi|^{-2})], \quad \xi \rightarrow +\infty.$$

Substitution of (2.11) and (2.9) into the general solution (2.7) yields

$$\psi(\xi) \approx b_2(\kappa) \exp\left(\frac{i\gamma\pi}{2}\right) \left(\frac{\xi}{\sqrt{2}}\right)^\gamma [1 + O(1)], \quad \xi \rightarrow +\infty. \quad (2.12)$$

From formula (2.9) we see that

$$b_2(k) \exp\left(\frac{i\gamma\pi}{2}\right) = \frac{p_-}{\sqrt{2}} \kappa^{\gamma+1} D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) \exp\left(\frac{\kappa^2}{8}\right). \quad (2.13)$$

Imposing the asymptotic condition (1.5) and using (2.12), (2.13) we finally obtain

$$\lim_{\xi \rightarrow +\infty} \frac{\psi(\xi)}{\xi^\gamma} = p_+ = p_- \left(\frac{\kappa}{\sqrt{2}}\right)^{\gamma+1} D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) \exp\left(\frac{\kappa^2}{8}\right) \quad (2.14)$$

which is equation (1.6).

To complete the proof of the Proposition we have to show that given any $p > 0$, (E) is uniquely solvable for κ . This is a consequence of uniqueness (Theorem 3.2). However, it can also be seen directly as follows. From [BO, p. 573]

$$D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right) = \frac{\sqrt{\pi}}{2^{\frac{\gamma+1}{2}} \Gamma\left(1 + \frac{\gamma}{2}\right)} \sum_{n=0}^{\infty} \frac{a_{2n}}{(2n)!} \left(\frac{\kappa}{\sqrt{2}}\right)^{2n} + \frac{\sqrt{\pi}}{2^{\frac{\gamma}{2}} \Gamma\left(\frac{1+\gamma}{2}\right)} \sum_{n=0}^{\infty} \frac{a_{2n+1}}{(2n+1)!} \left(\frac{\kappa}{\sqrt{2}}\right)^{2n+1}, \quad (2.15)$$

is an analytic function of κ , $-\infty < \kappa < \infty$, $\gamma > -1$; $a_0 = a_1 = 1$, $a_{n+2} = \left(\gamma + \frac{1}{2}\right)a_n + \frac{n}{4}(n-1)a_{n-2}$, and $D_{-\gamma-1}(0) = \frac{\sqrt{\pi}}{2^{(\gamma+1)/2} \Gamma\left(1 + \frac{\gamma}{2}\right)}$. Since the coefficients a_ν are positive, $D_{-\gamma-1}\left(-\frac{\kappa}{\sqrt{2}}\right)$ is a positive, strictly increasing function of κ for $0 \leq \kappa < \infty$, and by (1.6) so is $p(\kappa)$.

Moreover $p(0) = 0$. This completes the proof of Proposition 1.1.

We conclude this section by establishing two useful asymptotic estimates.

From (2.15) and (E)

$$p(\kappa) = \frac{\sqrt{\pi}}{2^{\frac{\gamma+1}{2}} \Gamma(1 + \frac{\gamma}{2})} \left(\frac{\kappa}{\sqrt{2}}\right)^{\gamma+1} \quad (\kappa \rightarrow 0^+) . \quad (2.16)$$

Moreover, [BO, p. 574]

$$D_{-\gamma-1} \left(-\frac{\kappa}{\sqrt{2}}\right) = \frac{\sqrt{2\pi}}{\Gamma(1 + \gamma)} \left(\frac{\kappa}{\sqrt{2}}\right)^{\gamma} \exp\left(\frac{\kappa^2}{8}\right) \quad (\kappa \rightarrow +\infty) ,$$

and therefore, from (E)

$$p(\kappa) = \frac{\sqrt{2\pi}}{\Gamma(1 + \gamma)} \left(\frac{\kappa}{\sqrt{2}}\right)^{2\gamma+1} \exp\left(\frac{\kappa^2}{4}\right) \quad (\kappa \rightarrow +\infty) . \quad (2.17)$$

3. EXISTENCE UNIQUENESS AND COMPARISON OF SOLUTIONS OF (P). In this section we state general existence and uniqueness results for (P), briefly discuss the comparison method, and sketch the proof of Theorem 1.2.

Consider the Cauchy problem (P) in $Q_T = \mathbb{R} \times [0, T]$ where $T > 0$, and assume that the datum $g \in L_{loc}^{\infty}(\mathbb{R})$ and satisfies

$$g(x) < c \exp(hx^2), \quad x \in \mathbb{R} , \quad (3.1)$$

for some constants $c, h > 0$. Define $g^-(x) := \max(-g(x), 0)$. For existence of solutions of (P) one has the following result proved in Vázquez [V1].

