Appendix

A Some Consequences of Egorov's Theorem

Let us first recall the statement of Egorov's theorem :

Theorem A.1 *Let (X, μ) be some measure space with finite positive measure. Consider a sequence (g_n) such that $g_n \to g$ almost everywhere. Then, for each $\varepsilon > 0$, there exists a measurable $E \subset X$ such that*

$$\mu(X \setminus E) < \varepsilon \quad \text{ and } g_n \to g \text{ uniformly on } E.$$

A.1 The Product Limit Theorem

We now give a corollary of Egorov's theorem, established by DiPerna and Lions [44], which is used repeatedly for the study of the Boltzmann equation and its hydrodynamic limits.

Proposition A.2 *Let (X, μ) be some measure space with finite positive measure. Consider two sequences of real-valued measurable functions defined on X, denoted (f_n) and (g_n). If (g_n) is bounded in $L^\infty(X)$ such that $g_n \to g$ almost everywhere, and $f_n \rightharpoonup f$ weakly in $L^1(X)$ then $f_n g_n \rightharpoonup fg$ weakly in $L^1(X)$.*

Proof. Without loss of generality, we can assume that $g = 0$.

Let δ be any fixed nonnegative constant. The sequence (f_n), being relatively weakly compact in $L^1(X)$, is equiintegrable. Thus, by picking $\alpha > 0$ sufficiently small, one has for every measurable set A such that $\mu(A) < \alpha$,

$$\int_A |f_n - f|(x) d\mu(x) < \delta \text{ uniformly in } n. \tag{A.1}$$

Fix such a constant α. By Egorov's theorem, as (g_n) is bounded in $L^\infty(X)$, and $g_n \to 0$ almost everywhere, there exists a measurable set A such that $\mu(A) < \alpha$ and

$$g_n \to 0 \text{ as } n \to \infty \text{ uniformly on } X \setminus A. \tag{A.2}$$

Fix such a set A. Then,

$$\int |(f_n - f)g_n| d\mu = \int_A |(f_n - f)g_n| d\mu + \int_{X\setminus A} |(f_n - f)g_n| d\mu$$

By (A.1) the first term in the right-hand side satisfies

$$\int_A |(f_n - f)g_n| d\mu \le \|g\|_{L^\infty(X)} \int_A |f_n - f| d\mu \le \|g\|_{L^\infty(X)} \delta,$$

whereas by (A.2) the second term converges to 0 as $n \to \infty$:

$$\int_{X\setminus A} |(f_n - f)g_n| d\mu \le \left(\sup_n \|f_n - f\|_{L^1(X)}\right) \|g_n\|_{L^\infty(X\setminus A)} \to 0.$$

Finally

$$\lim_{n\to\infty} \int |(f_n - f)g_n| d\mu \le \|g\|_{L^\infty(X)} \delta,$$

but δ was arbitrary, whence Proposition A.2 holds. □

A.2 An Asymptotic Result of Variables Separating

For the study of boundary conditions, we also need the following variant of the Product Limit theorem, which has been proved in [82] :

Proposition A.3 *Let (X, μ_X) and (Y, μ_Y) be two measure spaces of finite measures. Consider a family of nonnegative functions (χ_ε) uniformly bounded in $L^\infty(X \times Y)$ converging almost everywhere to 1 on $X \times Y$, and a family (ρ_ε) of nonnegative functions of $L^1(X)$ such that*

$$(\chi_\varepsilon \rho_\varepsilon) \textit{ is relatively weakly compact in } L^1(X \times Y)$$

Then any limit point ρ of $(\chi_\varepsilon \rho_\varepsilon)$ belongs to $L^1(X)$, namely does not depend on $y \in Y$.

Before giving the proof, let us notice that if (ρ_ε) were supposed to be relatively weakly compact in $L^1(X \times Y)$ then the conclusion of the lemma would be straightforward.

Proof. Consider a subsequence of $(\chi_\varepsilon \rho_\varepsilon)$ (still denoted $(\chi_\varepsilon \rho_\varepsilon)$) converging to ρ as $\varepsilon \to 0$. Let δ be any fixed nonnegative constant. As χ_ε converges almost everywhere to 1, there exist $A \subset X \times Y$ with $|X \times Y \setminus A| \le \delta$, and $\varepsilon_0 > 0$ such that

$$\forall \varepsilon \le \varepsilon_0, \quad \chi_{\varepsilon|A} \ge \frac{1}{2}$$

