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Non-uniqueness of weak solutions for the fractal Burgers equation

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ABSTRACT. The notion of Kruzhkov entropy solution was extended by the first author in 2007 to conservation laws with a fractional laplacian diffusion term; this notion led to well-posedness for the Cauchy problem in the L^∞ -framework. In the present paper, we further motivate the introduction of entropy solutions, showing that in the case of fractional diffusion of order strictly less than one, uniqueness of a weak solution may fail.

Keywords: fractional laplacian, non-local diffusion, conservation law, Lévy-Khintchine's formula, entropy solution, admissibility of solutions, Oleñnik condition, non-uniqueness of weak solutions

2000 MSC: 35L65, 35L67, 35L82, 35S10, 35S30

1 Introduction

This paper contributes to the study of the so-called fractal/fractional Burgers equation

$$\partial_t u(t, x) + \partial_x \left(\frac{u^2}{2} \right) (t, x) + \mathcal{L}_\lambda[u](t, x) = 0, \quad (t, x) \in \mathbb{R}^+ \times \mathbb{R}, \quad (1.1)$$

$$u(0, x) = u_0(x), \quad x \in \mathbb{R}, \quad (1.2)$$

where \mathcal{L}_λ is the non-local operator defined for all Schwartz function $\varphi \in \mathcal{S}(\mathbb{R})$ through its Fourier transform by

$$\mathcal{F}(\mathcal{L}_\lambda[\varphi])(\xi) := |\xi|^\lambda \mathcal{F}(\varphi)(\xi) \quad \text{with } \lambda \in (0, 1); \quad (1.3)$$

i.e. \mathcal{L}_λ denotes the fractional power of order $\lambda/2$ of the Laplacian operator $-\Delta$ with respect to (w.r.t. for short) the space variable.

This equation is involved in many different physical problems, such as overdriven detonation in gas [14] or anomalous diffusion in semiconductor growth [29], and appeared in a number of papers, such as [6, 7, 8, 9, 17, 20, 21, 18, 1, 2, 22, 24, 26, 27, 4, 16, 23, 12]. Recently, the notion of entropy solution has been introduced by Alibaud in [1] to show the global-in-time well-posedness in the L^∞ -framework.

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For the range of exponent $\lambda > 1$ the notion of weak solution (*i.e.* a solution in the sense of distributions; *cf.* Definition 2.2 below) is sufficient to ensure the uniqueness and stability result, see the work of Droniou, Gallouët and Vovelle in [17]. It seems that such results could be generalized to the critical case $\lambda = 1$, as suggested by the works of Chan and Czubak in [13] and Miao and Wu in [27] for a large class of initial data (either periodic or L^2 or in critical Besov spaces).

In this paper, we focus on the range of exponent $\lambda \in (0, 1)$. By analogy with the purely hyperbolic equation $\lambda = 0$ (*cf.* Oleřnik [28] and Kruzhkov [25]), a natural conjecture was that in that case a weak solution to the Cauchy problem (1.1)-(1.2) need not be unique. Indeed, it has been shown by Alibaud, Droniou and Vovelle in [2] that the assumption $\lambda < 1$ makes the diffusion term too weak to prevent the appearance of discontinuities in solutions of (1.1); see also the work of Kiselev, Nazarov and Shterenberg in [24]. To the best of our knowledge, yet it was unclear whether such discontinuities in a weak solution can violate the entropy conditions of [1].

Here we construct a stationary weak solution of Problem (1.1)-(1.2), $\lambda < 1$, which does violate the entropy constraint (constraint which can be expressed under the form of Oleřnik's inequality, *cf.* [28]). Thus the main result of this paper is the following.

Theorem 1.1. *Let $\lambda \in (0, 1)$. There exist initial data $u_0 \in L^\infty(\mathbb{R})$ such that uniqueness of a weak solution to the Cauchy problem (1.1)-(1.2) fails.*

2 Preliminaries

In this section, we fix some notations, recall the Lévy-Khintchine's formula for the fractional Laplacian and the associated notions of generalized solutions to fractal conservation laws.

2.1 Notations

Sets. Throughout this paper, \mathbb{R}^\pm denote the sets $(-\infty, 0)$ and $(0, +\infty)$, respectively; the set \mathbb{R}_* denotes $\mathbb{R} \setminus \{0\}$ and $\overline{\mathbb{R}}$ denotes $\{-\infty\} \cup \mathbb{R} \cup \{+\infty\}$.

Derivatives from the right. A function $m : \mathbb{R}^+ \rightarrow \mathbb{R}$ is said to be derivable from the right at $t_0 > 0$ if the limit $\lim_{t \geq t_0} \frac{m(t) - m(t_0)}{t - t_0}$ exists in \mathbb{R} ; in that case, this limit is denoted by $m'_r(t_0)$.

Function spaces. Further, $C_c^\infty = \mathcal{D}$ denotes the space of infinitely differentiable compactly supported test functions, \mathcal{S} the Schwartz space, \mathcal{D}' the distribution space and \mathcal{S}' the tempered distribution space. The space of k times continuously differentiable functions is denoted by C^k and C_b^k denotes the subspace of functions with bounded derivatives up to order k (if $k = 0$, the superscripts are omitted); C_c denotes the subspace of C of functions with compact support and C_0 the closure of C_c (for the norm of the uniform convergence); L^p and H^p denotes the classical Lebesgue and Sobolev spaces, respectively; the space of bounded variation functions is denoted by BV . Without anymore precision, these spaces are endowed by their usual strong topologies.

Weak- \star topology in BV . The space $L^1(\mathbb{R}) \cap BV(\mathbb{R})$ endowed with the strong topology of L^1 and the weak- \star topology in BV is denoted by $L^1(\mathbb{R}) \cap (BV(\mathbb{R}))_{w-\star}$; *i.e.*:

$$[v_k \rightarrow v \text{ in } L^1(\mathbb{R}) \cap (BV(\mathbb{R}))_{w-\star}] \iff \begin{cases} v_k \rightarrow v \text{ in } L^1(\mathbb{R}), \\ \partial_x v_k \xrightarrow{w-\star} \partial_x v \text{ in } C'_0(\mathbb{R}). \end{cases}$$

The same way, $(BV_{loc}(\mathbb{R}))_{w-\star} \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})$ denotes the topological space whose convergence notion is defined by:

$$[v_k \rightarrow v \text{ in } (BV_{loc}(\mathbb{R}))_{w-\star} \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})] \iff \begin{cases} v_k \rightarrow v \text{ in } H^1(\mathbb{R} \setminus [-R, R]), \forall R > 0, \\ \partial_x v_k \xrightarrow{w-\star} \partial_x v \text{ in } C'_c(\mathbb{R}). \end{cases}$$

Spaces of odd functions. In our construction, a key role is played by the spaces of odd functions v which are in the Sobolev space H^1

$$H_{odd}^1 := \{v \in H^1 \mid v \text{ is odd}\};$$

notice that $v \in H_{odd}^1(\mathbb{R}_*)$ can be discontinuous at zero so that $v(0^-) = -v(0^+)$ in the sense of traces, whereas $v(0^-) = v(0^+) = 0$ if $v \in H_{odd}^1(\mathbb{R})$.

Throughout, $H_{odd}^1(\mathbb{R}_*)$ and more generally $H^1(\mathbb{R}_*)$ are considered as subspaces of $L^2(\mathbb{R})$. The gradient of $v \in H^1(\mathbb{R}_*)$ in $\mathcal{D}'(\mathbb{R})$ is denoted by $\partial_x v$, so that $(\partial_x v)|_{\mathbb{R}_*} \in L^2(\mathbb{R})$ is the gradient of v in $\mathcal{D}'(\mathbb{R}_*)$. Notice that $(\partial_x v)|_{\mathbb{R}_*} = \partial_x v$ almost everywhere (a.e. for short) on \mathbb{R} if and only if (iff for short) v is continuous at zero; in the other case, one has $\partial_x v \notin L^1_{loc}(\mathbb{R})$. For the sake of simplicity the product $\int_{\mathbb{R}} (\partial_x v)|_{\mathbb{R}_*} (\partial_x \varphi)|_{\mathbb{R}_*}$ (with $\varphi \in H^1(\mathbb{R}_*)$) is sometimes denoted by $\int_{\mathbb{R}_*} \partial_x v \partial_x \varphi$.

Identity and Fourier operators. By Id we denote the identity function. The Fourier transform \mathcal{F} on $\mathcal{S}'(\mathbb{R})$ is denoted by \mathcal{F} ; for explicit computations, we use the following definition on $L^1(\mathbb{R})$:

$$\mathcal{F}(v)(\xi) := \int_{\mathbb{R}} e^{-2i\pi x \xi} v(x) dx.$$

Entropy-flux pairs. By η , we denote a convex function on \mathbb{R} ; following Kruzhkov [25], we call it an *entropy* and $q : u \mapsto \int_0^u s d\eta(s)$ is the associated *entropy flux*.

Truncature functions. The sign function is defined by:

$$u \mapsto \text{sign } u := \begin{cases} \pm 1 & \text{if } \pm u > 0, \\ 0 & \text{if } u = 0. \end{cases}$$

During the proofs, we shall need to regularize the function

$$u \mapsto \min\{|u|, n+1\} \text{sign } u,$$

where $n \in \mathbb{N}_*$ will be fixed; T_n denotes a regularization satisfying

$$\begin{cases} T_n \in C_b^\infty(\mathbb{R}) \text{ is odd,} \\ T_n = \text{Id on } [-n+1, n-1], \\ |T_n| \leq n. \end{cases} \quad (2.1)$$

2.2 Lévy-Khintchine's formula

Let $\lambda \in (0, 1)$. For all $\varphi \in \mathcal{S}(\mathbb{R})$ and $x \in \mathbb{R}$, we have

$$\mathcal{L}_\lambda[\varphi](x) = -G_\lambda \int_{\mathbb{R}} \frac{\varphi(x+z) - \varphi(x)}{|z|^{1+\lambda}} dz, \quad (2.2)$$

where $G_\lambda = \frac{\lambda \Gamma(\frac{1+\lambda}{2})}{2\pi^{\frac{1}{2}+\lambda} \Gamma(1-\frac{\lambda}{2})} > 0$ and Γ is Euler's function, see *e.g.* [10, 19] or [18, Theorem 2.1].

According to this formula, \mathcal{L}_λ extends to a bounded linear operator acting from $C_b^1(\mathbb{R})$ to $C_b(\mathbb{R})$.

2.3 Entropy and weak solutions

Formula (2.2) motivates the following notion of entropy solution introduced in [1].

