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Ergodicity of Hamilton-Jacobi equations with a non coercive non convex Hamiltonian in $\mathbb{R}^2/\mathbb{Z}^2$

Pierre Cardaliaguet *

December 18, 2008

Abstract The paper investigates the long time average of the solutions of Hamilton-Jacobi equations with a non coercive, non convex Hamiltonian in the torus $\mathbb{R}^2/\mathbb{Z}^2$. We give nonresonance conditions under which the long-time average converges to a constant. In the resonant case, we show that the limit still exists, although it is non constant in general. We compute the limit at points where it is not locally constant.

Résumé Nous considérons le comportement en temps grand de la moyenne temporelle de solutions d’équations de Hamilton-Jacobi pour un hamiltonien non convexe et non coercif dans le tore $\mathbb{R}^2/\mathbb{Z}^2$. Nous mettons en évidence des conditions de non-résonance sous lesquelles cette moyenne converge vers une constante. Dans le cas où il y a résonance, nous montrons que la limite existe, bien qu’étant non constante en général. Nous calculons la limite aux points où celle-ci est non localement constante.

1 Introduction

Since the pioneering work of Lions, Papanicolau and Varadhan [12], the ergodic problem for Hamilton-Jacobi equations has attracted considerable attention. For equations of evolutionary type:

$$\begin{cases}
  u_t + H(x, Du) = 0 & \text{in } \mathbb{R}^N \times (0, +\infty) \\
  u(x, 0) = 0 & \text{in } \mathbb{R}^N
\end{cases}$$

(1)

where $H : \mathbb{R}^N \times \mathbb{R}^N \to \mathbb{R}$ is continuous, one might be interested in the long time behavior of the time average $u(x, t)/t$. For equations of stationary type:

$$\lambda v_\lambda + H(x, Dv_\lambda) = 0 \quad \text{in } \mathbb{R}^N,$$

(2)

the object of investigation is the limiting behavior, when the discount factor $\lambda$ vanishes, of the quantity $\lambda v_\lambda$.

A typical result in this framework is the following: If $H(\cdot, p)$ is $\mathbb{Z}^N$—periodic and $H(x, \cdot)$ is coercive:

$$\lim_{|p| \to +\infty} H(x, p) = +\infty \text{ uniformly with respect to } x,$$

(3)

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the following ergodicity property holds:

\[
\lim_{t \to +\infty} \frac{u(x,t)}{t} = \lim_{\lambda \to 0} \lambda v_\lambda(x) = c \quad \text{uniformly with respect to } x,
\]

where \(c\) is the unique constant such that equation

\[
H(x, D\chi) = -c \quad \text{in } \mathbb{R}^N
\]

has a continuous, periodic solution \(\chi\). The periodicity condition has been relaxed in many situations (compact manifolds, almost periodic setting, stochastic homogenization, ...). However, for first order Hamilton-Jacobi equations, the coercivity of \(H(x, \cdot)\) plays a central role. Indeed, as can readily be seen from the equation, this condition ensures the family of functions \(\{v_\lambda\}\) to be equicontinuous, which in turn implies the existence of a corrector (or approximate corrector in more general frameworks), i.e., a solution of \((5)\).

When the Hamiltonian is not coercive, this crucial equicontinuity property fails and few results are available. Most of them rely on some partial coercivity or on some reduction property, which, somehow, compensates the lack of coercivity: let us quote Alvarez and Bardi [1, 2], Alvarez and Ishii [3], Artstein and Gaitsgory [4], Bardi [6], Barles [7], Birindelli and Wigniolle [8], Gomes [10] and Imbert and Monneau [11]. We follow here a completely different approach, based on nonresonance conditions, initiated for Hamilton-Jacobi equations by Arisawa and Lions [4]. In [4] the authors investigate—among other problems—equations \((1)\) and \((2)\) for Hamiltonians of the form

\[
H(x, p) = H(p) - \ell(x), \quad \forall (x, p) \in \mathbb{R}^N \times \mathbb{R}^N,
\]

where \(\ell : \mathbb{R}^N \to \mathbb{R}\) is continuous, \(\mathbb{Z}^N\)—periodic and \(H : \mathbb{R}^N \to \mathbb{R}\) is positively homogeneous and convex. Under these assumptions, \((4)\) holds as soon as

\[
\forall k \in \mathbb{Z}^N \setminus \{0\}, \exists a \in \partial H(0) \text{ with } k.a \neq 0.
\]

This is the nonresonance condition.

The first aim of our paper is to investigate nonresonance conditions for Hamilton-Jacobi equations with non convex Hamiltonians. Since this is a very delicate issue, we were able to obtain results only for plane problems and for equations of the form

\[
\begin{cases}
  u_t + H(Du) - \ell = 0 & \text{in } \mathbb{R}^2 \times (0, +\infty) \\
  u(x, 0) = 0
\end{cases}
\]

and of the form

\[
\lambda v_\lambda + H(Dv_\lambda) - \ell = 0 \quad \text{in } \mathbb{R}^2,
\]

where \(H : \mathbb{R}^2 \to \mathbb{R}\) is locally Lipschitz continuous and \(\ell : \mathbb{R}^2 \to \mathbb{R}\) is continuous and \(\mathbb{Z}^2\)—periodic. We now present our main result. Let us assume that there is some \(k \geq 1\) and some \(k\)—positively homogeneous, locally Lipschitz continuous Hamiltonian \(H_\infty : \mathbb{R}^2 \to \mathbb{R}\) such that

\[
\lim_{s \to 0^+} s^k H(p/s) = H_\infty(p) \quad \text{locally uniformly in } p.
\]
and such that
\[ \forall \bar{p} \in \mathbb{R}^2 \setminus \{0\} \text{ with } H_\infty(\bar{p}) = 0, \quad DH_\infty(\bar{p}) \text{ exists and is nonzero.} \]

Let us set
\[ \mathcal{P} = \{ p = (p_1, p_2) \in \mathbb{R}^2 \mid |p| = 1, \quad H_\infty(p) = H_\infty(-p) = 0, \quad p_2 \neq 0 \text{ and } p_1/p_2 \in \mathbb{Q}^* \}. \quad (9) \]

Then we show (Theorem 4.1) that if either \( \mathcal{P} = \emptyset \) or
\[ \lim_{s \to 0^+} \left| H \left( \frac{p}{s} \right) \right| = +\infty \quad (10) \]

then ergodicity (4) holds for any \( \ell : \mathbb{R}^2 \to \mathbb{R} \). For instance condition \( \mathcal{P} = \emptyset \) holds for \( H(p_1, p_2) = -|p_1| + \alpha |p_2| \) if and only if \( \alpha > 0 \) is irrational. For \( H(p_1, p_2) = -(p_1 + a)^2 + (p_2 + b)^2 \), we have \( \mathcal{P} = \{(\pm 1, \pm 1)\} \) and condition (10) holds if and only if \( |a| \neq |b| \).

In order to underline the difference between our result and the nonresonance condition of [4] described above, let us explain the main ideas of the proofs. As pointed out in [4], the interesting feature of equations (7) and (8) is that they provide uniform continuity of \( u(\cdot, t)/t \) in \( \mathbb{R}^2 \) for any \( t \geq 1 \) and of \( \lambda v_\lambda \) in \( \mathbb{R}^2 \) for any \( \lambda \in (0, 1] \) (this holds true in any space dimension). Let now \( w \) be a uniform limit of some subsequence \( (\lambda v_\lambda) \). Then classical arguments of viscosity solutions show that \( w \) is a Lipschitz continuous, periodic solution of
\[ H_\infty(Dw) = 0 \quad \text{in } \mathbb{R}^2. \quad (11) \]

The main issue amounts to establish some rigidity properties for the solutions of this equation. When \( H_\infty \) is convex and 1—positively homogeneous, then it is proved in [4] that any continuous, periodic solution \( w \) of (11) is also a solution of
\[ a.Dw = 0 \quad \text{in } \mathbb{R}^2 \quad (12) \]

for any \( a \in \partial H_\infty(0) \). Indeed, \( w \) is a viscosity subsolution of (12), hence a subsolution in the sense of distributions, and, integrating (12) over \([0, 1]^2\) readily gives that equality holds by periodicity. Note that equation (12) means that \( w \) is constant along the lines \( t \to x + ta \) for any \( a \in \partial H_\infty(0) \). In particular, if (6) holds, one can cover the torus by such lines and any continuous periodic solutions of (11) has to be constant.

If now \( H \) is non convex, then the reduction to linear equations of the form (12) does not hold. However we are able to show in the plane that, if (7) holds and if \( w \) is a Lipschitz continuous solution of the equation (11), then at any point \( \bar{x} \) at which \( w \) has a nonzero derivative, the map \( t \to w(\bar{x} - tDH(Dw(\bar{x}))) \) is constant on \([0, +\infty) \) (see Lemma 3.1). This result is somewhat surprising since the map \( t \to w(\bar{x} + tDH(Dw(\bar{x}))) \) need not be constant on \([0, +\infty) \). As a consequence we prove in Theorem 3.3 that any non constant, periodic solution of (11) is of the form \( w(x) = \bar{w}(\bar{p}.x) \) for some map \( \bar{w} : \mathbb{R} \to \mathbb{R} \) and some \( \bar{p} \in \mathcal{P} \). In particular, if \( \mathcal{P} = \emptyset \), any limit of \( (\lambda v_\lambda) \) is constant, which implies (4).

Ergodicity in the case (10) is more subtle and relies on the fact that any cluster point \( w \) of the \( (\lambda v_\lambda) \) for the uniform topology has to be of the form \( w(x) = \bar{w}(\bar{p}.x) \) for some \( \bar{p} \in \mathcal{P} \).
and some $\bar{w} : \mathbb{R} \to \mathbb{R}$.

The second aim of our paper is to analyse the behavior of the solutions of (7) and (8) in the resonant case ($P \neq \emptyset$). In this case, we cannot expect ergodicity to hold in general: for instance, if $H(p_1, p_2) = -|p_1| + |p_2|$ and $\ell(p_1, p_2) = \bar{\ell}(p_1 - p_2)$ for some continuous periodic function $\bar{\ell} : \mathbb{R} \to \mathbb{R}$, then one easily checks that $v_\lambda = \ell / \lambda$, so that (1) does not hold. In this resonant case, very few is known. The only work we are aware of is due to Quincampoix and Renault who show in [13] that, if $H$ is convex with respect to the gradient variable and has a “weak dependence” with respect to $x$, then there exists a limit for the $(u(\cdot, t)/t)$. We give a similar result for nonconvex $H$ in dimension 2: under suitable assumptions on $H$, the limits of $u(\cdot, t)/t$ and of $\lambda v_\lambda$ as $t \to +\infty$ and $\lambda \to 0^+$ exist and are equal (Theorem 5.1). Of course this common limit $w$ need not be constant in general. However, since $w$ is a Lipschitz continuous, periodic solution of (11), our rigidity result implies that $w$ has to be of the form $w(x) = \bar{w}(\bar{p}.x)$ for some function $\bar{w} : \mathbb{R} \to \mathbb{R}$ and some $\bar{p} \in P$. In fact we can compute explicitly $\bar{w}$ at any point $s \in \mathbb{R}$ at which $\bar{w}$ is not locally constant. The quantity $\bar{w}(s)$ is the sum of two terms: one is the average of $\ell$ over the line $\bar{p}.x = s$; the other is related to the behavior of $H(p)$ when $|p| \to +\infty$. The proof of these results relies on the existence of “correctors” of a linearized equation along the lines $\bar{p}.x = s$. We use these correctors in order to build sub-solutions with state constraints on sets of the form $\{w \geq \theta\}$.

The paper is organized in the following way. We first recall in section 2 some well-known results on equations (7) and (8). Then we establish in section 3 the rigidity property of equation (11). The proof of ergodicity is given in section 4, while section 5 is devoted to resonant case. We complete the paper by a discussion on some open problems.