Theorem 3.1. There exists $T = T(g) > (4\pi h)^{-1}$ and a function
 $v \in C([0, T] : L_{loc}^1(\mathbb{R}) \cap L_{loc}^{\infty}(Q_T))$ with the following properties:

- (i) $v(\cdot, t) \rightarrow g$ in $L_{loc}^1(\mathbb{R})$ as $t \rightarrow 0^+$.
- (ii) $v_t - \phi(v)_{xx} = 0$ in $\mathcal{D}'(Q_T)$.
- (iii) For every $t_1 < T$ there exists constants $h_1 > h$ and $c_1 > 0$ such that

$$-g^-(x) < v(x, t) < c_1 \exp(-h_1 x^2) \quad (3.2)$$

for every $0 < t < t_1$ and a.e. for $x \in \mathbb{R}$.

Uniqueness of solutions of (P) can be established in a larger class of functions which includes the class of solutions in Theorem 3.1; the proof is given in Vázquez [V1].

Theorem 3.2. Let $u, v \in C([0, T]; L^1_{loc}(\mathbb{R}) \cap L^\infty_{loc}(Q_T))$ satisfy the following properties:

- (i) $u_t - \phi(u)_{xx} = v_t - \phi(v)_{xx}$ in $\mathcal{D}'(Q_T)$;
- (ii) $u(\cdot, t) - v(\cdot, t) \rightarrow 0$ in $L^1_{loc}(\mathbb{R})$ as $t \rightarrow 0^+$;
- (iii) for every $t_1 < T$ there exist constants $c_1 > 0, h_1 > 0$ such that

$$u(x, t), v(x, t) < c_1 \exp(h_1 x^2) \text{ a.e. in } \mathbb{R} \times (0, t_1). \quad (3.3)$$
- (iv) $u^-(x, t), v^-(x, t) \in L^\infty_{loc}(Q_T)$.

Then $u(x, t) = v(x, t)$ a.e. in Q_T .

As a consequence of Theorems 3.1 and 3.2 the Cauchy problem (P) has a unique solution in Q_T for some $T > 0$ if the datum g satisfies (3.1). If the datum g has exponential growth as $|x| \rightarrow \infty$, the solution v of (P) will become infinite in finite time. This is evident because nonnegative solutions of the heat equation $v_t = v_{xx}$ have this property for exponentially growing data. On the other hand, if the datum g has at most polynomial growth at infinity, then by Theorem 3.1 the solution v of (P) exists on $0 < t < \infty$.

Next, we turn to the comparison method in the form it is needed in the proof of Theorem 1.2, see Vázquez [V1]. To state it we define

$$G(x) = \int_{-\infty}^x g(\xi) d\xi, \quad x \in \mathbb{R},$$

$$V(x, t) = \int_{-\infty}^x v(\xi, t) d\xi, \quad x \in \mathbb{R}, t > 0.$$

Proposition 3.3. Let v_1, v_2 be two solutions of (P) corresponding to data g_1, g_2 respectively, each satisfying assumptions (g), and $g_1, g_2 \in L^1(\mathbb{R})$. If $G_1(x) > G_2(x)$ for every $x \in \mathbb{R}$, then $V_1(x, t) > V_2(x, t)$ for every $x \in \mathbb{R}$, $t > 0$.

Remark. Proposition 3.3 holds for solutions v of (P) whenever ϕ is a continuous nondecreasing function: $\mathbb{R} \rightarrow \mathbb{R}$, and $\phi(0) = 0$. Observe that V satisfies the P.D.E. $V_t = \phi(V_x)$ and Proposition 3.3 is the maximum principle for this equation.

Sketch of Proof of Theorem 1.2. We assume that assumptions (g) are satisfied. Since the interest is in the regularity of the free boundary near $t = 0$, we assume without loss of generality that g has at most polynomial growth at infinity. Then the Cauchy problem (P), (g) exhibits a unique free boundary $x = s(t)$ defined on $0 < t < \infty$, $s(0) = 0$, $s \in C^1(0, \infty)$, and $s'(t) < 0$ for $t > 0$. In what follows we denote by $G(x)$ the primitive $\int_0^x g(\xi) d\xi$. An essential ingredient in the proof is the following refinement of Proposition 3.3. An analogous result for the porous medium equation has been proved by Vázquez [V2]; the proof is similar.

Lemma 3.4. Let v_1, v_2 be two solutions of (P) corresponding to initial data g_1, g_2 respectively, satisfying assumptions (g). Let s_1, s_2 be the corresponding free boundaries, $s_1(0) = s_2(0) = 0$. Assume that

$$0 > g_1(x) > g_2(x) \quad (3.4)$$

for small $x < 0$, and that

$$G_1(x) > G_2(x) \quad (3.5)$$

for every x on some interval $(0, \alpha)$, $\alpha > 0$, $G_1(\alpha) > 0$ and $G_1 \neq G_2$ on $(0, \alpha)$. Then

$$s_1(t) < s_2(t) \quad (3.6)$$

for $t > 0$ sufficiently small.