Definition 2.1. (Entropy solutions)

Let $\lambda \in (0, 1)$ and $u_0 \in L^\infty(\mathbb{R})$. A function $u \in L^\infty(\mathbb{R}^+ \times \mathbb{R})$ is said to be an entropy solution to (1.1)-(1.2) if for all non-negative test function $\varphi \in C_c^\infty([0, \infty) \times \mathbb{R})$, all entropy $\eta \in C^1(\mathbb{R})$ and all $r > 0$,

$$\begin{aligned} \int_{\mathbb{R}} \eta(u_0) \varphi(0) + \int_{\mathbb{R}^+} \int_{\mathbb{R}} (\eta(u) \partial_t \varphi + q(u) \partial_x \varphi) \\ + G_\lambda \int_{\mathbb{R}^+} \int_{\mathbb{R}} \int_{|z| > r} \eta'(u(t, x)) \frac{u(t, x+z) - u(t, x)}{|z|^{1+\lambda}} \varphi(t, x) dt dx dz \\ + G_\lambda \int_{\mathbb{R}^+} \int_{\mathbb{R}} \int_{|z| \leq r} \eta(u(t, x)) \frac{\varphi(t, x+z) - \varphi(t, x)}{|z|^{1+\lambda}} dt dx dz \geq 0. \end{aligned} \quad (2.3)$$

Remark 2.1. In the above definition, r plays the role of a cut-off parameter; taking $r > 0$ in (2.3), one avoids the technical difficulty while treating the singularity in the Lévy-Khintchine's formula (by doing this, one loses some information, recovered at the limit $r \rightarrow 0$). Let us refer to the recent paper of Karlsen and Ulusoy [23] for a different definition of the entropy solution, equivalent to the above one; note that the framework of [23] encompasses Lévy mixed hyperbolic/parabolic equations.

The notion of entropy solutions provides a well-posedness theory for the Cauchy problem for the fractional conservation law (1.1); the results are very similar to the ones for the classical Burgers equation (*cf.* e.g. [28, 25]).

Theorem 2.1 ([1]). *For all $u_0 \in L^\infty(\mathbb{R})$, there exists one and only one entropy solution $u \in L^\infty(\mathbb{R}^+ \times \mathbb{R})$ to Problem (1.1)-(1.2). Moreover, $u \in C([0, +\infty); L^1_{loc}(\mathbb{R}))$ (so that $u(0) = u_0$), and the solution depends continuously in $C([0, +\infty); L^1(\mathbb{R}))$ on the initial data in $L^1(\mathbb{R}) \cap L^\infty(\mathbb{R})$.*

As explained in the introduction, the purpose of this paper is to prove that the weaker solution notion below would not ensure uniqueness.

Definition 2.2. (Weak solutions)

Let $u_0 \in L^\infty(\mathbb{R})$. A function $u \in L^\infty(\mathbb{R}^+ \times \mathbb{R})$ is said to be a weak solution to (1.1)-(1.2) if for all $\varphi \in C_c^\infty([0, \infty) \times \mathbb{R})$,

$$\int_{\mathbb{R}^+} \int_{\mathbb{R}} \left(u \partial_t \varphi + \frac{u^2}{2} \partial_x \varphi - u \mathcal{L}_\lambda[\varphi] \right) + \int_{\mathbb{R}} u_0 \varphi(0) = 0. \quad (2.4)$$

3 Oleinik's inequality

Notice that it can be easily shown that an entropy solution is also a weak one. The converse statement is false, which we will prove by constructing a weak non-entropy solution. A key fact here is the well-known Oleinik's inequality (see [28]); in this section, we generalize it to entropy solutions of the fractal Burgers equation.

Proposition 3.1. (Oleinik’s inequality)

Let $u_0 \in L^\infty(\mathbb{R})$. Let $u \in L^\infty(\mathbb{R}^+ \times \mathbb{R})$ be the entropy solution to (1.1)-(1.2). Then, we have for all $t > 0$

$$\partial_x u(t) \leq \frac{1}{t} \quad \text{in } \mathcal{D}'(\mathbb{R}). \quad (3.1)$$

Remark 3.1. This result can be adapted to general uniformly convex fluxes. Moreover, we think that in this case, the Oleinik’s inequality gives a necessary and sufficient condition for a weak solution to be an entropy solution (as for pure scalar conservation laws, cf. [28, 25]). Nevertheless, for the sake of simplicity, we only prove the above result, which is sufficient for our purpose.

In order to prove this proposition, we need the following technical result:

Lemma 3.1. Let $v \in C^1(\mathbb{R}^+ \times \mathbb{R})$ be such that for all $b > a > 0$,

$$\lim_{|x| \rightarrow +\infty} \sup_{t \in (a,b)} v(t, x) = -\infty. \quad (3.2)$$

Define $m(t) := \max_{x \in \mathbb{R}} v(t, x)$ and $K(t) := \operatorname{argmax}_{x \in \mathbb{R}} v(t, x)$. Then m is continuous and derivable from the right on \mathbb{R}^+ with $m'_r(t) = \max_{x \in K(t)} \partial_t v(t, x)$.

For a proof of this result, see e.g. the survey book of Dansky [15] on the min max theory; for the reader’s convenience, a short proof is also given in Appendix A. We can now prove Oleinik’s inequality.

Proof of Proposition 3.1. For $\varepsilon > 0$ consider the regularized problem

$$\partial_t u_\varepsilon + \partial_x \left(\frac{u_\varepsilon^2}{2} \right) + \mathcal{L}_\lambda[u_\varepsilon] - \varepsilon \partial_{xx}^2 u_\varepsilon = 0 \quad \text{in } \mathbb{R}^+ \times \mathbb{R}, \quad (3.3)$$

$$u_\varepsilon(0) = u_0 \quad \text{on } \mathbb{R}. \quad (3.4)$$

It was shown in [17] that there exists a unique solution $u_\varepsilon \in L^\infty(\mathbb{R}^+ \times \mathbb{R})$ to Problem (3.3)-(3.4) in the sense of the Duhamel’s formula, and that $u_\varepsilon \in C_b^\infty((a, +\infty) \times \mathbb{R})$ for all $a > 0$. Furthermore, it has been proved in [4] that for all $T > 0$, u_ε converges to u in $C([0, T]; L_{loc}^1(\mathbb{R}))$ as $\varepsilon \rightarrow 0$. Inequality (3.1) being stable by this convergence, it suffices to prove that u_ε satisfies (3.1).

To do so, let us derivate (3.3) w.r.t. x . We get

$$\partial_t v_\varepsilon + v_\varepsilon^2 + u_\varepsilon \partial_x v_\varepsilon + \mathcal{L}_\lambda[v_\varepsilon] - \varepsilon \partial_{xx}^2 v_\varepsilon = 0, \quad (3.5)$$

with $v_\varepsilon := \partial_x u_\varepsilon$. Introduce a “barrier function” $\Phi \in C^2(\mathbb{R})$ such that Φ is non-negative, Φ' and Φ'' are bounded and

$$\lim_{|x| \rightarrow +\infty} \Phi(x) = +\infty. \quad (3.6)$$

One can see that $\mathcal{L}_\lambda[\Phi]$ is bounded, see e.g. [3, Lemma B.0.1]; hence, there exists a constant C_Φ such that $\|\partial_x \Phi\|_\infty + \|\partial_{xx}^2 \Phi\|_\infty + \|\mathcal{L}_\lambda[\Phi]\|_\infty \leq C_\Phi$. For $\delta > 0$ and $t > 0$, define

$$m_\delta(t) := \max_{x \in \mathbb{R}} \{v_\varepsilon(t, x) - \delta \Phi(x)\}.$$

Define $K_\delta(t) := \operatorname{argmax}_{x \in \mathbb{R}} \{v_\varepsilon(t, x) - \delta\Phi(x)\}$. This set is non-empty and compact, thanks to the regularity of v_ε and (3.6); moreover, by Lemma 3.1, m_δ is derivable from the right w.r.t. t with:

$$(m_\delta)'_r(t) = \max_{x \in K_\delta(t)} \partial_t v_\varepsilon(t, x) = \partial_t v_\varepsilon(t, x_\delta(t))$$

for some $x_\delta(t) \in K_\delta(t)$. This point is also a global maximum point of $v_\varepsilon(t) - \delta\Phi$, so that

$$\partial_x v_\varepsilon(t, x_\delta(t)) = \delta \partial_x \Phi(x_\delta), \quad \partial_{xx}^2 v_\varepsilon(t, x_\delta(t)) \leq \delta \partial_{xx}^2 \Phi(x_\delta) \quad \text{and} \quad \mathcal{L}_\lambda[v_\varepsilon] \geq \delta \mathcal{L}_\lambda[\Phi](t, x_\delta(t))$$

(the last inequality is easily derived from (2.2)). We deduce that

$$|\partial_x v_\varepsilon(t, x_\delta(t))| \leq \delta C_\Phi, \quad \partial_{xx}^2 v_\varepsilon(t, x_\delta(t)) \leq \delta C_\Phi \quad \text{and} \quad \mathcal{L}_\lambda[v_\varepsilon](t, x_\delta(t)) \geq -\delta C_\Phi.$$

By (3.5), we get $(m_\delta)'_r(t) + v_\varepsilon^2(t, x_\delta(t)) \leq C\delta$, for some constant C that only depends on ε , $\|u_\varepsilon\|_\infty$ and C_Φ . But, by construction $m_\delta(t) = v_\varepsilon(t, x_\delta(t)) - \delta\Phi(x_\delta(t))$ and Φ is non-negative, so that

$$(m_\delta)'_r(t) + (m_\delta(t) + \delta\Phi(x_\delta(t)))^2 \leq C\delta \quad \text{and} \quad (m_\delta)'_r(t) - C\delta + (\max\{m_\delta(t), 0\})^2 \leq 0.$$

Now we set $\tilde{m}_\delta(t) := m_\delta(t) - C\delta t$. Because the function $r \in \mathbb{R} \rightarrow (\max\{r, 0\})^2 \in \mathbb{R}$ is non-decreasing, we infer that $\tilde{m}_\delta \in C(\mathbb{R}^+)$ is derivable from the right with

$$(\tilde{m}_\delta)'_r(t) + (\max\{\tilde{m}_\delta(t), 0\})^2 \leq 0$$

for all $t > 0$. By Lemma B.1 in Appendix B, we can integrate this equation and conclude that $\tilde{m}_\delta(t) \leq \frac{1}{t}$ for all $t > 0$.

Finally, it is easy to prove that $\tilde{m}_\delta(t) = m_\delta(t) - C\delta t \rightarrow \sup_{x \in \mathbb{R}} v_\varepsilon(t, x)$ as $\delta \rightarrow 0$, so that $\sup_{x \in \mathbb{R}} \partial_x u_\varepsilon(t, x) \leq \frac{1}{t}$ (pointwise, for all $t > 0$). This proves (3.1) for u_ε in the place of u , and thus completes the proof of the proposition. \blacksquare

4 A stationary regularized problem

The plan to show Theorem (1.1) consists in proving the existence of an odd weak stationary solution to (1.1) with a discontinuity at $x = 0$ not satisfying the Oleinik's inequality. This non-entropy solution is constructed as limit of solutions to regularized problems, see Problem (4.2) below. This section focuses on the solvability of these problems. This is done in the second subsection; the first one lists some properties of \mathcal{L}_λ that will be needed.