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\section{Generalities}

In this section, we recall some known results on the Hamilton-Jacobi equations (7) and (8). We always work here in the framework of viscosity solutions [9]. Let us first focus on the stationary equation:

$$\lambda v_\lambda + H(Dv_\lambda) = \ell \quad \text{in } \mathbb{R}^N.$$

In the above equation, $H : \mathbb{R}^N \to \mathbb{R}$ is continuous and $\ell : \mathbb{R}^N \to \mathbb{R}$ is continuous and $\mathbb{Z}^N$-periodic. Under these assumptions, (8) has a unique viscosity solution $v_\lambda$. This solution is continuous and $\mathbb{Z}^N$-periodic. We set $w_\lambda = \lambda v_\lambda$.

\textbf{Lemma 2.1} $w_\lambda$ is continuous, uniformly with respect to $\lambda$. Moreover, if $\ell$ is Lipschitz continuous, then so is $w_\lambda$, with a Lipschitz constant independant of $\lambda$. 
Proof: Let $\omega$ be a modulus of continuity of $\ell$. For any $z \in \mathbb{R}^N$, $v_\lambda(z) + \omega(|z|)/\lambda$ (resp. $v_\lambda(z) - \omega(|z|)/\lambda$) is a supersolution (resp. a subsolution) of $\ell$. By comparison, we get

$$v_\lambda(x + z) - \omega(|z|)/\lambda \leq v_\lambda(x) \leq v_\lambda(x + z) + \omega(|z|)/\lambda \quad \forall x \in \mathbb{R}^N,$$

which implies that $\omega$ is a modulus of continuity for $w_\lambda$ for any $\lambda > 0$. Note that if $\ell$ is Lipschitz continuous with a Lipschitz constant $L$, then we can take $\omega(t) = Lt$, so that the $w_\lambda$ are all $L$-Lipschitz continuous. □

From now on we assume that $H$ has a recession function: there exists a continuous function $H_\infty : \mathbb{R}^N \to \mathbb{R}$ and $k \geq 1$ such that

$$\lim_{s \to 0^+} s^k H(p/s) = H_\infty(p) \text{ locally uniformly in } p. \quad (13)$$

Note that $H_\infty$ is $k$-positively homogeneous.

**Lemma 2.2** Under assumption $(13)$, if $w$ is any limit of a uniformly converging subsequence of $(w_\lambda)$ as $\lambda \to 0^+$, then $w$ satisfies

$$H_\infty(Dw) = 0 \quad (14)$$

Proof: Indeed $w_\lambda$ solves

$$\lambda^k w_\lambda + \lambda^k H(Dw_\lambda/\lambda) = \lambda^k \ell \quad \text{in } \mathbb{R}^N.$$

Letting $\lambda \to 0$ gives the result. □

**Lemma 2.3** Let $w$ be any limit of a uniformly converging subsequence of $(w_\lambda)$ as $\lambda \to 0^+$. Then

$$\limsup_{\lambda \to 0} \max_{x \in \mathbb{R}^N} w_\lambda(x) = \max_{x \in \mathbb{R}^N} w(x) \quad \text{and} \quad \liminf_{\lambda \to 0} \min_{x \in \mathbb{R}^N} w_\lambda(x) = \min_{x \in \mathbb{R}^N} w(x).$$

In particular, if $w$ is constant, then $(w_\lambda)$ uniformly converges to the constant $w$ as $\lambda \to 0$.

Proof: For any $\lambda, n$, let $x_{\lambda,n}$ be a maximum point of $v_\lambda - v_{\lambda,n}$. We have (formally)

$$Dv_\lambda(x_{\lambda,n}) = Dv_{\lambda,n}(x_{\lambda,n}).$$

From the equations satisfied by $v_\lambda$ and $v_{\lambda,n}$ we also have

$$\lambda v_\lambda(x_{\lambda,n}) - \lambda_n v_{\lambda,n}(x_{\lambda,n}) \leq -H(Dv_\lambda(x_{\lambda,n})) + H(Dv_{\lambda,n}(x_{\lambda,n})) = 0.$$

Hence

$$\max \lambda v_\lambda \leq \lambda \max_x (v_\lambda - \lambda v_{\lambda,n}) + \lambda \max_x v_{\lambda,n} \leq \lambda (v_\lambda(x_{\lambda,n}) - \lambda v_{\lambda,n}(x_{\lambda,n}) + \lambda \max v_{\lambda,n} \leq \lambda_n v_{\lambda,n}(x_{\lambda,n}) + 2\lambda |v_{\lambda,n}|_\infty.$$
When \( \lambda \to 0 \), \( x_{\lambda,n} \to x_n \) (up to some subsequence) and we get

\[
\limsup_{\lambda \to 0^+} \max \lambda v_\lambda \leq \lambda_n v_{\lambda_n}(x_n)
\]

Letting finally \( n \to +\infty \) we obtain

\[
\limsup_{\lambda \to 0^+} \max \lambda v_\lambda \leq \max_x w.
\]

The above argument can be made rigorous by using standard technique of doubling variables. The reverse inequality

\[
\liminf_{\lambda \to 0^+} \min \lambda v_\lambda \geq \min_x w.
\]

can be proved in the same way by minimizing \( v_\lambda - v_{\lambda_n} \).

□

We now turn to the analysis of the solutions of the evolution equation

\[
\begin{cases}
  u_t + H(Du) - \ell = 0 & \text{in } \mathbb{R}^N \times [0, +\infty[ \\
  u(x,0) = 0 & \text{in } \mathbb{R}^N
\end{cases}
\]

where, as before, \( H : \mathbb{R}^N \to \mathbb{R} \) is continuous, \( \ell : \mathbb{R}^N \to \mathbb{R} \) is continuous and \( \mathbb{Z}^N \)-periodic.

**Lemma 2.4** Under the above assumptions, \( w := u/t \) is periodic in \( x \), bounded and uniformly continuous in \( x \) for any \( t \geq 1 \).

**Proof**: By comparison principle, \( |u(x,t)| \leq t\|\ell\|_{\infty} \). So \( w \) is bounded for \( t \geq 1 \). Let \( \omega \) be a modulus of continuity of \( \ell \). Then, for any \( z \in \mathbb{R}^N \), \( (x,t) \to u(x+z,t) + \omega(z)(1+t) \) is a super-solution of \( \ell \). So \( u(x,t) \leq u(x+z,t) + \omega(z)(1+t) \), which proves that \( u(\cdot,t)/t \) has \( \omega \) as a modulus of continuity with respect to \( x \) for any \( t \geq 1 \).

□

### 3 Rigidity of equation \( H_\infty(Dw) = 0 \)

From now on we work in the plane. We denote by \((x_1,x_2)\) or \((p_1,p_2)\) a generic element of \( \mathbb{R}^2 \). The aim of this section is to investigate the continuous periodic solutions of equation

\( H_\infty(Dw) = 0 \). In order to simplify the notations, we denote by \( H \) the hamiltonians of this section. Our assumptions on \( H : \mathbb{R}^2 \to \mathbb{R} \) are:

\[
H \text{ is locally Lipschitz continuous, } k-\text{positively homogeneous, for some } k \geq 1. \tag{15}
\]

**Lemma 3.1** Let \( H : \mathbb{R}^2 \to \mathbb{R} \) satisfying \( \text{[15]} \). Let \( w \) be a locally Lipschitz continuous viscosity solution of \( H(Dw) = 0 \) in \( \mathbb{R}^2 \) and \( \bar{x} \) be a point of differentiability of \( w \) with \( Dw(\bar{x}) \neq (0,0) \). If \( DH(Dw(\bar{x})) \) exists, then

\[
w(\bar{x} - tDH(Dw(\bar{x}))) = w(\bar{x}) \quad \forall t \geq 0.
\]

**Remarks:**
1. Surprisingly equality \( w(\bar{x} + tDH(Dw(\bar{x})) = w(\bar{x}) \quad \forall t \geq 0 \) does not hold in general. For instance, if \( H(p_1, p_2) = -|p_1| + |p_2| \), then \( w(x_1, x_2) = \max\{x_1 + x_2, x_2 - x_1\} \) is a viscosity solution to \( H(Dw) = 0 \) in \( \mathbb{R}^2 \) and \((1,1)\) is a point of differentiability of \( w \) with \( Dw(1,1) = (1,1) \) and \( DH(Dw(\bar{x})) = (-1,1) \). However

\[
w((1,1) + tDH(Dw(\bar{x})) = \max\{2,2t\} > 2 = w(1,1) \quad \forall t > 1. \]

2. The result also holds if \( w \) is a solution of \( H(Dw) = 0 \) in an open set \( \mathcal{O} \subset \mathbb{R}^2 \). In this case, we have \( w(\bar{x} - tDH(Dw(\bar{x})) = w(\bar{x}) \) for any \( t > 0 \) such that \( \bar{x} - sDH(Dw(\bar{x}) \in \mathcal{O} \) for all \( s \in [0, t] \). The proof is exactly the same.

**Proof of Lemma 3.1:** Replacing \( H \) by \( \tilde{H}(p) = |p|H(p/|p|) \) if necessary, we can assume that \( H \) is \( 1 - \)positively homogeneous. Moreover, \( H \) is then globally Lipschitz continuous. Let \((e_1, e_2)\) be the canonical basis of \( \mathbb{R}^2 \) and let us set \( \bar{p} = Du(\bar{x}) \) and \( \xi = DH(Dw(\bar{x})) \). Without loss of generality we can also suppose that \( u(\bar{x}) = 0 \) and \( \bar{p} = e_1 \). Since \( H \) is positively homogeneous, we note for later use that \( \bar{p}, \xi = H(\bar{p}) = 0 \).

**Step 1:** We claim that, for any \( \varepsilon > 0 \) small enough there is some convex and positively homogeneous map \( H^+_{\varepsilon} : \mathbb{R}^2 \rightarrow \mathbb{R} \) such that

\[
H \leq H^+_{\varepsilon}, \quad H^+_{\varepsilon}(\bar{p}) = 0, \quad \partial H^+_{\varepsilon}(\bar{p}) \subset B_{\varepsilon}(\xi) \quad \text{and} \quad 0 \notin \partial H^+_{\varepsilon}(0). \tag{16}
\]

**Proof of step 1:** Since \( H \) is differentiable at \( \bar{p} \), for any \( \varepsilon > 0 \) we can find \( \eta > 0 \) such that

\[
|H(p) - \xi, (p - \bar{p})| \leq \varepsilon |p - \bar{p}| \quad \forall p \in B_\eta(\bar{p}). \tag{17}
\]

Let us denote by \( C_\eta \) the convex cone \( \{ p = (p_1, p_2) \in \mathbb{R}^2 \mid |p_2| \leq \eta |p_1| \} \). By homogeneity of \( H \) and using the fact that \( \xi, \bar{p} = 0 \) and \( \bar{p} = e_1 \), [17] leads to

\[
H(p) \leq \xi, p + \varepsilon |p_2| \quad \forall p = (p_1, p_2) \in C_\eta.
\]

Then, since \( H \) is Lipschitz continuous, we can choose a constant \( M \) such that \( H \leq H^+_{\varepsilon} \) where

\[
H^+_{\varepsilon}(p) = \xi, p + \varepsilon |p_2| + Md_{C_\eta}(p) \quad \forall p \in \mathbb{R}^2,
\]

where \( d_{C_\eta}(p) \) denotes the distance from \( p \) to \( C_\eta \). We note that \( H^+_{\varepsilon} \) is convex and positively homogeneous. Moreover, \( H^+_{\varepsilon}(\bar{p}) = 0 \) and \( \partial H^+_{\varepsilon}(\bar{p}) \subset B_{\varepsilon}(\xi) \) by construction. Finally, we note that, if we had \( 0 \in \partial H^+_{\varepsilon}(0) \), then this would imply that, for any \( h > 0 \) sufficiently small,

\[
0 = 0.(\bar{p} - h\xi) \leq H^+_{\varepsilon}(\bar{p} - h\xi) = -h|\xi|^2 + \varepsilon h|\xi| < 0,
\]
a contradiction if we choose \( \varepsilon > 0 \) small. So \( 0 \notin \partial H^+_{\varepsilon}(0) \).