To complete the proof of Theorem 1.2 we apply Lemma 3.4. Let $v_1 = v$, the solution of (P), (g) where the initial datum g satisfies assumptions (g) and (1.7). Let v_2 be the self similar solution of Proposition 1.1 corresponding to the model datum (D) with $p_+ = b(\gamma + 1) + \epsilon$, $p_- = a - \epsilon$, where $0 < \epsilon < a$. Then $G_2(x) > G_1(x)$ for small $x > 0$, $G_1 \neq G_2$, and $0 > g_2(x) > g_1(x)$ for $x < 0$. By Lemma 3.4 $s_2(t) < s_1(t)$ for small $t > 0$. Thus identifying s_1 with s and using the result of Proposition 1.1,

$$\liminf_{t \rightarrow 0^+} (-s(t)t^{1/2}) > \kappa\left(\frac{b(\gamma + 1) + \epsilon}{a - \epsilon}\right)$$

for every $0 < \epsilon < a$. Since κ is a continuous function of p_+/p_- , we let $\epsilon \rightarrow 0^+$ to obtain

$$\liminf_{t \rightarrow 0^+} (-s(t)t^{1/2}) > \kappa\left(\frac{b(\gamma + 1)}{a}\right). \quad (3.7)$$

By a similar argument, letting v_1 be the self similar solution of (P), (D) with p_+ and p_- defined as above, and letting v_2 be the solution of (P), (D) we obtain

$$\limsup_{t \rightarrow 0^+} (-s(t)t^{1/2}) < \kappa\left(\frac{b(\gamma + 1)}{a}\right). \quad (3.8)$$

The result (1.8) is a consequence of (3.7), (3.8). This completes the sketch of the proof.

REFERENCES

- [B] Bateman Manuscript Project, A. Erdélyi, ed., McGraw Hill, 1954.
- [BCPa] P. Benilan, M. G. Crandall and A. Pazy, M-Accretive operators, to appear.
- [BCPi] P. Benilan, M. G. Crandall and M. Pierre, Solutions of the porous medium equation in \mathbb{R}^n under optimal conditions on initial values, *Indiana Univ. Math. J.* 33 (1984), 51-87.
- [BMPE] M. Bertsch, P. de Mottoni and L. A. Peletier, The Stefan problem with heating: Appearance and disappearance of a mushy region, *Math. Inst. Univ. of Leiden, The Netherlands, Report No. 18, August, 1984.*
- [BO] C. Bender and S. Orszag, Advanced Mathematical Methods for Scientists and Engineers, McGraw Hill, 1978.
- [E] L. C. Evans, Application of nonlinear semigroup theory to certain partial differential equations, in: Nonlinear Evolution Equations, M. G. Crandall, ed., Academic Press, 1978.
- [FP1] A. Fasano and M. Primicerio, General free boundary problems for the heat equation, I, *J. Math. Anal. Appl.* 57 (1977), 694-723.
- [FP2] A. Fasano and M. Primicerio, General free boundary problems for the heat equation, II, *J. Math. Anal. Appl.* 58 (1977), 202-231.
- [H] K. Höllig, Existence of infinitely many solutions for a forward backward heat equation, *Trans. Amer. Math. Soc.* 278 (1983), 299-316.
- [HN1] K. Höllig and J. A. Nohel, A diffusion equation with a nonmonotone constitutive function, *Proceedings NATO/LONDON Math. Soc. Conf. on Systems of Nonlinear Partial Differential Equations*, J. M. Ball, ed., Reidel Publishing Co. (1983), 409-422.

- [HN2] K. Höllig and J. A. Nohel, A nonlinear integral equation occurring in a singular free boundary problem, Trans. Amer. Math. Soc. 283 (1984), 145-155.
- [HN3] K. Höllig and J. A. Nohel, A singular free boundary problem, MRC Technical Summary Report #2582, Mathematics Research Center, University of Wisconsin-Madison.
- [KN] D. Kinderlehrer and L. Nirenberg, Regularity in free boundary problems, Annali della SNS 4 (1977), 373-391.
- [S] D. Schaeffer, A new proof of the infinite differentiability of the free boundary in the Stefan problem, J. Diff. Equa. 20 (1976), 266-269.
- [V1] J. L. Vázquez, Degenerate Parabolic Problems, IMA, University of Minnesota (Preprint).
- [V2] J. L. Vázquez, The interfaces of one-dimensional flows in porous media, Trans. Amer. Math. Soc. 285 (1984), 717-737.

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$$\begin{aligned} v_t &= \phi(v)_{xx}, & x \in \mathbb{R}, t > 0, \\ v(x,0) &= g(x), \end{aligned} \tag{P}$$

where $\phi(v) = \max(v,0)$. The datum g is assumed smooth on $\mathbb{R} \setminus \{0\}$ with at most exponential growth at infinity and satisfies

$$xg(x) \geq 0, \quad x \neq 0, \quad g(0) = 0,$$

the inequality being strict near $x = 0$.

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