4.1 Main properties of the non-local operator

In the sequel, \mathcal{L}_λ is always defined by the Lévy-Khintchine's formula (2.2).

Lemma 4.1. *Let $\lambda \in (0, 1)$. The operator \mathcal{L}_λ defined by the Lévy-Khintchine's formula (2.2) enjoys the following properties:*

(i) *The linear operators \mathcal{L}_λ and $\mathcal{L}_{\lambda/2}$ are bounded as operators*

- (a) $\mathcal{L}_\lambda : C_b(\mathbb{R}_*) \cap C^1(\mathbb{R}_*) \rightarrow C(\mathbb{R}_*)$;
- (b) $\mathcal{L}_\lambda : H^1(\mathbb{R}_*) \rightarrow L^1_{loc}(\mathbb{R}) \cap L^2_{loc}(\overline{\mathbb{R}} \setminus \{0\})$;
- (c) $\mathcal{L}_\lambda : L^1(\mathbb{R}) \cap (BV(\mathbb{R}))_{w^*} \rightarrow L^1(\mathbb{R})$;

(d) $\mathcal{L}_{\lambda/2} : H^1(\mathbb{R}_*) \rightarrow L^2(\mathbb{R})$.

(ii) If $v \in H^1(\mathbb{R}_*)$, then Definition (1.3) of \mathcal{L}_λ by Fourier transform makes sense; more precisely,

$$\mathcal{L}_\lambda[v] = \mathcal{F}^{-1} \left(\xi \rightarrow |\xi|^\lambda \mathcal{F}(v)(\xi) \right) \quad \text{in } \mathcal{S}'(\mathbb{R}).$$

(iii) For all $v, w \in H^1(\mathbb{R}_*)$,

$$\int_{\mathbb{R}} \mathcal{L}_\lambda[v] w = \int_{\mathbb{R}} v \mathcal{L}_\lambda[w] = \int_{\mathbb{R}} \mathcal{L}_{\lambda/2}[v] \mathcal{L}_{\lambda/2}[w].$$

(iv) If $v \in H^1(\mathbb{R}_*)$ is odd (resp. even), then $\mathcal{L}_\lambda[v]$ is odd (resp. even).

(v) Let $0 \neq v \in C_b(\mathbb{R}_*) \cap C^1(\mathbb{R}_*)$ be odd. Assume that $x_* > 0$ is an extremum point of v such that

$$v(x_*) = \max_{\mathbb{R}^+} v \quad \text{and} \quad v(x_*) \geq 0 \quad (\text{resp. } v(x_*) = \min_{\mathbb{R}^+} v \quad \text{and} \quad v(x_*) \leq 0).$$

Then, we have $\mathcal{L}_\lambda[v](x_*) > 0$ (resp. $\mathcal{L}_\lambda[v](x_*) < 0$).

Remark 4.1. Item (v) can be interpreted as a positive reverse maximum principle for the fractional Laplacian acting on the space of odd functions.

The proofs of these results are gathered in Section 6.

4.2 The regularized problem

Throughout this section, $\varepsilon > 0$ is a fixed parameter. Consider the space $H_{odd}^1(\mathbb{R}_*)$ with the scalar product

$$\langle v, w \rangle := \varepsilon \int_{\mathbb{R}_*} \{ (vw + \partial_x v \partial_x w) + \mathcal{L}_{\lambda/2}[v] \mathcal{L}_{\lambda/2}[w] \}. \quad (4.1)$$

By the item (i) (d) of Lemma 4.1, $\langle \cdot, \cdot \rangle$ is well-defined and its associated norm $\| \cdot \| := \sqrt{\langle \cdot, \cdot \rangle}$ is equivalent to the usual $H^1(\mathbb{R}_*)$ -norm; in particular, $H_{odd}^1(\mathbb{R}_*)$ is an Hilbert space.

Let us construct a solution $v \in H_{odd}^1(\mathbb{R}_*)$ to the problem

$$\varepsilon(v_\varepsilon - \partial_{xx}^2 v_\varepsilon) + \partial_x \left(\frac{v_\varepsilon^2}{2} \right) + \mathcal{L}_\lambda[v_\varepsilon] = 0 \quad \text{in } \mathbb{R}_*, \quad (4.2)$$

$$v_\varepsilon(0^\pm) = \pm 1, \quad (4.3)$$

where Equation (4.2) is understood in the weak sense (e.g. in $\mathcal{D}'(\mathbb{R}_*)$) and the constraint (4.3) is understood in the sense of traces. Setting

$$\theta(x) := (1 - |x|)^+ \text{sign } x, \quad (4.4)$$

we equivalently look for a weak solution of (4.2) living in the affine subspace of $H_{odd}^1(\mathbb{R}_*)$ given by

$$E := \theta + H_{odd}^1(\mathbb{R}) = \{ v \in H_{odd}^1(\mathbb{R}_*) \mid v(0^\pm) = \pm 1 \text{ in the sense of traces} \}.$$

Here is the main result of this section.

Proposition 4.1. *Let $\lambda \in (0, 1)$ and $\varepsilon > 0$. Equation (4.2) admits a weak solution $v_\varepsilon \in E$ satisfying*

$$0 \leq v_\varepsilon(x) \operatorname{sign} x \leq 1 \quad \text{for all } x \in \mathbb{R}_*, \quad (4.5)$$

$$\sup_{\varepsilon \in (0,1)} \int_{\mathbb{R}} \left\{ \varepsilon (\partial_x v_\varepsilon)_{|\mathbb{R}_*}^2 + (\mathcal{L}_{\lambda/2}[v_\varepsilon])^2 \right\} < +\infty. \quad (4.6)$$

Proof. The proof is divided into several steps.

Step 1. We first fix $\bar{v} \in E$ and introduce the auxiliary equation with modified convection term:

$$\varepsilon(v - \partial_{xx}^2 v) + \rho_n \partial_x \left(\frac{(\rho_n T_n(\bar{v}))^2}{2} \right) + \mathcal{L}_\lambda[v] = 0, \quad (4.7)$$

where for $n \in \mathbb{N}_*$, the truncation functions T_n and ρ_n are given by (2.1) and $\rho_n(x) := \rho\left(\frac{x}{C(n,\varepsilon)}\right)$ with

$$\begin{cases} \rho \in C_c^\infty(\mathbb{R}) \text{ even,} \\ 0 \leq \rho \leq \rho(0) = 1, \\ -1 \leq \rho' \leq 0 \text{ on } \mathbb{R}^+ \end{cases}$$

and with

$$C(n, \varepsilon) := \frac{n^2}{\varepsilon} \quad (4.8)$$

(this choice of the constant is explained in Step 3). Note the property

$$\rho_n \xrightarrow{n \rightarrow +\infty} 1 \quad \text{uniformly on compact subsets of } \mathbb{R}. \quad (4.9)$$

It is straightforward to see that solving (4.7), (4.3) in the variational sense below,

$$\left| \begin{array}{l} \text{find } v \in E \text{ such that for all } \varphi \in H_{\text{odd}}^1(\mathbb{R}), \\ \int_{\mathbb{R}_*} \left\{ \varepsilon(v\varphi + \partial_x v \partial_x \varphi) + \mathcal{L}_{\lambda/2}[v] \mathcal{L}_{\lambda/2}[\varphi] \right\} = \int_{\mathbb{R}} \frac{(\rho_n T_n(\bar{v}))^2}{2} \partial_x(\rho_n \varphi), \end{array} \right. \quad (4.10)$$

is equivalent to finding a minimizer $v \in E$ for the functional

$$\mathcal{J}_{\bar{v},n} : \begin{array}{ll} E & \longrightarrow \mathbb{R} \\ u & \longmapsto \frac{1}{2} \int_{\mathbb{R}_*} \left\{ \varepsilon \left(u^2 + (\partial_x u)^2 \right) + (\mathcal{L}_{\lambda/2}[u])^2 - (\rho_n T_n(\bar{v}))^2 \partial_x(\rho_n u) \right\}. \end{array}$$

Notice that $\rho_n T_n(\bar{v}) \in L^\infty(\mathbb{R})$ and $\rho_n \in H^1(\mathbb{R})$, so that

$$(\rho_n T_n(\bar{v}))^2 (\partial_x(\rho_n u))_{|\mathbb{R}_*} \in L^1(\mathbb{R}) \quad \text{with} \quad \int_{\mathbb{R}_*} \left| (\rho_n T_n(\bar{v}))^2 \partial_x(\rho_n u) \right| \leq C_n \|u\|;$$

let us precise that here and until the end of this proof, C_n denotes a generic constant that depends only on n and eventually on the fixed parameter ε (and which can change from one expression to another). Then the functional $\mathcal{J}_{\bar{v},n}$ is well-defined on E and coercive, because

$$\mathcal{J}_{\bar{v},n}(u) = \frac{1}{2} \|u\|^2 - \frac{1}{2} \int_{\mathbb{R}_*} (\rho_n T_n(\bar{v}))^2 \partial_x(\rho_n u) \geq \frac{1}{2} \|u\|^2 - C_n \|u\| \quad (4.11)$$

tends to infinity as $\|u\| \rightarrow +\infty$.

Finally, it is clear that $\mathcal{J}_{\bar{v},n}$ is strictly convex and continuous. Thus we conclude that there exists a unique minimizer of $\mathcal{J}_{\bar{v},n}$, which is the unique solution of Problem (4.10). We denote this solution by $F_n(\bar{v})$, which defines a map $F_n : E \rightarrow E$.

Step 2: apply the Schauder fixed-point theorem to the map F_n .

Note that $F_n(E)$ is contained in the closed ball $\bar{B}_{R_n} := \bar{B}(0_{H^1_{odd}(\mathbb{R}_*)}, R_n)$ of $H^1_{odd}(\mathbb{R}_*)$ for some radius $R_n > 0$ (only depending on n and ε). Indeed, let $v := F_n(\bar{v})$; then by using (4.11), replacing the minimizer v with the function $\theta \in E$ in (4.4), and applying the Young inequality we get

$$\|v\|^2 \leq 2\mathcal{J}_{\bar{v},n}(v) + C_n\|v\| \leq 2\mathcal{J}_{\bar{v},n}(\theta) + \frac{1}{2}\|v\|^2 + C_n.$$

We can restrict F_n to the closed convex set $\mathcal{C} := E \cap \bar{B}_{R_n}$ of the Banach space $H^1_{odd}(\mathbb{R}_*)$. It remains to show that $F_n : \mathcal{C} \rightarrow \mathcal{C}$ is continuous and compact.