**Step 2:** Let us fix \( \delta > 0 \) small and let us denote by \( \bar{y}_\delta \) and \( \bar{z}_\delta \) a projection of \( \bar{x} \) onto the sets \( \{ l \leq -\delta \} \) and \( \{ l \geq \delta \} \). Since \( w \) is differentiable at \( \bar{x} \) with \( \bar{p} = Dw(\bar{x}) \neq 0 \), we have

\[
\lim_{\delta \rightarrow 0^+} \frac{\bar{x} - \bar{y}_\delta}{\delta} = \lim_{\delta \rightarrow 0^+} \frac{\bar{z}_\delta - \bar{x}}{\delta} = \frac{\bar{p}}{|\bar{p}|^2} = \bar{p}. \tag{18}
\]
In particular, for $\delta > 0$ sufficiently small, we have

$$-\delta < w(z) < \delta \quad \forall z \in ]\bar{y}_\delta, \bar{z}_\delta[.$$ (19)

We claim that

$$(\bar{y}_\delta - \bar{x}).\xi \leq 0 \quad \text{while} \quad (\bar{z}_\delta - \bar{x}).\xi \geq 0.$$ (20)

**Proof of claim [20]:** Let $1_{(w>\delta)}$ denote the indicatrix function of the set $\{w > -\delta\}$. From classical stability result the map $1_{(w>\delta)}$ is a super-solution of $H(Dw) = 0$. For $\delta > 0$ small, the map

$$z(x) = -\delta + (\delta^2 + |\bar{x} - \bar{y}_\delta|^2 - |\bar{x} - x|^2)^{\frac{1}{2}}$$

satisfies:

$$z(x) \leq |\bar{x} - \bar{y}_\delta| \leq 1 = 1_{(w>\delta)}(x) \quad \text{if} \quad |\bar{x} - x| < |\bar{x} - \bar{y}_\delta|$$

by definition of $\bar{y}_\delta$ and

$$z(x) \leq 0 \leq 1_{(w>\delta)}(x) \quad \text{if} \quad |\bar{x} - x| \geq |\bar{x} - \bar{y}_\delta|.$$ 

Since moreover $z(\bar{y}_\delta) = 0 = 1_{(w>\delta)}(\bar{y}_\delta)$, we have by definition of supersolutions:

$$H(Dz(\bar{y}_\delta)) = H\left(\frac{\bar{x} - \bar{y}_\delta}{\delta}\right) \geq 0.$$ 

Now we use the fact that we are in dimension 2, that $H(\bar{p}) = 0$, $\xi = DH(\bar{p}) \neq 0$, $(\bar{x} - \bar{y}_\delta)/\delta \to \bar{p}$ and that $H$ is homogeneous, to get that $(\bar{y}_\delta - \bar{x}).\xi \leq 0$. The other inequality of (20) can be proved in a symmetric way.

To proceed further we need the following Lemma, whose proof is postponed:

**Lemma 3.2** Let $G : \mathbb{R}^N \to \mathbb{R}$ be a convex positively homogeneous map and $w$ be a continuous super-solution of $G(Dw) = 0$. Then, for any $x_0 \in \mathbb{R}^N$, there is an absolutely continuous map $x : [0, +\infty) \to \mathbb{R}^N$ such that

$$x'(t) \in -\partial G(x(t))$$

for almost all $t \geq 0$ and $t \to w(x(t))$ is nonincreasing on $[0, +\infty)$.

**Step 3:** Let $H^+_\varepsilon : \mathbb{R}^2 \to \mathbb{R}^2$ be the convex, positively homogeneous map defined in step 1. Since $H \leq H^+_\varepsilon$, $w$ is a supersolution of $H^+_\varepsilon(Dw) = 0$. From Lemma 3.2 there is some absolutely continuous map $y_\delta : [0, +\infty) \to \mathbb{R}^2$ starting from $\bar{y}_\delta$ with

$$y'_\delta(t) \in -\partial H^+_\varepsilon(x(t))$$

for almost all $t \geq 0$ and $t \to w(y_\delta(t))$ is nonincreasing on $[0, +\infty)$.

Let us fix $T > 0$ and let $Q_\delta$ be the closed quadrilateral with vertices $\bar{y}_\delta$, $\bar{z}_\delta$, $\bar{z}_\delta - T\xi$, $\bar{y}_\delta - T\xi$. We set

$$\theta^-_\delta = \inf\{t \geq 0 \mid y_\delta(t) \notin Q_\delta\}.$$ 

Since $0 \notin \partial H^+_\varepsilon(0)$, the separation theorem states that there is some $\eta > 0$ and there is some direction $\zeta \in \mathbb{R}^2 \setminus \{0\}$ such that $y'_\delta(t).\zeta \geq \eta$ for almost all $t \geq 0$. Thus $\theta^-_\delta$ is well defined.
and finite because $Q_δ$ is bounded. We claim that $y_δ(θ_δ^-) \in [z_δ, z_δ - Tξ] \cup [z_δ - Tξ, y_δ - Tξ]$. 

**Proof of the claim:** By construction we have $w(y_δ(t)) \leq -δ$ for any $t \geq 0$. From (19) this implies that $y_δ(θ_δ^-) \notin [y_δ, z_δ]$. Since $y_δ(t) \in -∂H^+_ε(x(t))$ a.e., we have

$$y_δ(t).\bar{p} \geq -H^+_ε(\bar{p}) = 0 \quad \text{a.e.}$$

so that $(y_δ(t) - \bar{y}_δ).\bar{p} \geq 0$ for any $t \geq 0$. Thus $y_δ(θ_δ^-) \notin [y_δ, z_δ]$.

It remains to show that $y_δ(θ_δ^-) \neq \bar{y}_δ$. For this it is enough to prove that, if $y_δ(θ) = \bar{y}_δ$ for some $θ \geq 0$, then there is some $σ > 0$ such that $y_δ(θ + s) \in Q_δ$ for any $s \in [0, σ]$. Let us fix $θ \geq 0$ such that $y_δ(θ) = \bar{y}_δ$. Since the open ball $B^0(\bar{x}, |\bar{y}_δ - \bar{x}|)$ is contained in \{ $w > -δ$ \}, we have $y_δ(t) \notin B^0(\bar{x}, |\bar{y}_δ - \bar{x}|)$ for any $t \geq 0$. We now consider two cases. If $(\bar{y}_δ - \bar{x}).ξ < 0$, then there is some $η > 0$ such that

$$\{ z \in B(\bar{y}_δ, η) \mid z \notin B^0(\bar{x}, |\bar{y}_δ - \bar{x}|) \text{ and } (z - \bar{y}_δ).\bar{p} \geq 0 \} \subset Q_δ \,.$$ 

Since, for $s > 0$ small, the point $y_δ(θ + s)$ belongs to the set in the left-hand side, we have $y_δ(θ + s) \in Q_δ$ for any $s \in [0, σ]$ for some $σ > 0$. Let us now suppose that $(\bar{y}_δ - \bar{x}).ξ = 0$. This implies that $\bar{y}_δ - \bar{x} = -\bar{y}_δ - \bar{x}|\bar{p}$. Let $z$ be an accumulation point of $(y_δ(t) - \bar{y}_δ)/(t - θ)$ as $t \to θ^+$. Then $z \in -∂H^+_ε(0)$. In particular $z.\bar{p} \geq -H^+_ε(\bar{p}) = 0$. Since $y_δ(t) \notin B^0(\bar{x}, |\bar{y}_δ - \bar{x}|)$ for any $t \geq 0$, we also have

$$0 \leq (\bar{y}_δ - \bar{x}).z = -|\bar{y}_δ - \bar{x}|.\bar{p}.z .$$

Hence $z.\bar{p} = 0$ and $z = λξ$ for some $λ \in \mathbb{R}$. Since $∂H^+_ε(\bar{p}) \subset B^2ε(ξ)$ we can find $η > 0$ such that $∂H^+_ε(\bar{p} - hξ) \subset B^2ε(ξ)$ for any $h \in [0, η]$. So, for any $h \in (0, η]$, we have

$$z.(\bar{p} - hξ) \geq -H^+_ε(\bar{p} - hξ) \geq -H^+_ε(\bar{p}) + (\bar{p} - (\bar{p} - hξ)).q_h$$

for some $q_h \in ∂H^+_ε(\bar{p} + hξ) \subset B^2ε(ξ)$. Thus

$$-λh|ξ|^2 = z.(\bar{p} - hξ) \geq hξ.q_h \quad \forall h \in (0, η] ,$$

which entails that $λ \leq -|ξ|^2 + 2ε|ξ| < 0$. Therefore we have proved that any limit point $z$ of $(y_δ(t) - \bar{y}_δ)/(t - θ)$ as $t \to θ^+$ is of the form $z = λξ$ where $λ < 0$. The definition of $Q_δ$ then easily implies that there is some $σ > 0$ such that $y_δ(θ + s) \in Q_δ$ for any $s \in [0, σ]$.

**Step 4:** We now note that $-w$ is a solution to $-H(-Dw) = 0$. Arguing as in step 3 with $-w$, $-H(-\cdot)$ and $\bar{z}_δ$ instead of $w$, $H$ and $\bar{y}_δ$, we can find some absolutely continuous arc $z_δ : [0, +∞) \to \mathbb{R}^2$ starting from $\bar{z}_δ$ such that $w(z_δ(t)) \geq δ$ for any $t \geq 0$ and such that, if we set

$$θ_δ^+ = \inf\{t \geq 0 \mid z_δ(t) \notin Q_δ \} ,$$

then $θ_δ^+$ is finite and $z_δ(θ_δ^+) \in [\bar{y}_δ, \bar{y}_δ - Tξ] \cup [\bar{z}_δ - Tξ, \bar{y}_δ - Tξ]$. Since $w(y_δ(t)) \leq -δ$ and $w(z_δ(t)) \geq δ$ for any $t \geq 0$, $y_δ([0, θ_δ^-]) \cap z_δ([0, θ_δ^+]) = \emptyset$. Since we are in the plane, this implies that $y_δ(θ_δ^-) \in [\bar{z}_δ - Tξ, \bar{y}_δ - Tξ]$ and $z_δ(θ_δ^+) \in [\bar{z}_δ - Tξ, \bar{y}_δ - Tξ]$. Letting $δ \to 0^+$, the maps $y_δ$ and $z_δ$ converge, up to subsequence, to some absolutely continuous maps $y$ and $z$, while $θ_δ^- \to θ^-$ and $θ_δ^+ \to θ^+$ with $y(t) \in [\bar{x}, \bar{x} - Tξ]$ for any $t \in [0, θ^-]$ and
that periodic solution of (22). Then there is some point of differentiability \( x \) non constant, almost every \( t \) for almost all \( t \). Let \( p \) there is some map admits a non constant, Lipschitz continuous, \( z(\cdot, 0) = w \) in \( \mathbb{R}^N \). Therefore
\[
w(\bar{x} - t\xi) = w(\bar{x}) \quad \forall t \geq 0
\] (23)
Proof of Lemma 3.2: Since \( G \) is defined on \( \mathbb{R}^N \), convex and positively homogeneous, \( \partial G(0) \) is a convex compact subset of \( \mathbb{R}^N \). Let \( z : \mathbb{R}^N \to \mathbb{R} \) be the solution to
\[
\begin{cases}
z_t + G(Dz) = 0 \text{ in } \mathbb{R}^N \times (0, +\infty) \\
z(\cdot, 0) = w \text{ in } \mathbb{R}^N
\end{cases}
\]
Since \( w \) satisfies \( G(Dw) \geq 0 \), we have \( w(x) \geq z(x, t) \) for any \( (x, t) \). From Lax representation formula we get
\[w(x) \geq z(x, t) = \min_{(x-y)\in\partial G(0)} w(y) \quad \forall (x, t) \in \mathbb{R}^N \times (0, +\infty).\]
In particular we have proved that, for any \( x \in \mathbb{R}^N \) and any \( \tau > 0 \), there is some \( y \in \mathbb{R}^N \) such that \( (x-y)/\tau \in \partial G(0) \) and \( w(x) \geq w(y) \).

By induction, we can then show that there is a sequence \( (y_n)_n \) such that \( y_0 = x_0, y_{n+1} = y_n - \tau \partial G(0) \) and \( w(y_{n+1}) \leq w(y_n) \) for any \( n \in \mathbb{N} \). Let \( x_\tau : [0, +\infty) \to \mathbb{R}^N \) be an affine interpolation of \( (y_n) \) such that \( x_\tau(n\tau) = y_n \) for any \( n \in \mathbb{N} \). Note that \( x_\tau(t) \in -\partial G(0) \) for almost all \( t \geq 0 \). In particular the family \( x_\tau \) is equi-Lipschitz continuous and a subsequence converge to some \( x : [0, +\infty) \to \mathbb{R}^N \) such that \( x(0) = x_0, x'(t) \in -\partial G(0) \) for almost every \( t \geq 0 \) and \( w(x(t)) \leq w(x(s)) \) whenever \( t \geq s \).

As a consequence of Lemma 3.1 we get the following rigidity result:

**Theorem 3.3** Let \( H : \mathbb{R}^2 \to \mathbb{R} \) satisfy (15) and such that
\[
\forall \bar{p} \in \mathbb{R}^2\setminus\{0\} \text{ with } H(\bar{p}) = 0, DH(\bar{p}) \text{ exists and is nonzero.}
\] (21)
Then equation
\[
H(Dw) = 0 \quad \text{in } \mathbb{R}^2
\] (22)
admits a non constant, Lipschitz continuous, \( \mathbb{Z}^2 \)-periodic solution if and only if there is some \( \bar{p} = (\bar{p}_1, \bar{p}_2) \in \mathbb{R}^2\setminus\{0\} \) such that \( H(\bar{p}) = H(-\bar{p}) = 0 \) and such that \( \bar{p}_2 \neq 0 \) and \( \bar{p}_1/\bar{p}_2 \in \mathbb{Q}^* \).

In this case, any continuous, periodic solution \( w \) of (22) is one-dimensional: namely, there is some map \( \bar{w} : \mathbb{R} \to \mathbb{R} \) and some \( \bar{p} \in \mathbb{R}^2\setminus\{0\} \) with \( H(\bar{p}) = H(-\bar{p}) = 0, \bar{p}_2 \neq 0 \) and \( \bar{p}_1/\bar{p}_2 \in \mathbb{Q}^* \) such that
\[
w(x) = \bar{w}(x, \bar{p}) \quad \forall x \in \mathbb{R}^2.
\]

For instance, if \( H(p) = -|p_1| + \alpha |p_2| \) for some \( \alpha > 0 \), then equation (22) admits a non constant, \( \mathbb{Z}^2 \)-periodic Lipschitz continuous solution if and only if \( \alpha \in \mathbb{Q} \).

**Proof of Theorem 3.3:** Let \( w \) be a non constant, Lipschitz continuous and periodic solution of (22). Then there is some point of differentiability \( \bar{x} \in \mathbb{R}^2 \) of \( w \) such that \( \bar{p} := Dw(\bar{x}) \neq 0 \). From Lemma 3.1 we have
\[
w(\bar{x} - t\xi) = w(\bar{x}) \quad \forall t \geq 0
\] (23)
where $\xi = DH(Dw(x))$. Let us consider the set

$$E = \{ x \in \mathbb{R}^2/\mathbb{Z}^2 \mid \exists t_n \to +\infty, \ x - t_n \xi \to x \text{ in } \mathbb{R}^2/\mathbb{Z}^2 \}.$$ 

Then $E$ is a closed subset of $\mathbb{R}^2/\mathbb{Z}^2$ and $w = w(\bar{x})$ on $E$. Moreover $E$ satisfies

$$x - t \xi \in E \quad \forall x \in E, \forall t \in \mathbb{R}.$$ 

It is known that a set of the form $\{ x - t \xi \mid t \in \mathbb{R} \}$ is dense in $\mathbb{R}^2/\mathbb{Z}^2$ if and only if $\xi$ has rationally independant coordonates. In this case, $w$ has to be constant, which contradicts of assumption. So the pair $(\xi_1, \xi_2)$ is not rationally independant, which amounts to saying that $\xi_2 \neq 0$ and $\xi_1/\xi_2 \in \mathbb{Q}^*$. Since $\bar{p}, \xi = 0$ and $\bar{p} \neq 0$, this also implies that $\bar{p}_2 \neq 0$ and $\bar{p}_1/\bar{p}_2 \in \mathbb{Q}^*$.

We now claim that $w$ is one-dimensional. Indeed let $\bar{x}'$ be another point of differentiability of $w$ such that $w(\bar{x}') \neq w(\bar{x})$ and $\bar{p}' = Dw(\bar{x}') \neq 0$. Let $\xi' = DH(\bar{p}')$. According to the previous discussion, we have $\xi'_2 \neq 0$ and $\xi'_1/\xi'_2 \in \mathbb{Q}^*$. Let

$$E' = \{ x \in \mathbb{R}^2/\mathbb{Z}^2 \mid \exists t_n \to +\infty, \ x' - t_n \xi' \to x \text{ in } \mathbb{R}^2/\mathbb{Z}^2 \}.$$ 

As before we have $w = w(\bar{x}')$ in $E'$. From the particular form of $\xi$ and $\xi'$ we also have

$$E = \bar{x} + \mathbb{R}\xi \quad \text{and} \quad E' = \bar{x}' + \mathbb{R}\xi'.$$ 

Note that $E \cap E' = \emptyset$ because $w = w(\bar{x})$ on $E$ and $w = w(\bar{x}')$ on $E'$ and $w(\bar{x}) \neq w(\bar{x}')$. So $\xi$ and $\xi'$ are parallel, which implies that $\bar{p}$ and $\bar{p}'$ are also parallel: indeed we have $\xi, \bar{p} = 0$ and $\xi', \bar{p}' = 0$ and we are in dimension 2. This shows that any level-set of $w$ is invariant by the flow $x \to x + t\xi$, which implies that $w$ is one-dimensional: there is some $\bar{w} : \mathbb{R} \to \mathbb{R}$ such that $w(x) = \bar{w}(\bar{p}.x)$ for any $x$.

We now check that $H(-\bar{p}) = 0$. Indeed, otherwise, one has $H(-\lambda \bar{p}) \neq 0$ for any $\lambda > 0$ because $H$ is homogeneous. Since $H(Dw) = H(\bar{w}^*\bar{p}) = 0$, this implies that, for almost all $s \in \mathbb{R}$, $\bar{w}'(s) \geq 0$. Hence $\bar{w}$ is non nondecreasing, which contradicts the assumption that $w$ is periodic and non constant.

Conversely, let us assume that there exists $\bar{p} = (\bar{p}_1, \bar{p}_2) \in \mathbb{R}^2\setminus\{0\}$ such that $H(\bar{p}) = H(-\bar{p}) = 0$, $\bar{p}_2 \neq 0$ and $\bar{p}_1/\bar{p}_2 \in \mathbb{Q}^*$. Let $(a, b) \in \mathbb{Z}^* \times \mathbb{N}^*$ with $a/b = \bar{p}_1/\bar{p}_2$. Then

$$w(x) = \sin((a, b).x)$$

is a periodic, non constant Lipschitz continuous solution of $H(Dw) = 0$ because $w$ is smooth and

$$H(Dw(x)) = \left(\frac{b}{\bar{p}_2}\right)^k H\left(\cos((a, b).x)\bar{p}\right) = 0 \quad \forall x \in \mathbb{R}^2.$$ 

$\square$
4 Ergodicity

In this section we investigate conditions under which equations (7) and (8) have an ergodic behavior. Recall that $u = u(x,t)$ is the solution of the evolution equation (7) while, for any $\lambda > 0$, $v_\lambda = v_\lambda(x)$ is the solution of (8).

Let $H : \mathbb{R}^2 \to \mathbb{R}$ be locally Lipschitz continuous such that there is some $k \geq 1$ and some $k-$positively homogeneous, locally Lipschitz continuous Hamiltonian $H_\infty : \mathbb{R}^2 \to \mathbb{R}$ with

$$\lim_{s \to 0^+} s^k H(p/s) = H_\infty(p) \quad \text{locally uniformly in } p.$$  

We also assume that $H_\infty$ satisfies

$$\forall \bar{p} \in \mathbb{R}^2 \backslash \{0\} \text{ with } H_\infty(\bar{p}) = 0, \text{ } DH_\infty(\bar{p}) \text{ exists and is nonzero}.$$  

In view of Theorem 3.3 we introduce the notation:

$$\mathcal{P} = \{p = (p_1, p_2) \in \mathbb{R}^2 \mid |p| = 1, \ H_\infty(p) = H_\infty(-p) = 0, \ p_2 \neq 0 \text{ and } p_1/p_2 \in \mathbb{Q}^+\}.$$  

Then equation $H_\infty(Dw) = 0$ admits a non-constant, Lipschitz continuous, $\mathbb{Z}^2-$periodic solution if and only if $\mathcal{P} \neq \emptyset$. In particular, if $\mathcal{P} = \emptyset$, then combining Lemma 2.3 and Theorem 3.3 readily entails the convergence of the $(\lambda v_\lambda)$ towards a constant as $\lambda \to 0$. Hence condition $\mathcal{P} = \emptyset$ can be understood as a non-resonance condition.

Very surprisingly, ergodicity actually holds under a much weaker assumption. Namely:

**Theorem 4.1** Assume that either $\mathcal{P} = \emptyset$ or that

$$\forall p \in \mathcal{P}, \quad \lim_{s \to 0^+} \left| H \left( \frac{p}{s} \right) \right| = +\infty$$  

Then the $(\lambda v_\lambda)$ and the $u(t, \cdot)/t$ converge to the same constant as $\lambda \to 0$ and $T \to +\infty$.

For instance, if $H_\infty$ is some $k-$positively homogeneous Hamiltonian (for some $k > 1$) satisfying (24) and $H(p) = H_\infty(p + a)$ where $DH_\infty(p).a \neq 0$ for any $p \in \mathcal{P}$, then (26) holds, because

$$\left| H \left( \frac{p}{s} \right) \right| = (1/s)^k |H_\infty(p + sa)| = (1/s)^k |H_\infty(p) + sDH_\infty(p).a + o(s)|$$

$$= (1/s)^{k-1} |DH_\infty(p).a + o(1)| \to +\infty \quad \text{as } s \to 0^+.$$

**Proof of Theorem 4.1**: We first analyse the behaviour of the $(\lambda v_\lambda)$. For this we assume that $\ell : \mathbb{R}^2 \to \mathbb{R}$ is Lipschitz continuous. This assumption is removed later.