In order to justify the compactness of $F_n(\mathcal{C})$, take a sequence $(v_k)_k \subset F_n(\mathcal{C})$ and an associated sequence $(\bar{v}_k)_k \subset \mathcal{C}$ with $v_k = F_n(\bar{v}_k)$. Because \mathcal{C} is bounded, there exists a (not relabelled) subsequence of $(\bar{v}_k)_k$ that converges weakly in $H^1(\mathbb{R}_*)$ and strongly in $L^2_{loc}(\mathbb{R})$ by standard embedding theorems; let v_∞ be its limit. One has $v_\infty \in \mathcal{C}$ because \mathcal{C} is weakly closed as strongly closed convex subset. We can assume without loss of generality that the corresponding subsequence of $(v_k)_k$ converges weakly to some $v_\infty \in \mathcal{C}$ in $H^1_{odd}(\mathbb{R}_*)$. Let us prove that v_k converges strongly to v_∞ in $H^1_{odd}(\mathbb{R}_*)$ and that $v_\infty = F_n(\bar{v}_\infty)$.

By the above convergences, and the facts that $T_n \in C_b^\infty(\mathbb{R})$ and $\rho_n \in C_c^\infty(\mathbb{R})$, one can see that

$$\int_{\mathbb{R}_*} (\rho_n T_n(\bar{v}_k))^2 \partial_x(\rho_n v_k) \rightarrow \int_{\mathbb{R}_*} (\rho_n T_n(\bar{v}_\infty))^2 \partial_x(\rho_n v_\infty) \quad \text{as } k \rightarrow +\infty.$$

Moreover, using that v_k is the minimizer of $\mathcal{J}_{\bar{v}_k,n}$, we also have

$$\begin{aligned} \|v_k\|^2 - \int_{\mathbb{R}_*} (\rho_n T_n(\bar{v}_k))^2 \partial_x(\rho_n v_k) &= 2\mathcal{J}_{\bar{v}_k,n}(v_k) \\ &\leq 2\mathcal{J}_{\bar{v}_k,n}(v_\infty) = \|v_\infty\|^2 - \int_{\mathbb{R}_*} (\rho_n T_n(\bar{v}_k))^2 \partial_x(\rho_n v_\infty). \end{aligned}$$

Thus passing to the limit as $k \rightarrow +\infty$ in this inequality yields: $\|v_\infty\| \geq \limsup_{k \rightarrow +\infty} \|v_k\|$. It follows that the convergence of v_k to v_∞ is actually strong in $H^1_{odd}(\mathbb{R}_*)$; this completes the proof of the compactness of $F_n(\mathcal{C})$.

To prove the continuity of F_n , one simply assumes that $\bar{v}_k \rightarrow \bar{v}_\infty$ strongly in $H^1_{odd}(\mathbb{R}_*)$ and repeats the above reasoning for each subsequence of $(v_k)_k$. One gets that such subsequence converges (up to another subsequence if necessary) strongly to v_∞ . Passing to the limit as $k \rightarrow +\infty$ in the variational formulation (4.10) written for v_k and \bar{v}_k , we deduce by the uniqueness of a solution to (4.10) that $v_\infty = F_n(\bar{v}_\infty)$. This shows that from all subsequence of $(v_k)_k$ one can extract a subsequence strongly converging to $F_n(\bar{v}_\infty)$; hence, the proof of the continuity of F_n is complete.

We conclude that there exists a fixed point u_n of F_n in \mathcal{C} . Then $v := \bar{v} = u_n$ satisfies the formulation (4.10). In addition, (4.10) is trivially satisfied with a test function $\varphi \in H^1(\mathbb{R})$ which

is even. Indeed, using the definitions of T_n and ρ_n and Lemma 4.1 (iv), we see that

$$\varepsilon(v\varphi + \partial_x v \partial_x \varphi) + \mathcal{L}_{\lambda/2}[v] \mathcal{L}_{\lambda/2}[\varphi] - \frac{(\rho_n T_n(\bar{v}))^2}{2} \partial_x(\rho_n \varphi)$$

is an odd function, so that its integral on \mathbb{R}_* is null. Since all function in $H^1(\mathbb{R})$ can be split into the sum of an odd function in $H^1_{\text{odd}}(\mathbb{R})$ and an even function in $H^1(\mathbb{R})$, we have proved that the fixed point $u_n \in E$ of F_n satisfies for all $\varphi \in H^1(\mathbb{R})$,

$$\int_{\mathbb{R}} \left\{ \varepsilon \left(u_n \varphi + (\partial_x u_n)|_{\mathbb{R}_*} \partial_x \varphi \right) + \mathcal{L}_{\lambda/2}[u_n] \mathcal{L}_{\lambda/2}[\varphi] \right\} = \int_{\mathbb{R}} \frac{(\rho_n T_n(u_n))^2}{2} \partial_x(\rho_n \varphi) \quad (4.12)$$

(notice that the Rankine-Hugoniot condition is contained in the fact that $\frac{u_n^2}{2}$ is even). In particular, using Lemma 4.1 (iii), one has

$$\varepsilon(\partial_{xx}^2 u_n - u_n) = \rho_n \partial_x \left(\frac{(\rho_n T_n(u_n))^2}{2} \right) + \mathcal{L}_{\lambda}[u_n] \quad \text{in } \mathcal{D}'(\mathbb{R}_*). \quad (4.13)$$

Step 3: uniform estimates on the sequence $(u_n)_n$.

First, in order to prove a maximum principle for u_n let us point out that u_n is regular. Indeed, thanks to Lemma 4.1 (i) (b) and the facts that $T_n \in C_b^\infty(\mathbb{R})$ and $\rho_n \in C_c^\infty(\mathbb{R})$, the right-hand side of (4.13) belongs to $L^1(I)$ for all compact interval $I \subset \mathbb{R}_*$. Equation (4.13) then implies that $u_n \in W_{loc}^{2,1}(\mathbb{R}_*) \subset C^1(\mathbb{R}_*)$. Recall that $u_n \in H^1(\mathbb{R}_*) \subset C_b(\mathbb{R}_*)$; thus using Lemma 4.1 (i) (a), we see that the right-hand side of (4.13) belongs to $C(I)$. Exploiting once more Equation (4.13), we infer that $u_n \in C^2(\mathbb{R}_*)$ and (4.13) holds pointwise on \mathbb{R}_* .

Now, we are in a position to prove that for all $x > 0$ and $n \in \mathbb{N}_*$, $0 \leq u_n(x) \leq 1$. Indeed, because $u_n \in H^1(\mathbb{R}^+)$, we have $\lim_{x \rightarrow +\infty} u_n(x) = 0$; in addition, $u_n(0^+) = 1$. Thus if $u_n(x) \notin [0, 1]$ for some $x \in \mathbb{R}^+$, there exists $x_* \in \mathbb{R}^+$ such that either $u_n(x_*) = \max_{\mathbb{R}^+} u > 1$ or $u_n(x_*) = \min_{\mathbb{R}^+} u < 0$. Consider the first case. Since $u_n \in C^2(\mathbb{R}_*)$, we have $\partial_x u_n(x_*) = 0$ and $\partial_{xx}^2 u_n(x_*) \leq 0$. In addition, by Lemma 4.1 (v) we have $\mathcal{L}[u_n](x_*) > 0$. Therefore using (4.13) at the point x_* , by the choice of ρ_n and $C(n, \varepsilon)$ in (4.8) we infer

$$\begin{aligned} \varepsilon u_n(x_*) &= \varepsilon \partial_{xx}^2 u_n(x_*) - \mathcal{L}_{\lambda}[u_n](x_*) - \rho_n(x_*) \partial_x \left(\frac{(\rho_n(x_*) T_n(u_n(x_*)))^2}{2} \right) \\ &\leq -(\rho_n(x_*) T_n(u_n(x_*)))^2 \partial_x \rho_n(x_*) \leq n^2 \frac{1}{C(n, \varepsilon)} \sup_{\mathbb{R}^+} (-\partial_x \rho) \leq \varepsilon. \end{aligned}$$

Thus $u(x_*) \leq 1$, which contradicts the definition of x_* . The case $u_n(x_*) = \min_{\mathbb{R}^+} u < 0$ is similar; we use in addition the fact that $\partial_x \rho_n \leq 0$ on \mathbb{R}^+ .

The function u_n being even, from the maximum principle of Step 3 we have $|u_n| \leq 1$ on \mathbb{R}_* . Since $T_n = \text{Id}$ on $[-n+1, n-1]$, we have $T_n(u_n) = u_n$ in (4.13) for all $n \geq 2$.

Let us finally derive the uniform $H^1_{\text{odd}}(\mathbb{R}_*)$ -bound on $(u_n)_n$. To do so, replace the minimum u_n

of the functional $\mathcal{J}_{u_n, n}$ by the fixed function $\theta \in E$ in (4.4); we find

$$\begin{aligned}
& \|u_n\|^2 \\
&= 2\mathcal{J}_{u_n, n}(u_n) + \int_{\mathbb{R}_*} (\rho_n u_n)^2 \partial_x (\rho_n u_n), \\
&\leq 2\mathcal{J}_{u_n, n}(\theta) + 2 \int_{\mathbb{R}_*} \partial_x \left(\frac{(\rho_n u_n)^3}{3} \right), \\
&= 2\mathcal{J}_{u_n, n}(\theta) - \frac{4}{3} \quad \text{since } \rho_n(0) = 1 = \pm u_n(0^\pm), \\
&= \|\theta\|^2 - \int_{\mathbb{R}_*} (\rho_n u_n)^2 \partial_x (\rho_n \theta) - \frac{4}{3}.
\end{aligned}$$

To estimate the integral term, we use that θ is supported by $[-1, 1]$ with $|\partial_x(\rho_n \theta)| \leq 1 + \frac{\varepsilon}{n^2}$, thanks again to the choice of ρ_n in (4.8); Using finally the bound $|u_n| \leq 1$ derived above, we get

$$- \int_{\mathbb{R}_*} (\rho_n u_n)^2 \partial_x (\rho_n \theta) \leq 2 + \frac{2\varepsilon}{n^2};$$

hence, we obtain the following uniform estimate:

$$\|u_n\|^2 \leq \|\theta\|^2 + \frac{2}{3} + \frac{2\varepsilon}{n^2}. \quad (4.14)$$

Step 4: passage to the limit as $n \rightarrow +\infty$.