Let $w$ be the uniform limit of some sequence $(\lambda_n v_{\lambda_n})$ where $\lambda_n \to 0$. Let us assume that $w$ is not constant. Since the $\lambda v_\lambda$ are uniformly Lipschitz continuous and $\mathbb{Z}^2-$periodic, so is $w$. Since, from Lemma 2.2, $w$ is a solution of $H_\infty(Dw) = 0$, Theorem 3.3 states that there is some $\bar{p} \in \mathcal{P}$ and some continuous map $\bar{w} : \mathbb{R} \to \mathbb{R}$ such that $w(x) = \bar{w}((\bar{p}x)$ for any $x \in \mathbb{R}^2$. To fix the ideas, let us assume for instance that

$$\lim_{s \to 0^+} H \left( \frac{p}{s} \right) = +\infty.$$  

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We claim that, for any smooth test function $\varphi : \mathbb{R} \to \mathbb{R}$ such that $\bar{w} - \varphi$ has a strict local maximum at some point $\bar{z}$, we have $\varphi' (\bar{z}) \leq 0$. Indeed assume on the contrary that $\varphi' (\bar{z}) > 0$. From standard perturbation arguments, there is a sequence $(x_n)$ such that $\lambda_n v_{\lambda_n} - \varphi (\langle \bar{p}, \cdot \rangle)$ has a maximum at $x_n$ and $x_n, \bar{p} \to \bar{z}$. Then, setting $z_n = x_n, \bar{p}$, we have

$$\varphi(z_n) + H \left( \frac{1}{\lambda_n} \varphi'(z_n) \bar{p} \right) - \ell(x_n) \leq 0.$$ 

Since $\varphi'(z_n) \to \varphi' (\bar{z}) > 0$, our assumption states that

$$\lim_{n} H \left( \frac{1}{\lambda_n} \varphi'(z_n) \bar{p} \right) = +\infty,$$

which leads to a contradiction since $\varphi(z_n) \to \varphi (\bar{z})$ and $\ell$ is bounded.

So for any smooth test function $\varphi : \mathbb{R} \to \mathbb{R}$ such that $\bar{w} - \varphi$ has a strict local maximum at some point $\bar{z}$, we have $\varphi' (\bar{z}) \leq 0$. This implies that $\bar{w}$ is nonincreasing. But the function $w(x) = \bar{w}(\bar{p}, x)$ is $Z^2$-periodic. Hence $w$ is constant. Thanks to Lemma 2, we can now complete the proof of the convergence of the $(\lambda v_{\lambda})$ towards a constant in the case where $\ell$ is Lipschitz continuous.

If $\ell$ is only continuous, we proceed by approximation: Let $(\ell_k)$ be a sequence of smooth periodic functions converging to $\ell$ as $k \to +\infty$. Let $v^k_\lambda$ be the unique bounded solution to

$$\lambda v^k_\lambda + H(Dw^k_\lambda) - \ell_k = 0 \quad \text{in } \mathbb{R}^2.$$ 

Then from comparison principle we have:

$$\|\lambda v^k_\lambda - \lambda v_\lambda\|_{\infty} \leq \|\ell_k - \ell\|_{\infty} \quad \forall k \geq 0, \forall \lambda > 0 \quad (27).$$

Since $\ell_k$ is smooth, we already know that the $(\lambda v^k_{\lambda})$ converge to a constant $c_k$ as $\lambda \to 0^+$. From $(27)$ we easily see that $(c_k)$ is a Cauchy sequence and hence converges to some $c \in \mathbb{R}$. Since

$$\|c - \lambda v_\lambda\|_{\infty} \leq |c - c_k| + \|c_k - \lambda v^k_{\lambda}\|_{\infty} + \|\lambda v^k_{\lambda} - \lambda v_\lambda\|_{\infty},$$

inequality $(27)$ shows that the $(\lambda v_{\lambda})$ converge to $c$ as $\lambda \to 0^+$.

We now consider the convergence of the $u(t, \cdot)/t$. Let us denote by $c \in \mathbb{R}$ the limit of the $\lambda v_{\lambda}$. The proof is then standard: let us fix $\varepsilon > 0$ and let $\lambda$ sufficiently small so that $\|\lambda v_{\lambda} - c\|_{\infty} \leq \varepsilon$. Let

$$Z(x, t) = v_\lambda + (c - \varepsilon)t - \|v_\lambda\|_{\infty}.$$ 

Then $Z$ is a sub-solution of $(7)$ because $Z(x, 0) \leq 0$ and

$$Z_t + H(DZ) - \ell = c - \varepsilon + H(Dv_{\lambda}) - \ell = c - \varepsilon - \lambda v_{\lambda} \leq 0.$$ 

By comparison, we have $u(x, t) \geq Z(x, t)$ for any $(x, t) \in \mathbb{R}^2 \times [0, +\infty)$. Thus

$$\lim_{t \to +\infty} \min_{x \in \mathbb{R}^2} \frac{u(x, t)}{t} \geq \lim_{t \to +\infty} \min_{x \in \mathbb{R}^2} \frac{Z(x, t)}{t} = c - \varepsilon.$$
In the same way one can show that

\[
\limsup_{t \to +\infty} \max_{x \in \mathbb{R}^2} \frac{u(x, t)}{t} \leq c - \varepsilon ,
\]

which completes the proof since \(\varepsilon\) is arbitrary. □

**Remark 4.2** In fact we have proved the following result: if there is a sequence \(\lambda_n \to 0^+\), \(\bar{p} \in \mathcal{P}\) and a nonconstant, periodic map \(w(x) = \bar{w}(\bar{p},x)\) such that the sequence \((\lambda_n v_{\lambda_n})\) uniformly converges to \(w\), then

\[
\liminf_{s \to 0^+} \left| H \left( \frac{\bar{p}}{s} \right) \right| < +\infty \quad \text{and} \quad \liminf_{s \to 0^+} \left| H \left( \frac{-\bar{p}}{s} \right) \right| < +\infty .
\]

**Application to homogenization:** Theorem 4.1 can be applied to the homogenization of HJ equations of the form

\[
\begin{aligned}
\tag{28}
\left\{ \begin{array}{ll}
z_t^\varepsilon + H(Dz^\varepsilon(x)) - \ell(x/\varepsilon) = 0 & \text{in } \mathbb{R}^2 \times (0,T) \\
z^\varepsilon(x,0) = z_0(x) & \text{in } \mathbb{R}^2
\end{array} \right.
\end{aligned}
\]

where \(H\) and \(\ell\) are as above.

**Corollary 4.3** Let \(H : \mathbb{R}^2 \to \mathbb{R}\) be a Lipschitz continuous map. Let us assume that (24) holds with \(k = 1\) and that \(\mathcal{P} = \emptyset\), where \(\mathcal{P}\) is defined by (25). Then there is a Lipschitz continuous Hamiltonian \(h : \mathbb{R}^2 \to \mathbb{R}\) such that, for any bounded uniformly continuous map \(z_0 : \mathbb{R}^2 \to \mathbb{R}\), the solution \(z^\varepsilon\) to (28) uniformly converges to the solution \(z\) of

\[
\begin{aligned}
\tag{28}
\left\{ \begin{array}{ll}
z_t + h(Dz(x)) = 0 & \text{in } \mathbb{R}^2 \times (0,T) \\
z(x,0) = z_0(x) & \text{in } \mathbb{R}^2
\end{array} \right.
\end{aligned}
\]

**Remark:** We do not know if the result holds true when \(H\) is only locally Lipschitz continuous.

**Proof:** For any \(p \in \mathbb{R}^2\), let \(v_\lambda^p\) be the unique continuous \(\mathbb{Z}^2\)-periodic solution of

\[
\lambda v_\lambda^p + H(Dv_\lambda^p + p) - \ell = 0 \quad \text{in } \mathbb{R}^2 .
\]

From Theorem 4.1, we know that \(\lambda v_\lambda^p\) uniformly converges to some constant that we denote \(-h(p)\). Since \(H\) is Lipschitz continuous, then so is \(h\) because, for any \(p_1, p_2 \in \mathbb{R}^2\), we have by comparison principle:

\[
\|\lambda v_\lambda^{p_1} - \lambda v_\lambda^{p_2}\|_\infty \leq \text{Lip}(H)|p_1 - p_2| .
\]

The rest of the proof is standard. □
5 Case of resonance

Let again \( u = u(x,t) \) and \( v_\lambda = v_\lambda(x) \) denote the solution to (7) and (8) respectively. In this section we investigate the existence of a limit for \( u/t \) and \( \lambda v_\lambda \) in case of resonance.

For this we assume that \( H : \mathbb{R}^2 \to \mathbb{R} \) is locally Lipschitz continuous and that there is some \( 1 \)-positively homogeneous, Lipschitz continuous Hamiltonian \( H_\infty : \mathbb{R}^2 \to \mathbb{R} \) such that

\[
\lim_{s \to 0^+} s \ H(p/s) = H_\infty(p) \quad \text{locally uniformly in } p.
\]

We also assume that \( H_\infty \) satisfies

\[
\forall \bar{p} \in \mathbb{R}^2 \setminus \{0\} \text{ with } H_\infty(\bar{p}) = 0, \ D H_\infty(\bar{p}) \text{ exists and is nonzero.} \quad (29)
\]

We still use the notation:

\[
\mathcal{P} = \{ p = (p_1, p_2) \in \mathbb{R}^2 \mid |p| = 1, \ H_\infty(p) = H_\infty(-p) = 0, \ p_2 \neq 0 \text{ and } p_1/p_2 \in \mathbb{Q}^* \}
\]

and we denote by \( \mathcal{P}_0 \) the subset of \( p \in \mathcal{P} \) such that

\[
\liminf_{s \to 0^+} \left| H \left( \frac{p}{s} \right) \right| < +\infty \quad \text{and} \quad \liminf_{s \to 0^+} \left| \frac{-p}{s} \right| < +\infty.
\]

We have seen in Theorem 4.1 that, if \( \mathcal{P}_0 = \emptyset \), then the \( (u/t) \) and \( (\lambda v_\lambda) \) converge to a constant. In order to investigate the resonant case, we assume that \( \mathcal{P}_0 \neq \emptyset \) and that, for any \( \bar{p} \in \mathcal{P}_0 \), there are \( \alpha(\bar{p}) \in \mathbb{R}^2 \setminus \{0\} \) and \( \beta(\bar{p}) \in \mathbb{R} \) such that, for any \( M > 0 \), the convergence

\[
\lim_{s \to 0^+} H \left( \frac{\theta \bar{p}}{s} + b \right) = \alpha(\bar{p}).b + \beta(\bar{p}) \quad (30)
\]

holds uniformly with respect to \( \theta \geq 1/M \) and \( b \in \mathbb{R}^2 \) with \( |b| \leq M \). We note that \( \alpha(\bar{p}).\bar{p} = 0 \). In particular, since \( \bar{p} \in \mathcal{P} \) and \( \alpha(\bar{p}) \neq 0 \), we have \( \alpha(\bar{p}) = (\alpha_1, \alpha_2) \) with \( \alpha_2 \neq 0 \) and \( \alpha_1/\alpha_2 \in \mathbb{Q}^* \). Hence there is some \( T(\bar{p}) > 0 \) such that \( T(\bar{p})\alpha(\bar{p}) \in \mathbb{Z}^2 \).

**Example:** Let us assume that \( H_\infty : \mathbb{R}^2 \to \mathbb{R} \) is positively homogeneous, satisfies (29) and that \( \mathcal{P} \neq \emptyset \). Let \( H(p) = H_\infty(p + a) \) for some \( a \in \mathbb{R}^2 \). Then (30) holds because \( \mathcal{P}_0 = \mathcal{P} \) and

\[
H \left( \frac{\theta \bar{p}}{s} + b \right) = \frac{\theta}{s} H_\infty \left( \bar{p} + \frac{s}{\theta} (a + b) \right) = \frac{\theta}{s} \left( H_\infty(\bar{p}) + \frac{s}{\theta} D H_\infty(\bar{p}).(a + b) + o(1) \right)
\]

where \( \alpha(\bar{p}) = D H_\infty(\bar{p}) \neq 0 \) and \( \beta(\bar{p}) = D H_\infty(\bar{p})a \).

Our main result in the case of resonance is the following:

**Theorem 5.1** Under the above assumptions, there is a continuous \( \mathbb{Z}^2 \)-periodic function
\( w : \mathbb{R}^2 \to \mathbb{R} \) such that

\[
w(x) = \lim_{t \to +\infty} \frac{u(x,t)}{t} = \lim_{\lambda \to 0^+} v_\lambda(x) \quad \text{uniformly w.r.t. } x \in \mathbb{R}^2. \quad (31)
\]
In order to describe the limit function, we will say that a map \( \bar{w} : \mathbb{R} \to \mathbb{R} \) has a point of increase at \( \bar{s} \in \mathbb{R} \) if there is a sequence \( s_n \to \bar{s} \) and a sequence \( h_n \to 0^+ \) such that \( \bar{w}(s_n + h_n) > \bar{w}(s_n) \). The map \( \bar{w} \) has a point of decrease at \( \bar{s} \) if \( -\bar{w} \) has a point of increase at \( \bar{s} \).

**Proposition 5.2** Let \( w \) be defined by (31). There is some \( \bar{p} \in \mathcal{P}_0 \) and some continuous map \( \bar{w} : \mathbb{R} \to \mathbb{R} \) such that

\[ w(x) = \bar{w}(\bar{p}.x) \quad \forall x \in \mathbb{R}^2. \]

Moreover, we have at any point of increase \( s \) of \( w \):

\[ \bar{w}(s) = \frac{1}{T(\bar{p})} \int_0^{T(\bar{p})} \ell(s\bar{p} + t\alpha(\bar{p}))ds - \beta(\bar{p}), \]

while at any point of decrease \( s \) we have:

\[ \bar{w}(s) = \frac{1}{T(\bar{p})} \int_0^{T(\bar{p})} \ell(s\bar{p} + t\alpha(\bar{p}))ds - \beta(-\bar{p}). \]

The proofs of Theorem 5.1 and of Proposition 5.2 require several steps. From now on we assume that \( \ell \) is a smooth function. This restriction is removed at the end of the proof. Recall that \( w_\lambda = \lambda v_\lambda \). Let \( \mathcal{W} \) be the set of cluster points in the uniform topology of \( w_\lambda \) as \( \lambda \to 0 \). The key step in the proof amounts to show that \( \mathcal{W} \) consists in a singleton. From Lemma 2.2 we know that \( H_\infty(Dw) = 0 \) for any \( w \in \mathcal{W} \).

**Lemma 5.3** There is some \( \bar{p} \in \mathcal{P}_0 \) such that, for any \( w \in \mathcal{W} \), \( w(x) = \bar{w}(\bar{p}.x) \) for some \( \bar{w} : \mathbb{R} \to \mathbb{R} \).

**Proof:** If \( \mathcal{W} \) contains a constant function \( \bar{w} \), then Lemma 2.3 states that \( \mathcal{W} = \{ \bar{w} \} \), and the result is obvious. Otherwise, for any \( \bar{p} \in \mathcal{P}_0 \), let \( \mathcal{W}_\bar{p} \) the set of \( w \in \mathcal{W} \) such that \( w(x) = \bar{w}(\bar{p}.x) \) for some \( \bar{w} : \mathbb{R} \to \mathbb{R} \). Combining Theorem 3.3 and Remark 4.2 we have

\[ \bigcup_{\bar{p} \in \mathcal{P}_0} \mathcal{W}_\bar{p} = \mathcal{W}. \]

Moreover the \( \mathcal{W}_\bar{p} \) are closed in \( \mathcal{W} \). Since we work in the plane, for any \( \bar{p} \neq \bar{p}' \in \mathcal{P}_0 \), either \( \bar{p} = -\bar{p}' \), in which case \( \mathcal{W}_\bar{p} = \mathcal{W}_{\bar{p}'} \), or the set \( \mathcal{W}_\bar{p} \cap \mathcal{W}_{\bar{p}'} \) only consists of constant functions. So we actually have either \( \mathcal{W}_\bar{p} = \mathcal{W}_{\bar{p}'} \) or \( \mathcal{W}_\bar{p} \cap \mathcal{W}_{\bar{p}'} = \emptyset \). Since the set \( \mathcal{W} \) is connected, this implies that \( \mathcal{W}_\bar{p} = \mathcal{W} \) for some \( \bar{p} \in \mathcal{P}_0 \).

From now on we fix \( \bar{p} \) as in Lemma 5.3. In order to simplify the notations, we set \( \alpha^\pm = \alpha(\pm \bar{p}) \), \( T^\pm = T(\pm \bar{p}) \) and \( \beta^\pm = \beta(\pm \bar{p}) \). We note that, since \( \alpha^+ \bar{p} = \alpha^- \bar{p} = 0 \), the vectors \( \alpha^+ \) and \( \alpha^- \) are in fact proportionnal. Finally we set \( \hat{\alpha}^\pm = \alpha^\pm / |\alpha^\pm| \). Recall that \( |\bar{p}| = 1 \).
The first step of the proof consists in building special sub- and super-solutions of the Hamilton-Jacobi equation (8). Let us set

\[ \tilde{c}(s) = \frac{1}{T^+} \int_0^{T^+} \ell(s\bar{p} + t\alpha^+)dt \quad \forall s \in \mathbb{R}, \quad (32) \]

\[ \chi^\pm(x) = \int_0^{\alpha^+ / |\alpha^+|} \ell((\bar{p},x)\bar{p} + t\alpha^+)dt - \frac{\hat{\alpha}^\pm x}{|\alpha^+|T^+} \tilde{c}(\bar{p},x) \quad \forall x \in \mathbb{R}^2. \quad (33) \]

We note that \( \tilde{c}(s) \) is the average of \( \ell \) on the set \( \bar{p},x = s \).

**Lemma 5.4** The \( \chi^\pm \) are smooth and the maps \( x \rightarrow \tilde{c}(\bar{p},x) \) and \( \chi^\pm \) are \( m\mathbb{Z}^2 \)-periodic for some \( m \in \mathbb{N}^* \). Moreover,

\[ \alpha^\.D\chi^\pm(x) = \ell(x) - \tilde{c}(\bar{p},x) \quad \forall x \in \mathbb{R}^2. \quad (34) \]

**Proof :** By definition of \( T^+ \), \( (a,b) := T^+\alpha^+ \in \mathbb{Z}^2 \). Since \( \alpha^+.\bar{p} = 0 \), we have \( \bar{p} = -\bar{p}/b \), and, since \( |p| = 1 \), \( \bar{p} = \pm(1 + (a/b)^2)^{1/2} \). We also note that \( \hat{\alpha}^+/|\alpha^+| = T^+(a,b)/(a^2 + b^2) \). Setting \( m = b^4(a^2 + b^2) \in \mathbb{N}^* \) we get

\[ (\bar{p},k)\bar{p} \in \mathbb{Z}^2 \quad \text{and} \quad \frac{\hat{\alpha}^+.k}{|\alpha^+|} \in T^+\mathbb{Z} \quad \forall k \in m\mathbb{Z}^2. \]

This proves the \( m\mathbb{Z}^2 \)-periodicity of \( x \rightarrow \tilde{c}(\bar{p},x) \) and of \( \chi^+ \). The periodicity of \( \chi^- \) can be established with similar arguments (changing \( m \) if necessary), and assertion (34) is straightforward. \( \square \)

**Lemma 5.5** Let \( \varepsilon \in \{-1,1\} \) and \( \varphi : [c,d] \rightarrow \mathbb{R} \) be a smooth function such that \( \varepsilon \varphi' > 0 \) and \( \varphi \leq \tilde{c} - \beta^\pm \) in \([c,d]\). Then, for any \( \eta > 0 \) there is some \( \tilde{\lambda} > 0 \) such that, for any \( \lambda \in (0,\tilde{\lambda}) \), the map

\[ x \rightarrow \frac{1}{\lambda}(\varphi(\bar{p},x) - \beta^\pm - \eta) + \chi^\varepsilon(x) - \|\chi^\varepsilon\|_\infty \]

is a sub-solution with state-constraints of (8) in the set \( \{ x \in \mathbb{R}^2 | c \leq \bar{p} \cdot x < d \} \) if \( \varepsilon = 1 \) and in the set \( \{ x \in \mathbb{R}^2 | c \leq \bar{p} \cdot x \leq d \} \) if \( \varepsilon = -1 \).

**Proof of Lemma 5.5** Let us assume for instance that \( \varepsilon = -1 \) and that \( \varphi : [c,d] \rightarrow \mathbb{R} \) is a smooth function such that \( \varphi' < 0 \) and \( \varphi \leq \tilde{c} - \beta^- \) in \([c,d]\). For any \( \lambda > 0 \), let us set

\[ \zeta_\lambda(x) = \frac{1}{\lambda}(\varphi(\bar{p},x) - \beta^\pm - \eta) + \chi^- (x) - \|\chi^-\|_\infty \quad \forall x \in \mathbb{R}^2. \]

Let \( M > 0 \) be such that

\[ \|\chi^-\|_\infty \leq M \quad \text{and} \quad \varphi'(t) \leq -\frac{1}{M} \quad \forall t \in [c,d]. \]
From assumption (30) we can find $\bar{\lambda} > 0$ such that $$H\left(-\frac{\theta \bar{p}}{\lambda} + b\right) \leq \alpha^- b + \beta^- + \eta \quad \forall|b| \leq M, \theta \geq \frac{1}{M}, \lambda \in (0, \bar{\lambda}).$$

Then for any $\lambda \in (0, \bar{\lambda})$ and at any point $x \in \mathbb{R}^2$ with $c < \bar{p}.x < d$, we have

$$\lambda \zeta_\lambda + H(D\zeta_\lambda) - \ell = \varphi - \beta^- - \eta + \lambda(\chi^- - \|\chi^-\|_\infty) + H\left(\frac{\phi'}{\lambda} + D\chi^-\right) - \ell$$

$$\leq \varphi - \beta^- - \eta + (\alpha^- D\chi^- + \beta^- + \eta) - \ell$$

$$\leq \varphi - \beta^- - \eta + (\ell - \bar{c} + \beta^- + \eta) - \ell \leq 0$$

where we have used the definition of $\bar{\lambda}$, (34) and the fact that $\bar{\delta} \leq \bar{c} - \beta^-$ respectively.

Let now $\lambda \in (0, \bar{\lambda})$, $\bar{x} \in \mathbb{R}^2$ such that $\bar{p}.\bar{x} = d$ and $\psi$ be a smooth test function such that $\zeta_\lambda - \psi$ has a local maximum at $\bar{x}$ on the set $\{c < \bar{p}.x \leq d\}$. Then there is some $\theta_\lambda \geq 0$ such that

$$D(\zeta_\lambda - \psi)(\bar{x}) = \theta_\lambda \bar{p}.$$

Arguing as above, we get

$$\lambda \zeta_\lambda + H(D\psi) - \ell = \varphi - \beta^- - \eta + \lambda(\chi^- - \|\chi^-\|_\infty) + H\left(\frac{\phi'}{\lambda} - \theta_\lambda \bar{p} + D\chi^-\right) - \ell$$

$$\leq \varphi - \beta^- - \eta + (\alpha^- \bar{p} + \beta^- + \eta) - \ell$$

$$\leq \varphi - \beta^- - \eta + (\ell - \bar{c} + \beta^- + \eta) - \ell \leq 0$$

Lemma 5.6 Let $w \in \mathcal{W}$, $\bar{w} : \mathbb{R} \to \mathbb{R}$ be such that $w(x) = \bar{w}(\bar{p}.x)$ and $\psi : \mathbb{R} \to \mathbb{R}$ be a smooth test function such that $\psi \leq \bar{w}$ (resp. $\psi \geq \bar{w}$) with an equality at $\bar{s} \in \mathbb{R}$. If $\pm \psi'(\bar{s}) > 0$, then

$$\bar{w}(\bar{s}) \geq \bar{c}(\bar{s}) - \beta^\pm$$

(resp. $\bar{w}(\bar{s}) \leq \bar{c}(\bar{s}) - \beta^\pm$),

where $\bar{c}$ is defined by (32).