The $H^1_{\text{odd}}(\mathbb{R}_*)$ -estimate of Step 3 permits to extract a (not relabelled) subsequence $(u_n)_n$ which converges weakly in $H^1(\mathbb{R}_*)$ and strongly in $L^2_{\text{loc}}(\mathbb{R})$, to a limit that we denote v_ε . We have $(u_n)_n \subset E$ which is a closed affine subspace of $H^1(\mathbb{R}_*)$, so that $v_\varepsilon \in E$. The above convergences and the convergence of ρ_n in (4.9) are enough to pass to the limit in the weak formulation (4.12); at the limit, we conclude that v_ε is a weak solution of (4.2). Notice that v_ε inherits the bounds on u_n , namely the bound (4.14) and the maximum principle $0 \leq u_n(x) \text{ sign } x \leq 1$. This yields (4.5) and Estimate (4.6), thanks to the definition of $\|\cdot\|$ via the scalar product (4.1). \blacksquare

Remark 4.2. When passing to the limit as $n \rightarrow +\infty$ in (4.12) in the last step, one gets:

$$\int_{\mathbb{R}} \left\{ \varepsilon \left(v_\varepsilon \varphi + (\partial_x v_\varepsilon)|_{\mathbb{R}_*} \partial_x \varphi \right) + v_\varepsilon \mathcal{L}_\lambda[\varphi] \right\} = \int_{\mathbb{R}} \frac{v_\varepsilon^2}{2} \partial_x \varphi \quad \text{for all } \varphi \in H^1(\mathbb{R}). \quad (4.15)$$

5 A non-entropic stationary solution

We are now able to construct a stationary non-entropic solution to (1.1) by passing to the limit in v_ε as $\varepsilon \rightarrow 0$. Let us explain our strategy. First, we have to use the uniform estimates of Proposition 4.1 to get compactness estimates; this is done *via* the following lemma which is proved in Appendix A:

Lemma 5.1. *Assume that for all $\varepsilon \in (0, 1)$, $v_\varepsilon \in H^1(\mathbb{R}_*)$ satisfies (4.5)-(4.6). Then the family $\{v_\varepsilon : \varepsilon \in (0, 1)\}$ is relatively compact in $L^2_{\text{loc}}(\mathbb{R})$.*

With this result in hands, we can prove the convergence of a subsequence of v_ε , as $\varepsilon \rightarrow 0$, to some stationary weak solution v of (1.1). Next, we need to control the traces of v at $x = 0^\pm$. This is done by reformulating Definition 2.2 and by exploiting the Green-Gauss formula.

Let us begin with giving a characterization of odd weak stationary solutions of the fractional Burgers equation.

Proposition 5.1. *An odd function $v \in L^\infty(\mathbb{R})$ satisfies*

$$\partial_x \left(\frac{v^2}{2} \right) + \mathcal{L}_\lambda[v] = 0 \quad \text{in } \mathcal{D}'(\mathbb{R}), \quad (5.1)$$

iff (i) and (ii) below hold true:

(i) *there exists the trace $\gamma v^2 := \lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h v^2(x) dx$;*

(ii) *for all odd compactly supported in \mathbb{R} test function $\varphi \in C_b^\infty(\mathbb{R}_*)$,*

$$\int_{\mathbb{R}_*} (v \mathcal{L}_\lambda[\varphi] - \frac{v^2}{2} \partial_x \varphi) = \varphi(0^+) \gamma v^2.$$

Proof. Assume (5.1). For all $h > 0$, let us set $\psi_h(x) := \frac{1}{h}(h - |x|)^+ \text{sign } x$. Let us recall that $\theta(x) = (1 - |x|)^+ \text{sign } x$. First consider

$$\theta_h(x) := \begin{cases} \theta(x), & x < 0 \\ -\psi_h(x), & x \geq 0 \end{cases} \quad \text{and} \quad \theta_0(x) = \begin{cases} \theta(x), & x < 0 \\ 0, & x \geq 0. \end{cases}$$

By construction, $\theta_h \in H^1(\mathbb{R})$; therefore θ_h can be approximated in $H^1(\mathbb{R})$ by functions in $\mathcal{D}(\mathbb{R})$ and thus taken as a test function in (5.1). This gives

$$- \int_{\mathbb{R}^+} \frac{v^2}{2} \partial_x \psi_h = - \int_{\mathbb{R}^-} \frac{v^2}{2} \partial_x \theta + \int_{\mathbb{R}} v \mathcal{L}_\lambda[\theta_h].$$

But, it is obvious that $\theta_h \rightarrow \theta_0$ in $L^1(\mathbb{R}) \cap (BV(\mathbb{R}))_{w^*}$ as $h \rightarrow 0^+$; thus using Lemma 4.1 (i) (c), we conclude that the limit in item (i) of Proposition 5.1 does exist, and

$$\gamma v^2 := \lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h v^2 = - \lim_{h \rightarrow 0^+} \int_{\mathbb{R}^+} v^2 \partial_x \psi_h = - \int_{\mathbb{R}^-} v^2 \partial_x \theta + 2 \int_{\mathbb{R}} v \mathcal{L}_\lambda[\theta_0]. \quad (5.2)$$

Further, take a function φ as in item (ii) of Proposition 5.1 and set $\varphi_h(x) := \varphi(x) - \varphi(0^+) \psi_h(x)$. One can take $\varphi_h \in H^1(\mathbb{R})$ as a test function in (5.1). Taking into account the fact that $\frac{v^2}{2} \partial_x \varphi_h$ and $v \mathcal{L}_\lambda[\varphi_h]$ are even, thanks again to Lemma 4.1 (iv), we get

$$2 \int_{\mathbb{R}^+} (v \mathcal{L}_\lambda[\varphi] - \frac{v^2}{2} \partial_x \varphi) = 2\varphi(0^+) \int_{\mathbb{R}^+} (v \mathcal{L}_\lambda[\psi_h] - \frac{v^2}{2} \partial_x \psi_h).$$

Now we pass to the limit as $h \rightarrow 0^+$. As previously, because $\psi_h \rightarrow 0$ in $L^1(\mathbb{R}) \cap (BV(\mathbb{R}))_{w^*}$, the term $\mathcal{L}_\lambda[\psi_h]$ vanishes in $L^1(\mathbb{R})$. Using (5.2), we get item (ii) of Proposition 5.1.

Conversely, assume that an odd function v satisfies items (i) and (ii) of Proposition 5.1. Take a test function $\xi \in \mathcal{D}(\mathbb{R})$ and write $\xi = \varphi + \psi$ with $\varphi \in \mathcal{D}(\mathbb{R})$ odd (so that $\varphi(0^+) = 0$) and $\psi \in \mathcal{D}(\mathbb{R})$ even. Then (ii) and the symmetry considerations, including Lemma 4.1 (iv), show that

$$\int_{\mathbb{R}} (v \mathcal{L}_\lambda[\varphi] - \frac{v^2}{2} \partial_x \varphi) = \varphi(0^+) \gamma v^2 = 0, \quad \int_{\mathbb{R}} (v \mathcal{L}_\lambda[\psi] - \frac{v^2}{2} \partial_x \psi) = 0.$$

Hence we deduce that v satisfies (5.1). ■

Here is the existence result of a non-entropic stationary solution.

Proposition 5.2. *Let $\lambda \in (0, 1)$. There exists $v \in L^\infty(\mathbb{R})$ that satisfies (5.1) and such that for all $c > 0$, v does not satisfy $\partial_x v \leq \frac{1}{c}$ in $\mathcal{D}'(\mathbb{R})$.*

Proof. First, by Proposition 4.1 and Lemma 5.1 there exists $v \in L^\infty(\mathbb{R})$ and a sequence $(\varepsilon_k)_k$, $\varepsilon_k \downarrow 0$ as $k \rightarrow +\infty$, such that the solution v_{ε_k} of (4.2) with $\varepsilon = \varepsilon_k$ tends to v in $L^2_{loc}(\mathbb{R})$ by being bounded by 1 in L^∞ -norm. Using in particular (4.6) to vanish the term $\sqrt{\varepsilon} (\partial_x v_\varepsilon)|_{\mathbb{R}_*}$, we can pass to the limit in the weak formulation (4.15) and infer (5.1).

In order to conclude the proof, we will show that there exist the limits

$$\lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h v = 1, \quad \lim_{h \rightarrow 0^+} \frac{1}{h} \int_{-h}^0 v = -1. \quad (5.3)$$

Indeed, (5.3) readily implies that for all $c > 0$, the function $(v - \frac{1}{c} \text{Id})$ does not admit a non-increasing representative. Since $\partial_x (v - \frac{1}{c} \text{Id}) = \partial_x v - \frac{1}{c}$, the inequality $\partial_x v - \frac{1}{c} \leq 0$ in the distribution sense fails to be true.

Thus it remains to show (5.3). To do so, we exploit the formulation (i)-(ii) of Proposition 5.1, the analogous formulation of the regularized problem (4.2), the fact that $v_{\varepsilon_k}(0^\pm) = \pm 1$, and the Inequalities (4.5).

Let us fix some odd compactly supported in \mathbb{R} test function $\varphi \in C^\infty(\mathbb{R}_*)$ such that $\varphi(0^+) = 1$. As in the proof of Proposition 5.1, we can take the function $\varphi_h(x) := \varphi(x) - \psi_h(x) \in H^1(\mathbb{R})$ as a test function in (4.15). We infer

$$\int_{\mathbb{R}_*} \left\{ \varepsilon (v_\varepsilon \varphi_h + \partial_x v_\varepsilon \partial_x \varphi_h) + v_\varepsilon \mathcal{L}_\lambda[\varphi_h] - \frac{v_\varepsilon^2}{2} \partial_x \varphi_h \right\} = 0.$$

Each term in the above integrand is even; moreover, letting $h \rightarrow 0^+$ and using Lemma 4.1 (i) (c) on $\mathcal{L}_\lambda[\psi_h]$, we infer

$$\begin{aligned} & \int_{\mathbb{R}_*} \left\{ \varepsilon (v_\varepsilon \varphi + \partial_x v_\varepsilon \partial_x \varphi) + v_\varepsilon \mathcal{L}_\lambda[\varphi] - \frac{v_\varepsilon^2}{2} \partial_x \varphi \right\} \\ &= 2 \lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h \left(\frac{v_\varepsilon^2}{2} - \varepsilon \partial_x v_\varepsilon \right) = 1 - \frac{2\varepsilon}{h} [v_\varepsilon]_0^h = 1 - \frac{2\varepsilon}{h} (v_\varepsilon(h) - 1) \geq 1; \end{aligned} \quad (5.4)$$

here in the last inequality, we have used $0 \leq v_\varepsilon(x) \leq 1 = v_\varepsilon(0^+)$ for $x > 0$.

Letting $\varepsilon_k \rightarrow 0$ in (5.4), using again (4.6) to vanish $\int_{\mathbb{R}_*} \varepsilon \partial_x v_\varepsilon \partial_x \varphi$, we infer

$$\int_{\mathbb{R}_*} \left\{ v \mathcal{L}_\lambda[\varphi] - \frac{v^2}{2} \partial_x \varphi \right\} \geq 1. \quad (5.5)$$

Recall that v is odd and solves (5.1); thus it satisfies (i) and (ii) of Proposition 5.1. From (ii), we infer that $\lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h v^2 = \gamma v^2 \geq 1$. But we also have $0 \leq v \leq 1$ on $[0, h]$. Therefore

$$\lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h |1 - v| = \lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h \frac{1 - v^2}{1 + v} \leq \lim_{h \rightarrow 0^+} \frac{1}{h} \int_0^h (1 - v^2) = 1 - \gamma v^2 \leq 0.$$

Whence the first equality in (5.3) follows. The second one is clear because v is an odd function. This concludes the proof. \blacksquare

From Propositions 3.1 and 5.2, Theorem 1.1 readily follows.