Proof of Lemma 5.6: Let $\lambda_n \to 0$ be such that $(\lambda_n v_n := \lambda_n v_{\lambda_n})$ uniformly converges to $w$. To fix the ideas, we assume that there is some $\delta \in (0, 1/2)$ such that $\psi(t) < \bar{w}(t)$ for $t \in [\bar{s} - \delta, \bar{s} + \delta] \setminus \{\bar{s}\}$, $\psi'(\bar{s}) = \bar{w}(\bar{s})$ and $\psi'(t) > 0$ for $t \in [\bar{s} - \delta, \bar{s} + \delta]$.

Let $\chi^+$ be defined by (33). For $n$ large enough, the function

$$\zeta_n(x) = v_n(x) - \left(\frac{1}{\lambda_n} \psi(\bar{p}.x) + \chi^+(x)\right)$$

is $m \mathbb{Z}^2$—periodic for some $m \in \mathbb{N}^*$ in the set $\{|\bar{p}.x - \bar{s}| \leq \delta\}$. So $\zeta_n$ has a maximum point in $\{|\bar{p}.x - \bar{s}| \leq \delta\}$ at a point $x_n$ such that $|\alpha^+ x_n| \leq m$. In particular the sequence $(x_n)$ is bounded. Since the function $\chi^+$ is also bounded, $(x_n)$ converges, up to a subsequence, to a maximum point of $x \to w(x) - \psi(\bar{p}.x)$ in $\{|\bar{p}.x - \bar{s}| \leq \delta\}$. Hence $(\bar{p}.x_n)$ converges to $\bar{s}$ and $x_n$ is an interior maximum point of $\zeta_n$ for any $n$ large enough.
Since $v_n$ is the solution of (8) we have, for $n$ large enough,

$$
\lambda_n v_n(x_n) + \Phi \left( \frac{\psi'(\bar{p},x_n)}{\lambda_n} \bar{p} + D\chi^+(x_n) \right) - \ell(x_n) \leq 0.
$$

Arguing as in the proof of Lemma 5.5, for any $\eta > 0$ we have, for $n$ large enough:

$$
\lambda_n v_n(x_n) - \bar{c}(\bar{p},x_n) + \beta^+ - \eta \leq 0.
$$

Letting $n \to +\infty$ and then $\eta \to 0^+$ gives the desired result. □

**Corollary 5.7** Let $w \in \mathcal{W}$ and $\bar{w}$ be such that $w(x) = \bar{w}(\bar{p},x)$. If $\bar{w}$ has a point of increase (resp. decrease) at $\bar{s}$, then

$$
\bar{w}(\bar{s}) = \bar{c}(\bar{s}) - \beta^+ \quad \text{(resp. } \bar{w}(\bar{s}) = \bar{c}(\bar{s}) - \beta^-),
$$

where $\bar{c}$ is defined by (32). In particular, $\bar{w}$ lies in the intersection of the range of $s \to \bar{c}(s) - \beta^+$ and of the range of $s \to \bar{c}(s) - \beta^-$. 

**Proof**: Since $\bar{w}$ has a point of increase at $\bar{s}$, there are $s_n \to \bar{s}$ and $h_n \to 0^+$ such that $\bar{w}(s_n + h_n) > \bar{w}(s_n)$. Hence one can find some smooth functions $\phi_n$ and $\psi_n$ and points $a_n, b_n \in (s_n, s_n + h_n)$ such that

- $\phi_n \geq \bar{w}$ on $(s_n, s_n + h_n)$ with an equality at $a_n$ and $\phi''_n(a_n) > 0$,
- $\psi_n \leq \bar{w}$ on $(s_n, s_n + h_n)$ with an equality at $b_n$ and $\psi''_n(b_n) > 0$.

From Lemma 5.6 we have

$$
\bar{w}(a_n) \geq \bar{c}(a_n) - \beta^+ \quad \text{and} \quad \bar{w}(b_n) \leq \bar{c}(b_n) - \beta^+.
$$

Letting $n \to +\infty$ gives the result. □

Let $E$ be a closed subset of $\mathbb{R}^2$ and $\eta > 0$. We denote by $E + \eta B$ the set of points $x \in \mathbb{R}^2$ such that $d_E(x) \leq \eta$, where $d_E(x)$ denotes distance from $x$ to $E$. Recall that the integer $m \in \mathbb{N}^*$ is given by Lemma 5.4.

**Lemma 5.8** Let $w \in \mathcal{W}$ and $\lambda_n \to 0$ be such that $(\lambda_n v_{\lambda_n})$ uniformly converges to $w$ as $n \to +\infty$. Then for any $\theta \in (\min w, \max w)$, $\eta > 0$ sufficiently small and $n$ large enough, there is a Lipschitz continuous, $m \mathbb{Z}^2$-periodic function $\tilde{v}_{\lambda_n}$ which is a state-constraint viscosity sub-solution of (8) in $\{w \geq \theta\} + \eta B$ and such that $\lambda_n \tilde{v}_{\lambda_n} \geq \theta - \eta$ in $\{w \geq \theta\} + \eta B$.

**Proof**: Let $\bar{w}: \mathbb{R} \to \mathbb{R}$ be such that $w(x) = \bar{w}(\bar{p},x)$ and let $\theta \in (\min w, \max w)$. From Corollary 5.7 $\theta$ lies in the intersection of the ranges of $\bar{c} - \beta^+$ and of $\bar{c} - \beta^-$. Hence, perturbing slightly $\theta$ if necessary, we can assume without loss of generality that $\theta$ is a non critical value of $\bar{c} - \beta^+$ and of $\bar{c} - \beta^-$. Let $E^+ = \{w \geq \theta\}$. Since $w(x) = \bar{w}(\bar{p},x)$ is periodic and $\bar{p} \in \mathcal{P}$, the set $E^+$ is of the form

$$
E^+ = \{x \in \mathbb{R}^2 \mid \bar{p}, x \in I^+\}.
$$
where $I^+$ is a closed, periodic subset of $\mathbb{R}$ (the period is not 1 in general). From Corollary 5.7, $w(x) = \theta \in \{\bar{c}(x) - \beta^+, \bar{c}(x) - \beta^-\}$ for any $x \in \partial E^+$. The value $\theta$ being non critical for $\bar{c} - \beta^+$ and for $\bar{c} - \beta^-$, the sets $(\bar{c} - \beta^+)^{-1}(\theta)$ and $(\bar{c} - \beta^-)^{-1}(\theta)$ are locally finite and thus the set $I^+$ consists locally in a finite number of closed, disjoint intervals. Let $[a, b]$ be such an interval. Then $\bar{c}'(a) \neq 0$ and $\bar{c}'(b) \neq 0$. From Corollary 5.7 again, we can find $\eta \in (0, 1)$ such that

- $\bar{w}(s) = \bar{c}(s) - \beta^+$ and $\bar{c}'(s) > 0$ if $s \in [a - 2\eta, a]$
- $\bar{w}(s) = \bar{c}(s) - \beta^-$ and $\bar{c}'(s) < 0$ if $s \in [b, b + 2\eta]$

We also choose $\sigma > 0$ so small that, if we set

$$\varphi_b(s) := \bar{c}(s) - \sigma(b + \eta - s)^2$$

then $\varphi_b' < 0$ on $[b, b + 2\eta]$ and $\varphi_a' > 0$ on $[a - 2\eta, a]$. Then Lemma 5.5 states that, for any $n$ sufficiently large,

$$\xi^n_b(x) := \frac{1}{\lambda_n}(\varphi_b(\bar{p}.x) - \beta^- - \eta) + \chi^-(x) - \|\chi^-\|_\infty$$

is a state-constraint sub-solution in $\{b < x - y \leq b + \eta\}$ while

$$\xi^n_a(x) := \frac{1}{\lambda_n}(\varphi_a(\bar{p}.x) - \beta^+ - \eta) + \chi^+(x) - \|\chi^+\|_\infty$$

is a state-constraint sub-solution in $\{a - \eta \leq x - y < a\}$. Let us finally set

$$\tilde{v}_{\lambda_n}(x) = \begin{cases} \max\{v_{\lambda_n}(x) - \frac{\eta + \sigma\eta^4}{\lambda_n}, \xi^n_b(x)\} & \text{if } b < \bar{p}.x \leq b + \eta \\ \max\{v_{\lambda_n}(x) - \frac{\eta + \sigma\eta^4}{\lambda_n}, \xi^n_a(x)\} & \text{if } a - \eta \leq \bar{p}.x < a \\ v_{\lambda_n}(x) - \frac{\eta + \sigma\eta^4}{\lambda_n} & \text{if } a \leq \bar{p}.x \leq b \end{cases}$$

We note that, if $\bar{p}.x = b + \eta$, then

$$\lim_{n \to +\infty} \lambda_n(v_{\lambda_n}(x) - \frac{\eta + \sigma\eta^4}{\lambda_n}) = \bar{c}(b + \eta) - \beta^- - \eta - \sigma\eta^4$$

and

$$\lim_{n \to +\infty} \lambda_n\xi^n_b(x) = \bar{c}(b + \eta) - \beta^- - \eta,$$

while, if $\bar{p}.x = b$, then

$$\lim_{n \to +\infty} \lambda_n(v_{\lambda_n}(x) - \frac{\eta + \sigma\eta^4}{\lambda_n}) = \bar{c}(b) - \beta^- - \eta - \sigma\eta^4$$

and

$$\lim_{n \to +\infty} \lambda_n\xi^n_b(x) = \bar{c}(b) - \beta^+ - \eta - \sigma\eta^2.$$

Since $\eta \in (0, 1)$, for $n$ large enough we have

$$\tilde{v}_{\lambda_n}(x) = v_{\lambda_n}(x) - (\eta + \sigma\eta^4)/\lambda_n \text{ for } \bar{p}.x \text{ close to } b$$

and

$$\tilde{v}_{\lambda_n}(x) = \xi^n_b(x) \text{ for } \bar{p}.x \text{ close to } b + \sigma$$

Therefore $\tilde{v}_{\lambda_n}$ is a Lipschitz continuous state-constraint sub-solution of (8) in $\{a < \bar{p}.x \leq b + \eta\}$ if $n$ is large enough. Arguing in the same way we can show that $\tilde{v}_{\lambda_n}$ is a sub-solution.
of \([8]\) with state-constraints in \(\{a - \eta \leq \bar{p}.x < b\}\) if \(n\) is large enough. Doing the same construction on each connected component of \(I^+\) then completes the proof thanks to the periodicity of \(I^+\). □

**Proof of the existence of a limit of the \((v_{\lambda})\) for smooth \(\ell\)'s:** Let us fix \(w \in \mathcal{W}\) and let \(\lambda_n \to 0\) be such that \(\lambda_n v_{\lambda_n} \to \bar{w}\) uniformly. Let \(m \in \mathbb{N}_+\) be defined by Lemma 5.4, \(\theta \in (\min \bar{w}, \max \bar{w})\) and let \(\eta > 0\) be sufficiently small. From Lemma 5.8, for \(n\) large enough one can find some Lipschitz continuous, \(m\mathbb{Z}^2\)–periodic function \(\tilde{v}_{\lambda_n}\) which is a sub-solution with state-constraints in the set \(K := \{w \geq \theta\} + \eta B\) of \([8]\) and which is such that \(\tilde{v}_{\lambda_n} \geq \theta - \eta\) in \(\{w \geq \theta\} + \eta B\). Let us fix such a \(n\).