Proof of Theorem 1.1. Take $u_0 := v$. From (5.1) we derive that the function defined by $u(t) := v$ for all $t \geq 0$ is a weak solution to (1.1)–(1.2). But it is not the entropy solution, because it fails to satisfy (3.1). \blacksquare

6 Proof of Lemma 4.1

We end this paper by proving the main properties of the fractional Laplacian acting on spaces of odd functions. First, we have to state and prove some lemmata that will be needed.

Here are (probably classical) embedding and density results; for the reader's convenience, short proofs are gathered in Appendix A.

Lemma 6.1. *The following embeddings are continuous:*

$$H^1(\mathbb{R}_*) \rightarrow BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^\infty(\mathbb{R}) \cap L^2(\mathbb{R}); \quad (6.1)$$

the following one is compact:

$$BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \xrightarrow{c} L^2(\mathbb{R}). \quad (6.2)$$

Lemma 6.2. *The space $\mathcal{D}(\mathbb{R})$ is dense in $H^1(\mathbb{R}_*)$ for the $(BV_{loc}(\mathbb{R}))_{w-\star} \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\})$ -topology.*

The next lemma states weak continuity results for the fractional Laplacian. Until the end of this section, \mathcal{L}_λ denotes the operator defined by (2.2) and $\mathcal{L}_\lambda^{\mathcal{F}}$ the one defined by (1.3).

Lemma 6.3. *Let $\lambda \in (0, 1)$. Then the following operators are continuous:*

$$\begin{aligned} \mathcal{L}_\lambda &: (BV_{loc}(\mathbb{R}))_{w-\star} \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^1_{loc}(\mathbb{R}) \cap L^2_{loc}(\overline{\mathbb{R}} \setminus \{0\}), \\ \mathcal{L}_{\lambda/2}^{\mathcal{F}} &: (BV_{loc}(\mathbb{R}))_{w-\star} \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^2(\mathbb{R}). \end{aligned}$$

Proof. The proof is divided in several steps.

Step 1: strong continuity of \mathcal{L}_λ .

Let $v \in BV_{loc}(\mathbb{R}) \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})$ and let us derive some estimates on $\mathcal{L}_\lambda[v]$. For all $r, R > 0$, one has

$$\begin{aligned}
& \int_{-R}^R \int_{\mathbb{R}} \frac{|v(x+z) - v(x)|}{|z|^{1+\lambda}} dx dz \\
&= \int_{-R}^R \int_{|z| \leq r} \frac{|v(x+z) - v(x)|}{|z|^{1+\lambda}} dx dz + \int_{-R}^R \int_{|z| > r} \frac{|v(x+z) - v(x)|}{|z|^{1+\lambda}} dx dz, \\
&\leq |v|_{BV((-R-r, R+r))} \int_{|z| \leq r} |z|^{-\lambda} dz \\
&+ \left(\sup_{|z| > r} \|v\|_{L^1((-R+z, R+z))} + \|v\|_{L^1((-R, R))} \right) \int_{|z| > r} |z|^{-1-\lambda} dz \quad \text{by integrating first w.r.t } x, \\
&= \frac{2r^{1-\lambda}}{1-\lambda} |v|_{BV((-R-r, R+r))} + \frac{2}{\lambda r^\lambda} \left(\sup_{|z| > r} \|v\|_{L^1((-R+z, R+z))} + \|v\|_{L^1((-R, R))} \right). \tag{6.3}
\end{aligned}$$

By Lemma 6.1 (6.1) and the Cauchy-Schwarz inequality to control the L^1 -norms by the L^2 -norm, one sees that formula (2.2) makes sense a.e. with

$$\|\mathcal{L}_\lambda[v]\|_{L^1((-R, R))} \leq \frac{2G_\lambda r^{1-\lambda}}{1-\lambda} |v|_{BV((-R-r, R+r))} + \frac{4G_\lambda}{\lambda r^\lambda} \sqrt{2R} \|v\|_{L^2(\mathbb{R})}, \tag{6.4}$$

for all $r, R > 0$

The same way, one has for $R > r > 0$

$$\begin{aligned}
& \left(\int_{\mathbb{R} \setminus [-R, R]} \left(\int_{\mathbb{R}} \frac{|v(x+z) - v(x)|}{|z|^{1+\lambda}} dz \right)^2 dx \right)^{\frac{1}{2}} \\
&\leq \int_{\mathbb{R}} \left(\int_{\mathbb{R} \setminus [-R, R]} \frac{|v(x+z) - v(x)|^2}{|z|^{2+2\lambda}} dx \right)^{\frac{1}{2}} dz \quad \text{thanks to the Minkowski inequality,} \\
&= \int_{|z| \leq r} |z|^{-1-\lambda} \left(\int_{\mathbb{R} \setminus [-R, R]} |v(x+z) - v(x)|^2 dx \right)^{\frac{1}{2}} dz \\
&+ \int_{|z| > r} |z|^{-1-\lambda} \left(\int_{\mathbb{R} \setminus [-R, R]} |v(x+z) - v(x)|^2 dx \right)^{\frac{1}{2}} dz, \\
&\leq \frac{2r^{1-\lambda}}{1-\lambda} \|\partial_x v\|_{L^2(\mathbb{R} \setminus [-R+r, R-r])} + \frac{4}{\lambda r^\lambda} \|v\|_{L^2(\mathbb{R})};
\end{aligned}$$

therefore, one gets

$$\|\mathcal{L}_\lambda[v]\|_{L^2(\mathbb{R} \setminus [-R, R])} \leq \frac{2G_\lambda r^{1-\lambda}}{1-\lambda} \|\partial_x v\|_{L^2(\mathbb{R} \setminus [-R+r, R-r])} + \frac{4G_\lambda}{\lambda r^\lambda} \|v\|_{L^2(\mathbb{R})} \tag{6.5}$$

for all $R > r > 0$.

Now (6.4)-(6.5) imply that $\mathcal{L}_\lambda : BV_{loc}(\mathbb{R}) \cap H^1(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^1_{loc}(\mathbb{R}) \cap L^2_{loc}(\overline{\mathbb{R}} \setminus \{0\})$ is well-defined and bounded.

Step 2: weak continuity of \mathcal{L}_λ .

Consider a sequence $(v_k)_k$ converging to zero in $(BV_{loc}(\mathbb{R}))_{w-\star} \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\})$. For all $R > 0$, $(v_k)_k$ is bounded in the norm of $H^1(\mathbb{R} \setminus [-R, R])$ and the semi-norm of $BV((-R, R))$ by some constant C_R . By (6.4), one deduces that

$$\limsup_{k \rightarrow +\infty} \|\mathcal{L}_\lambda[v_k]\|_{L^1((-R, R))} \leq \frac{2G_\lambda r^{1-\lambda}}{1-\lambda} C_{R+r}.$$

Letting $r \rightarrow 0$, one concludes that $\mathcal{L}_\lambda[v_k]$ converges to zero in $L^1((-R, R))$. The same way, one can prove that $\mathcal{L}_\lambda[v_k]$ converges to zero in $L^2(\mathbb{R} \setminus [-R, R])$ by using (6.5). Since R is arbitrary, the proof of Lemma 6.3 is complete.

Step 3: strong continuity of $\mathcal{L}_{\lambda/2}^{\mathcal{F}}$.

Let us derive an L^2 -estimate on $\mathcal{L}_{\lambda/2}^{\mathcal{F}}[v]$. Recall that by Lemma 6.1 (6.1), one has $v \in L^2(\mathbb{R})$ so that $|\cdot| \mathcal{F}(v) \in L^1_{loc}(\mathbb{R})$ and $\mathcal{L}_{\lambda/2}^{\mathcal{F}}[v]$ is well-defined in $\mathcal{S}'(\mathbb{R})$.

Further consider some fixed $\rho \in C_c^\infty(\mathbb{R})$ such that $\rho = 1$ on some neighborhood of the origin, say on $[-1/2, 1/2]$, and $\text{supp } \rho \subseteq [-1, 1]$. Then one has $v = \rho v + (1-\rho)v$ with $\text{supp } (\rho v) \subseteq [-1, 1]$, $\rho v \in L^1(\mathbb{R}) \cap BV(\mathbb{R})$ (since $v \in L^2(\mathbb{R})$) and $(1-\rho)v \in H^1(\mathbb{R})$; moreover, one readily sees that

$$\|\rho v\|_{L^1(\mathbb{R})} \leq C_\rho \|v\|_{L^2(\mathbb{R})}, \quad (6.6)$$

$$|\rho v|_{BV(\mathbb{R})} \leq C_\rho (|v|_{BV((-1/2, 1/2))} + \|v\|_{H^1(\mathbb{R} \setminus [-1/2, 1/2])}), \quad (6.7)$$

$$\|(1-\rho)v\|_{L^2(\mathbb{R})} \leq C_\rho \|v\|_{L^2(\mathbb{R})}, \quad (6.8)$$

$$\|\partial_x((1-\rho)v)\|_{L^2(\mathbb{R})} \leq C_\rho \|v\|_{H^1(\mathbb{R} \setminus [-1/2, 1/2])}, \quad (6.9)$$

where here and until the end of the proof of this proof, C_ρ denotes a generic constant only depending on ρ (and which can change from one expression to another).