For \(\sigma, \mu > 0\) let us consider a minimum point \((x_{\mu,\sigma}, x'_{\mu,\sigma})\) on the set \(\mathbb{R}^2 \times K\) of the function

\[
\Phi_{\sigma}(x, x') = v_{\mu}(x) - \tilde{v}_{\lambda_n}(x') - \frac{1}{2\sigma} |x - x'|^2.
\]

Since \(v_{\mu}\) and \(\tilde{v}_{\lambda_n}\) are \(m\mathbb{Z}^2\)–periodic, we can assume that \((x_{\mu,\sigma})\) and \((x'_{\mu,\sigma})\) are bounded and converge up to some subsequence to some \(x_{\mu}\) as \(\sigma \to 0\). Then \(x_{\mu}\) is a minimum point of \(v_{\mu} - \tilde{v}_{\lambda_n}\) on \(K\):

\[
\min_{x \in K}(v_{\mu} - \tilde{v}_{\lambda_n})(x) = (v_{\mu} - \tilde{v}_{\lambda_n})(x_{\mu}). \tag{35}
\]

Since \(v_{\mu}\) is a solution of \([8]\) and \(\tilde{v}_{\lambda_n}\) is a subsolution with state constraints in \(K\) of \([8]\) we have

\[
\mu v_{\mu}(x_{\mu,\sigma}) + H \left(\frac{1}{\sigma}(x_{\mu,\sigma} - x'_{\mu,\sigma})\right) - \ell(x_{\mu,\sigma}) \geq 0
\]

while

\[
\lambda_n \tilde{v}_{\lambda_n}(x'_{\mu,\sigma}) + H \left(\frac{1}{\sigma}(x_{\mu,\sigma} - x'_{\mu,\sigma})\right) - \ell(x'_{\mu,\sigma}) \leq 0
\]

where

\[
|x_{\mu,\sigma} - x'_{\mu,\sigma}| \leq 2 \left(\|v_{\mu}\|_{\infty} + \|\tilde{v}_{\lambda_n}\|_{\infty}\right)^{\frac{1}{2}} \sqrt{\sigma}.
\]

This implies that

\[
\mu v_{\mu}(x_{\mu,\sigma}) - \lambda_n \tilde{v}_{\lambda_n}(x'_{\mu,\sigma}) \geq -2Lip(\ell) \left(\|v_{\mu}\|_{\infty} + \|\tilde{v}_{\lambda_n}\|_{\infty}\right)^{\frac{1}{2}} \sqrt{\sigma}.
\]

Letting \(\sigma \to 0\) and using the definition \(\tilde{v}_{\lambda_n}\) leads to

\[
\mu v_{\mu}(x_{\mu}) \geq \lambda_n \tilde{v}_{\lambda_n}(x_{\mu}) \geq \theta - \eta. \tag{36}
\]

Let now \(w' \in \mathcal{W}\) and \(\mu_p \to 0\) be such that \(\mu_p v_{\mu_p} \to w'\) uniformly. Then

\[
\min_{K} w' = \lim_{p} \min_{K} \mu_p v_{\mu_p} \geq \lim_{p} \inf_{K} \mu_p (v_{\mu_p} - \tilde{v}_{\lambda_n}) = \lim_{p} \inf_{K} \mu_p (v_{\mu_p} - \tilde{v}_{\lambda_n})(x_{\mu_p}),
\]

where the last equality comes from (35). Note that, from (36), we have

\[
\lim_{p} \inf_{K} \mu_p (v_{\mu_p} - \tilde{v}_{\lambda_n})(x_{\mu_p}) \geq \theta - \eta - \lim_{p} \sup_{K} \mu_p \tilde{v}_{\lambda_n}(x_{\mu_p}) = \theta - \eta.
\]

So \(\min_{K} w' \geq \theta - \eta\). Letting \(\varepsilon \to 0\) then gives

\[
w' \geq \theta \quad \text{in } \{w \geq \theta\} \quad \forall \theta \in (\min w, \max w). \tag{37}
\]
Hence we have established that \( w' \geq w \). Reversing the roles of \( w \) and \( w' \) finally shows \( w = w' \), i.e., that \( \mathcal{W} \) is a singleton. □

**Proof of the existence of a limit of the \((v_\lambda)\) for general \(\ell's\):** We proceed by approximation. Let \((\ell_k)\) be a sequence of smooth periodic functions converging to \(\ell\) as \( k \to +\infty \). Let \(w^k_\lambda\) be the unique bounded solution to
\[
\lambda w^k_\lambda + H(Dw^k_\lambda) - \ell_k = 0 \quad \text{in } \mathbb{R}^2.
\]
Then from the comparison principle we have:
\[
\|w^k_\lambda - w_\lambda\|_\infty \leq \|\ell_k - \ell\|_\infty \quad \forall k \geq 0, \forall \lambda > 0.
\]
(38)
Since \(\ell_k\) is smooth, we already know that \(w^k_\lambda\) converges to a limit \(w^k\) as \(\lambda \to 0^+\). From (38) we easily see that \((w^k)\) is a Cauchy sequence. Hence \((w^k)\) uniformly converges to some continuous periodic function \(w\). Since
\[
\|w - w_\lambda\|_\infty \leq \|w - w^k\|_\infty + \|w^k - w^k_\lambda\|_\infty + \|w^k_\lambda - w_\lambda\|_\infty,
\]
inequality (38) shows that \(w_\lambda\) converges to \(w\) as \(\lambda \to 0^+\).

Let us now assume that \(w\) is not constant. Then \(w^k\) is not constant for \(k\) large enough. Since the \(\ell_k\) are smooth there is some \(\bar{p}_k \in \mathcal{P}_0\) and some \(\bar{w}_k : \mathbb{R} \to \mathbb{R}\) such that \(w^k(x) = \bar{w}_k(\bar{p}_k,x)\). From assumption (29) the set \(\mathcal{P}_0\) is finite. So we can as well assume that \(\bar{p}_k\) is constant: \(\bar{p}_k = \bar{p}\) for all \(k \geq 0\) where \(\bar{p} \in \mathcal{P}_0\). We note that \(\bar{w}_k\) uniformly converges to \(\bar{w}\).

Let now \(\bar{s}\) be a point of increase of \(\bar{w}\): there exists a sequence \(s_n \to s\) and a sequence \(h_n \to 0^+\) such that \(\bar{w}(s_n + h_n) > \bar{w}(s_n)\). Let us fix \(n\). Then for \(k\) large enough, \(\bar{w}_k(s_n + h_n) > \bar{w}_k(s_n)\). This means that there is a point of increase \(t_{nk} \in (s_n, s_n + h_n)\) for \(\bar{w}_k\). Hence, from Corollary 5.7
\[
\bar{w}_k(t_{nk}) = \frac{1}{T(\bar{p})} \int_0^{T(\bar{p})} \ell_k(t_{nk}\bar{p} + t\alpha(\bar{p}))dt - \beta(\bar{p}) .
\]
(Indeed the quantities \(T(\bar{p})\), \(\alpha(\bar{p})\), \(\beta(\bar{p})\) only depend on \(H\) and \(\bar{p}\), which are fixed here). Letting first \(t_{nk} \to t_n \in [s_n, s_n + h_n]\) up to a subsequence as \(k \to +\infty\), and then \(t_n \to \bar{s}\) gives the desired equality:
\[
\bar{w}(\bar{s}) = \frac{1}{T(\bar{p})} \int_0^{T(\bar{p})} \ell(\bar{s}\bar{p} + t\alpha(\bar{p}))dt - \beta(\bar{p}) .
\]
The proof of the symmetric equality in the case of decrease can be obtained in the same way. □

**Proof of the existence of a limit of the \((u(\cdot,t)/t)\):** We again assume that \(\ell\) is a smooth function: this restriction can be removed exactly as for the \((v_\lambda)\). Let \(w\) be the limit of the \((\lambda v_\lambda)\) and \(\bar{p} \in \mathcal{P}_0\) and \(\bar{w} : \mathbb{R} \to \mathbb{R}\) be such that \(w(x) = \bar{w}(\bar{p},x)\) for any \(x \in \mathbb{R}^2\).

We first note that
\[
\min_x w(x) \leq \liminf_{t \to +\infty} \min_x \frac{u(x,t)}{t} \leq \limsup_{t \to +\infty} \min_x \frac{u(x,t)}{t} \leq \max_x w(x) .
\]
(39)
Indeed, let $\eta > 0$ and $\lambda$ small enough such that $\lambda v_\lambda \leq \max w + \eta$. Then the map
\[
Z(x, t) = t(\max w + \eta) + v_\lambda + \|v_\lambda\|_\infty
\]
is a supersolution of (8). By comparison we get
\[
\limsup_{t \to +\infty} \max_x \frac{u(x, t)}{t} \leq \limsup_{t \to +\infty} \max_x \frac{Z(x, t)}{t} = \max w + \eta.
\]
Whence the right-hand side of (39) since $\eta$ is arbitrary. The left-hand side can be proved by symmetric arguments.

Let now $\theta \in (\min w, \max w)$. From Lemma 5.8, for any $\eta > 0$ and for any $\lambda > 0$ small enough, there is some Lipschitz continuous, periodic function $\tilde{v}_\lambda$ which is state-constraint sub-solution of (8) in $K := \{w \geq \theta\} + \eta B$ and which is such that $\tilde{v}_\lambda \geq \theta - \eta$ in $K$.

As in the proof of Theorem 4.1 one can check that
\[
Z(x, t) = t(\theta - \eta) + \tilde{v}_\lambda(x) - \|\tilde{v}_\lambda\|_\infty
\]
is a state-constraint sub-solution of (7) in $K \times (0, +\infty)$. By comparison we get
\[
u(x, t) \geq Z(x, t) \quad \forall (x, t) \in K \times [0, +\infty).
\]
This implies that
\[
\liminf_{t \to +\infty} \frac{u(x, t)}{t} \geq \theta - \eta \quad \text{in } K.
\]
Since $\eta$ is arbitrary, we have
\[
\liminf_{t \to +\infty} \frac{u(x, t)}{t} \geq \theta \quad \text{in } \{w \geq \theta\} \quad \forall \theta \in (\min w, \max w). \tag{40}
\]
In the same way, working with $-u$ instead of $u$, we can prove that
\[
\limsup_{t \to +\infty} \frac{u(x, t)}{t} \leq \theta \quad \text{in } \{w \leq \theta\} \quad \forall \theta \in (\min w, \max w). \tag{41}
\]
Combining (39), (40) and (41) finally gives the equality
\[
\lim_{t \to +\infty} \frac{u(x, t)}{t} = w(x) \quad \forall x \in \mathbb{R}^2.
\]
\[\square\]

6 Conclusion and open problems

In this paper we have addressed two questions: the first one is the existence of an ergodic limit for Hamilton-Jacobi equations with non convex Hamiltonians; the second one is related to the existence of a (nonconstant) limit for the solutions of (7) and (8). Although
our results shed some new light on these problems, we are very far from having a complete picture and many very intriguing questions remain open.

First the analysis in higher dimension has to be invented: we suspect that our rigidity result (Lemma 3.1) still holds for \( N \geq 3 \). However the consequence of such a result on the ergodic problem is not clear.

Second, even in dimension 2, our analysis is not complete:

- when \( \mathcal{P} = \emptyset \), we have no characterization of the limit constant \( c \). In particular, we do not know if one can associate to the constant \( c \) a cell-problem of the form \([5] \).
- We are able to treat the resonant case only under a global Lipschitz continuity assumption on \( H \): for instance we cannot deal with \( H(p_1, p_2) = -p_1^2 + p_2^2 \).
- Even when we know in the resonant case that there exist a limit and that this limit is of the form \( w = \bar{w}(\bar{p}, x) \) for some \( \bar{p} \in \mathcal{P} \), we do not know how this vector \( \bar{p} \) is related to the function \( \ell \). For instance, when \( H(p_1, p_2) = -|p_1 + p_2| \), then \( \mathcal{P} = \{\pm 1, \pm 1\} \); is there a criterium on \( \ell \) to explain that the limit is of the form \( \bar{w}(x - y) \) or of the form \( \bar{\ell}(x + y) \)?
- Finally, although we can compute explicitly the limit function \( \bar{w} \) at points \( s \) where \( \bar{w} \) has a point of increase or of decrease, we do not know how to compute \( \bar{w} \) at points where \( \bar{w} \) is locally constant. In particular what are the maxima and minima of \( \bar{w} \)?

References