By Plancherel's equality, we have

$$\begin{aligned} \left\| \mathcal{L}_{\lambda/2}^{\mathcal{F}}[v] \right\|_{L^2(\mathbb{R})} &= \int_{\mathbb{R}} |\xi|^\lambda |\mathcal{F}(v)(\xi)|^2 d\xi \\ &= \int_{\mathbb{R}} |\xi|^\lambda |\mathcal{F}(\rho v)(\xi)|^2 d\xi + \int_{\mathbb{R}} |\xi|^\lambda |\mathcal{F}((1-\rho)v)(\xi)|^2 d\xi =: I + J. \end{aligned} \quad (6.10)$$

Let us begin by bounding J from above. For all $r > 0$, one has

$$\begin{aligned} J &= \int_{|\xi| > r} |\xi|^\lambda |\mathcal{F}((1-\rho)v)(\xi)|^2 d\xi + \int_{|\xi| \leq r} |\xi|^\lambda |\mathcal{F}((1-\rho)v)(\xi)|^2 d\xi, \\ &\leq \int_{|\xi| > r} |\xi|^{\lambda-2} |\xi|^2 |\mathcal{F}((1-\rho)v)(\xi)|^2 d\xi + r^\lambda \|\mathcal{F}((1-\rho)v)\|_{L^2(\mathbb{R})}^2, \\ &\leq \frac{1}{r^{2-\lambda}} \int_{|\xi| > r} |\xi|^2 |\mathcal{F}((1-\rho)v)(\xi)|^2 d\xi + r^\lambda \|(1-\rho)v\|_{L^2(\mathbb{R})}^2 \quad \text{thanks to Plancherel's equality.} \end{aligned}$$

On using the formula

$$\mathcal{F}(\partial_x w) = 2i\pi\xi \mathcal{F}(w) \quad (6.11)$$

and again Plancherel's equality, one gets

$$J \leq \frac{1}{4\pi^2 r^{2-\lambda}} \|\partial_x((1-\rho)v)\|_{L^2(\mathbb{R})}^2 + r^\lambda \|(1-\rho)v\|_{L^2(\mathbb{R})}^2;$$

so that by (6.8)-(6.9), one has

$$J \leq \frac{C_\rho}{r^{2-\lambda}} \|v\|_{H^1(\mathbb{R} \setminus [-1/2, 1/2])}^2 + C_\rho r^\lambda \|v\|_{L^2(\mathbb{R})}^2. \quad (6.12)$$

To bound I from above, one uses the boundeness of $\mathcal{F} : L^1(\mathbb{R}) \rightarrow L^\infty(\mathbb{R})$ and the pointwise estimate (from (6.11)) $|\xi| |\mathcal{F}(w)(\xi)| \leq \frac{1}{2\pi} |w|_{BV(\mathbb{R})}$. We get

$$\begin{aligned} I &= \int_{|\xi|>r} |\xi|^\lambda |\mathcal{F}(\rho v)(\xi)|^2 d\xi + \int_{|\xi|\leq r} |\xi|^\lambda |\mathcal{F}(\rho v)(\xi)|^2 d\xi, \\ &\leq \frac{1}{4\pi^2} |\rho v|_{BV(\mathbb{R})}^2 \int_{|\xi|>r} |\xi|^{\lambda-2} d\xi + \|\rho v\|_{L^1(\mathbb{R})}^2 \int_{|\xi|\leq r} |\xi|^\lambda d\xi, \\ &= \frac{1}{2\pi^2(1-\lambda)r^{1-\lambda}} |\rho v|_{BV(\mathbb{R})}^2 + \frac{2r^{1+\lambda}}{1+\lambda} \|\rho v\|_{L^1(\mathbb{R})}^2; \end{aligned}$$

so that by (6.6)-(6.7), one has

$$I \leq \frac{C_\rho}{(1-\lambda)r^{1-\lambda}} \left(|v|_{BV((-1/2, 1/2))} + \|v\|_{H^1(\mathbb{R} \setminus [-1/2, 1/2])} \right)^2 + \frac{C_\rho r^{1+\lambda}}{1+\lambda} \|v\|_{L^2(\mathbb{R})}^2. \quad (6.13)$$

We deduce from (6.10), (6.12) and (6.13) the final estimate:

$$\begin{aligned} \left\| \mathcal{L}_{\lambda/2}^{\mathcal{F}}[v] \right\|_{L^2(\mathbb{R})} &\leq \\ &C_\rho \left(\frac{1}{r^{2-\lambda}} + \frac{1}{(1-\lambda)r^{1-\lambda}} \right) \left(|v|_{BV((-1/2, 1/2))} + \|v\|_{H^1(\mathbb{R} \setminus [-1/2, 1/2])} \right)^2 \\ &\quad + C_\rho \left(r^\lambda + \frac{r^{1+\lambda}}{1+\lambda} \right) \|v\|_{L^2(\mathbb{R})}^2. \end{aligned} \quad (6.14)$$

for all $r > 0$.

One infers that $\mathcal{L}_{\lambda/2}^{\mathcal{F}} : BV_{loc}(\mathbb{R}) \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^2(\mathbb{R})$ is bounded.

Step 4: weak continuity of $\mathcal{L}_{\lambda/2}^{\mathcal{F}}$.

By Lemma 6.1 (6.2), one sees that if $v_k \rightarrow 0$ in $(BV_{loc}(\mathbb{R}))_{w^*} \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})$, then $v_k \rightarrow 0$ in $L^2(\mathbb{R})$. One then argues exactly as in Step 2 by using (6.14) instead of (6.4)-(6.5); one deduces that $\mathcal{L}_{\lambda/2}^{\mathcal{F}}[v_k] \rightarrow 0$ in $L^2(\mathbb{R})$; this completes the proof of the lemma. \blacksquare

We can now prove the main properties of \mathcal{L}_λ stated in Subsection 4.1.

Proof of Lemma 4.1. Let us prove the different items step by step.

Step 1: item (i) (a) and (b).

Item (i) (a) is an immediate consequence of the theorem of continuity under the integral sign; the details are left to the reader. As far as item (i) (b), it is clear from Lemmata 6.1 and 6.3.

Step 2: item (i) (c).

Passing to the limit $R \rightarrow +\infty$ in (6.3), one gets

$$\|\mathcal{L}_\lambda[v]\|_{L^1(\mathbb{R})} \leq \frac{2G_\lambda r^{1-\lambda}}{1-\lambda} |v|_{BV(\mathbb{R})} + \frac{4G_\lambda}{\lambda r^\lambda} \|v\|_{L^1(\mathbb{R})}, \quad (6.15)$$

for all $v \in L^1(\mathbb{R}) \cap BV(\mathbb{R})$ and $r > 0$. With this estimate in hands, we can argue as in the second step of the proof of Lemma 6.3.

Step 3: items (ii) and (i) (d).

Let us prove item (ii) first. By Lemma 6.2, $v \in H^1(\mathbb{R}_*)$ can be approximated by $v_k \in \mathcal{S}(\mathbb{R})$ in $(BV_{loc}(\mathbb{R}))_{w-\star} \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})$. One has $\mathcal{L}_\lambda[v_k] = \mathcal{L}_\lambda^{\mathcal{F}}[v_k]$ thanks to the classical Lévy-Kintchine's formula. By Lemma 6.3, we infer that $\mathcal{L}_\lambda[v_k]$ converges toward $\mathcal{L}_\lambda[v]$ in $\mathcal{S}'(\mathbb{R})$ as $k \rightarrow +\infty$. But Lemma 6.1 (6.2) implies that $v_k \rightarrow v$ in $L^2(\mathbb{R})$ so that $\mathcal{F}(v_k) \rightarrow \mathcal{F}(v)$ in $L^2(\mathbb{R})$. It follows that $|\cdot|^\lambda \mathcal{F}(v_k) \rightarrow |\cdot|^\lambda \mathcal{F}(v)$ in $\mathcal{S}'(\mathbb{R})$; hence, taking the inverse Fourier transform, one sees that $\mathcal{L}_\lambda^{\mathcal{F}}[v_k] \rightarrow \mathcal{L}_\lambda^{\mathcal{F}}[v]$ in $\mathcal{S}'(\mathbb{R})$. By uniqueness of the limit, one has $\mathcal{L}_\lambda[v] = \mathcal{L}_\lambda^{\mathcal{F}}[v]$ and the proof of item (ii) is complete.

As an immediate consequence, one deduces item (i) (d) by using in particular Lemmata 6.1 and 6.3.

Step 4: item (iii).

Take $v_k, w_k \in \mathcal{S}(\mathbb{R})$ converging to $v, w \in H^1(\mathbb{R}_*)$ in $(BV_{loc}(\mathbb{R}))_{w-\star} \cap H_{loc}^1(\overline{\mathbb{R}} \setminus \{0\})$. One has

$$\int_{\mathbb{R}} \mathcal{L}_\lambda[v_k] w_k = \int_{\mathbb{R}} v_k \mathcal{L}_\lambda[w_k] = \int_{\mathbb{R}} \mathcal{L}_{\lambda/2}[w_k] \mathcal{L}_{\lambda/2}[v_k]$$

(to see this, it suffices to use formula (1.3)). By Lemma 6.3, one has

$$\mathcal{L}_\lambda[u_k] \rightarrow \mathcal{L}_\lambda[u] \quad \text{in } L_{loc}^1(\mathbb{R}) \cap L_{loc}^2(\overline{\mathbb{R}} \setminus \{0\})$$

for $u = v, w$. By Lemma 6.1, one has the following convergence (up to a subsequence)

$$u_k \rightarrow u \quad \text{in } L^2(\mathbb{R}) \text{ and in } L^\infty(\mathbb{R}) \text{ weak-}\star$$

for $u = v, w$; indeed, (6.2) implies the strong convergence in L^2 and (6.1) the one in L^∞ weak- \star (since $(u_k)_k$ is bounded in L^∞). Hence, one clearly can pass to the limit:

$$\int_{\mathbb{R}} \mathcal{L}_\lambda[v] w = \lim_{k \rightarrow +\infty} \int_{\mathbb{R}} \mathcal{L}_\lambda[v_k] w_k = \lim_{k \rightarrow +\infty} \int_{\mathbb{R}} v_k \mathcal{L}_\lambda[w_k] = \int_{\mathbb{R}} v \mathcal{L}_\lambda[w].$$

To pass to the limit in $\int_{\mathbb{R}} \mathcal{L}_{\lambda/2}[w_k] \mathcal{L}_{\lambda/2}[v_k]$, one uses Lemma 6.3 and item (ii). The proof of item (iii) is complete.

Step 5: item (iv).

It suffices to change the variable by $z \rightarrow -z$ in (2.2).

Step 6: item (v).

We prove only the case where $v(x_*) = \max_{\mathbb{R}^+} v \geq 0$, since the other case $v(x_*) = \min_{\mathbb{R}^+} v \leq 0$ is symmetric. Simple computations show that

$$\begin{aligned}\mathcal{L}_\lambda[v](x_*) &= -G_\lambda \int_{\mathbb{R}} \frac{v(x_* + z) - v(x_*)}{|z|^{1+\lambda}} dz, \\ &= -G_\lambda \int_{-x_*}^{+\infty} \frac{v(x_* + z) - v(x_*)}{|z|^{1+\lambda}} dz - G_\lambda \int_{-\infty}^{-x_*} \frac{v(x_* + z) - v(x_*)}{|z|^{1+\lambda}} dz, \\ &= -G_\lambda \int_{-x_*}^{+\infty} \frac{v(x_* + z) - v(x_*)}{|z|^{1+\lambda}} dz - G_\lambda \int_{-x_*}^{+\infty} \frac{v(-x_* - z') - v(x_*)}{|z' + 2x_*|^{1+\lambda}} dz',\end{aligned}$$

after having changed the variable by $z' = -z - 2x_*$. By the oddity of v , we get

$$\mathcal{L}_\lambda[v](x_*) = -G_\lambda \int_{-x_*}^{+\infty} \left\{ \frac{v(x_* + z) - v(x_*)}{|z|^{1+\lambda}} - \frac{v(x_* + z) + v(x_*)}{|z + 2x_*|^{1+\lambda}} \right\} dz.$$

Let $f(z)$ denote the integrand above. Let us prove that this integrand is non-positive for $0 \neq z > -x_*$. It is readily seen that for such z , one always has $\left\{ \frac{1}{|z|^{1+\lambda}} - \frac{1}{|z + 2x_*|^{1+\lambda}} \right\} > 0$. Then, one has

$$\begin{aligned}f(z) &= v(x_* + z) \left\{ \frac{1}{|z|^{1+\lambda}} - \frac{1}{|z + 2x_*|^{1+\lambda}} \right\} - v(x_*) \left\{ \frac{1}{|z|^{1+\lambda}} + \frac{1}{|z + 2x_*|^{1+\lambda}} \right\}, \\ &\leq v(x_*) \left\{ \frac{1}{|z|^{1+\lambda}} - \frac{1}{|z + 2x_*|^{1+\lambda}} \right\} - v(x_*) \left\{ \frac{1}{|z|^{1+\lambda}} + \frac{1}{|z + 2x_*|^{1+\lambda}} \right\},\end{aligned}$$

since $x_* + z \in \mathbb{R}^+$ so that $v(x_* + z) \leq v(x_*)$. We infer that $f(z) \leq -v(x_*) \frac{2}{|z + 2x_*|^{1+\lambda}} \leq 0$ and conclude that $\mathcal{L}_\lambda[v](x_*) \geq 0$. To finish, observe that f can not be identically equaled to zero, whenever v is non-trivial. This proves that $\mathcal{L}_\lambda[v](x_*) > 0$ and completes the proof of the lemma. \blacksquare

A Appendix: proofs of Lemmata 3.1, 5.1 and 6.1

Proof of Lemma 3.1. It is quite easy to show that v is continuous and we only detail the proof of the derivability from the right. The supremum $m(t)$ is achieved because of (3.2), so that $K(t) \neq \emptyset$; moreover, one has for all $b > a > 0$

$$\sup_{t \in (a, b), x \in K(t)} |x| < \infty. \quad (\text{A.1})$$

Let $t_0 > 0$ be fixed and $(t_k)_{k \geq 1}, (x_k)_{k \geq 1}$ be such that $\lim_{k \rightarrow +\infty} t_k = t_0$, $t_k > t_0$ and $x_k \in K(t_k)$ for all $k \geq 1$. By (A.1), $(x_k)_{k \geq 1}$ is bounded; hence, taking a subsequence if necessary, one can assume that x_k converges toward some x_0 . One has

$$\begin{aligned}\limsup_{k \rightarrow +\infty} \frac{m(t_k) - m(t_0)}{t_k - t_0} &= \limsup_{k \rightarrow +\infty} \frac{v(t_k, x_k) - m(t_0)}{t_k - t_0}, \\ &\leq \limsup_{k \rightarrow +\infty} \frac{v(t_k, x_k) - v(t_0, x_k)}{t_k - t_0}, \\ &= \partial_t v(t_0, x_0),\end{aligned}$$

thanks to the C^1 -regularity of v . But, one has $x_0 \in K(t_0)$; indeed, for all $x \in \mathbb{R}$, one has $v(t_k, x_k) \geq v(t_k, x)$ so that the limit as $k \rightarrow +\infty$ gives $v(t_0, x_0) \geq v(t_0, x)$. Hence, one has proved that $\limsup_{k \rightarrow +\infty} \frac{m(t_k) - m(t_0)}{t_k - t_0} \leq \sup_{x \in K(t_0)} \partial_t v(t_0, x)$. The same way, for all $x \in K(t_0)$, one has

$$\liminf_{k \rightarrow +\infty} \frac{m(t_k) - m(t_0)}{t_k - t_0} \geq \liminf_{k \rightarrow +\infty} \frac{v(t_k, x) - v(t_0, x)}{t_k - t_0} = \partial_t v(t_0, x).$$

This shows that

$$\liminf_{k \rightarrow +\infty} \frac{m(t_k) - m(t_0)}{t_k - t_0} \geq \max_{x \in K(t_0)} \partial_t v(t_0, x) \geq \limsup_{k \rightarrow +\infty} \frac{m(t_k) - m(t_0)}{t_k - t_0},$$

for all $t_0 > 0$ and $(t_k)_{k \geq 1}$ such that $t_k \rightarrow t_0$, $t_k > t_0$. That is to say, m is derivable from the right with $m'_r(t_0) = \max_{x \in K(t_0)} \partial_t v(t_0, x)$ on \mathbb{R}^+ . \blacksquare

Proof of Lemma 5.1. Let us estimate the translations of v_ε . Fix $h \in \mathbb{R}$ and define $\mathcal{T}_h v_\varepsilon(x) := v_\varepsilon(x - h)$. Classical formula gives $\mathcal{F}(\mathcal{T}_h v_\varepsilon)(\xi) = e^{-2i\pi\xi h} \mathcal{F}(v_\varepsilon)(\xi)$. By Plancherel's equality, we deduce that

$$\begin{aligned} \int_{\mathbb{R}} |\mathcal{T}_h v_\varepsilon - v_\varepsilon|^2 &= \int_{\mathbb{R}} |e^{-2i\pi\xi h} - 1|^2 |\mathcal{F}(v_\varepsilon)(\xi)|^2 d\xi, \\ &= \int_{\mathbb{R}} \frac{|e^{-2i\pi\xi h} - 1|^2}{|\xi|^\lambda} |\xi|^\lambda |\mathcal{F}(v_\varepsilon)(\xi)|^2 d\xi, \\ &\leq M_h \int_{\mathbb{R}} |\xi|^\lambda |\mathcal{F}(v_\varepsilon)(\xi)|^2 d\xi, \end{aligned}$$

where $M_h := \max_{\xi \in \mathbb{R}} \frac{|e^{-2i\pi\xi h} - 1|^2}{|\xi|^\lambda}$. Lemma 4.1 item (ii) and Plancherel's equality imply that

$$\int_{\mathbb{R}} |\mathcal{T}_h v_\varepsilon - v_\varepsilon|^2 \leq M_h \int_{\mathbb{R}} |\mathcal{L}_{\lambda/2}[v_\varepsilon]|^2.$$

By the assumptions of the lemma, we deduce that $\int_{\mathbb{R}} |\mathcal{T}_h v_\varepsilon - v_\varepsilon|^2 \leq C_0 M_h$ for some constant C_0 (from (4.6)). Using that $e^z - 1 = O(|z|)$ in a neighborhood, it is easy to see that $\lim_{h \rightarrow 0} M_h = 0$, because $\lambda \in (0, 2]$. By Kolmogorov's theorem, the bounded family $\{v_\varepsilon : \varepsilon \in (0, 1)\}$ in $L^\infty(\mathbb{R})$ is relatively compact in $L^2_{loc}(\mathbb{R})$. \blacksquare

Proof of Lemma 6.1. For all $v \in H^1(\mathbb{R}_*)$, there are the traces $\gamma v^\pm \in \mathbb{R}$, $|\gamma v^\pm| \leq \|v\|_{H^1(\mathbb{R}_*)}$, such that for all $\pm x > 0$,

$$v(x) = \gamma v^\pm + \int_0^x (\partial_x v)|_{\mathbb{R}_*}(y) dy. \quad (\text{A.2})$$

It follows that for all $R > 0$, one has $v \in BV((-R, R))$ with

$$|v|_{BV((-R, R))} \leq |\gamma v^+ - \gamma v^-| + \|(\partial_x v)|_{\mathbb{R}_*}\|_{L^1((-R, R))} \leq (2 + \sqrt{2R}) \|v\|_{H^1(\mathbb{R}_*)}.$$

This shows that $H^1(\mathbb{R}_*) \rightarrow BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\})$ is bounded.

Take now $v \in BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\})$. Then v is continuous on \mathbb{R}_* and

$$v(x) = v(1) + \int_1^x \partial_x v(y) dy,$$

where $\partial_x v$ can be a Radon measure with singular part supported by $\{0\}$. By the embedding $H^1(\mathbb{R} \setminus [-1, 1]) \rightarrow C_b(\mathbb{R} \setminus (-1, 1))$, one deduces that v is bounded outside $(-1, 1)$; since v is bounded by $|v(1)| + |v|_{BV((-1, 1))}$ on $[-1, 1]$, $BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^\infty(\mathbb{R})$ is continuous. From this result, it is easy to show (6.1).

The compact embedding is clear from (6.1). Indeed, Helly's theorem and L^q, L^p interpolation inequalities imply that $L^\infty(\mathbb{R}) \cap BV_{loc}(\mathbb{R}) \xrightarrow{c} L^p_{loc}(\mathbb{R})$ is compact for all $p \in [1, +\infty)$; hence, one has $BV_{loc}(\mathbb{R}) \cap H^1_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \xrightarrow{c} L^p_{loc}(\mathbb{R}) \cap L^2_{loc}(\overline{\mathbb{R}} \setminus \{0\}) \rightarrow L^2(\mathbb{R})$. ■

Proof of Lemma 6.2. From (A.2), one deduces that if $v \in H^1(\mathbb{R}_*)$ then $\partial_x v = (\partial_x v)|_{\mathbb{R}_*} + (\gamma v^+ - \gamma v^-)\delta_0$, where $(\partial_x v)|_{\mathbb{R}_*} \in L^2(\mathbb{R})$ and δ_0 is the Dirac delta at zero. Let $(\rho_k)_k \subset \mathcal{D}(\mathbb{R})$ be an approximate unit and define $v_k := \rho_k * v$. Then it is easy to check that $v_k \rightarrow v$ in $L^2(\mathbb{R})$ and that $\partial_x v_k = (\partial_x v)|_{\mathbb{R}_*} * \rho_k + (\gamma v^+ - \gamma v^-)\rho_k$ converges to $\partial_x v$ in $L^2_{loc}(\overline{\mathbb{R}} \setminus \{0\})$ and in $C'_c(\mathbb{R})$. ■

B Appendix: a technical result

Lemma B.1. *Let $m \in C(\mathbb{R}^+)$ be derivable from the right with*

$$m'_r(t) + (\max\{m, 0\})^2 \leq 0 \quad \text{on } \mathbb{R}^+. \quad (\text{B.1})$$

Then, one has $m(t) \leq \frac{1}{t}$ for all $t > 0$.

Proof. Let $t_0 > 0$ be such that $m(t_0)$ is positive. The function m has to be positive on some neighborhood of t_0 ; since (B.1) implies that m is non-increasing, this neighborhood has to contain the interval $(0, t_0]$. Dividing (B.1) by $m^2 = (\max\{m, 0\})^2$ on this interval, we get

$$\left(-\frac{1}{m}\right)'_r \leq -1 \quad \text{in } (0, t_0).$$

Integrating this inequation, we get for all $t < t_0$, $\frac{1}{m(t)} - \frac{1}{m(t_0)} \leq t - t_0$, which implies that

$$m(t_0) \leq \left(\frac{1}{m(t)} + t_0 - t\right)^{-1} \leq (t_0 - t)^{-1}.$$

Letting $t \rightarrow 0$, we conclude that $m(t_0) \leq \frac{1}{t_0}$ whenever $m(t_0)$ is positive. The proof is complete. ■

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