By the Product Limit theorem, as $\left(\frac{\mathbf{1}_A}{\chi_\varepsilon}\right)_{\varepsilon\leq\varepsilon_0}$ is bounded in $L^\infty(X \times Y)$ and converges a.e. to $\mathbf{1}_A$,

$$\rho_\varepsilon \mathbf{1}_A = \rho_\varepsilon \chi_\varepsilon \frac{\mathbf{1}_A}{\chi_\varepsilon} \rightharpoonup \rho \mathbf{1}_A \text{ weakly in } L^1(X \times Y).$$

Define

$$A_X = \left\{ x \in X \,/\, \int \mathbf{1}_A(x,y)d\mu_Y(y) \geq \frac{\mu_Y(Y)}{2} \right\}.$$

From Bienaymé Tchebichev's inequality

$$\begin{aligned} \mathbf{1}_{A_X}(x)\rho_\varepsilon(x) &\leq \mathbf{1}_{A_X}(x)\rho_\varepsilon(x)\frac{2\int \mathbf{1}_A(x,y)d\mu_Y(y)}{\mu_Y(Y)} \\ &= \frac{2\mathbf{1}_{A_X}}{\mu_Y(Y)} \int \rho_\varepsilon(x)\mathbf{1}_A(x,y)d\mu_Y(y) \end{aligned} \tag{A.3}$$

we deduce that $(\mathbf{1}_{A_X}\rho_\varepsilon)$ is weakly compact in $L^1(X)$. Then, up to extraction of a subsequence,

$$\mathbf{1}_{A_X}\rho_\varepsilon \rightharpoonup \tilde{\rho} \text{ weakly in } L^1(X)$$

By the Product Limit theorem, as (χ_ε) is bounded in $L^\infty(X \times Y)$ and converges a.e. to 1,

$$\mathbf{1}_{A_X}\rho_\varepsilon\chi_\varepsilon \rightharpoonup \tilde{\rho} \text{ weakly in } L^1(X \times Y)$$

from which we deduce that

$$\rho \mathbf{1}_{A_X} = \tilde{\rho} \in L^1(X) \tag{A.4}$$

On the other hand, if $x \notin A_X$,

$$\int \mathbf{1}_{X\times Y\setminus A}(x,y)d\mu_Y(y) = \int (1 - \mathbf{1}_A)(x,y)d\mu_Y(y) \geq \frac{\mu_Y(Y)}{2}$$

Then,

$$\begin{aligned} \int \mathbf{1}_{X\setminus A_X}(x)d\mu_X(x) &\leq \int \mathbf{1}_{X\setminus A_X}(x)\frac{2\int \mathbf{1}_{X\times Y\setminus A}(x,y)d\mu_Y(y)}{\mu_Y(Y)}d\mu_X(x) \\ &\leq \frac{2}{\mu_Y(Y)}\delta \end{aligned} \tag{A.5}$$

As there exists A_X satisfying (A.4) and (A.5) for all $\delta > 0$, ρ depends only on the variable x, and thus $\rho \in L^1(X)$. □

B Classical Trace Results on the Solutions of Transport Equations

In order to deal with kinetic equations involving reflection conditions at the boundary, we need the following fundamental result due to Cessenat [32] following Bardos [3] and Ukai [104], which allows to define the trace of any weak solution to the free-transport equation in a very general setting.

B.1 Definition of the Trace

Proposition B.1 *For any smooth subset Ω of $\mathbf{R}^3$, denote by $W^p(\Omega)$ the functional space*

$$\{f \in L^p(\mathbf{R} \times \Omega \times \mathbf{R}^3) \,/\, (\mathrm{St}\partial_t + v \cdot \nabla_x) f \in L^p(\mathbf{R} \times \Omega \times \mathbf{R}^3)\}.$$

Then the trace operator

$$\gamma : f \in W^p(\Omega) \mapsto f_{|\partial\Omega} \in L^p(\mathbf{R} \times \partial\Omega \times \mathbf{R}^3, dt d\sigma_x |v \cdot n(x)|^2 (1+|v|)^{-1} dv)$$

is continuous.

Proof. Without loss of generality, we can restrict our attention to nonnegative functions.

By Green's formula, we have for any bounded function $\varphi \in C^1(\bar{\Omega} \times \mathbf{R}^3)$,

$$\begin{aligned} &p \iiint \varphi(x,v) f^{p-1} (\mathrm{St}\partial_t + v \cdot \nabla_x) f(t,x,v) dt dx dv \\ &+ \iiint (v \cdot \nabla_x) \varphi(x,v) f^p(t,x,v) dt dx dv \\ &= \iiint \varphi(x,v) f^p(t,x,v) (v \cdot n(x)) dt d\sigma_x dv \end{aligned} \tag{B.6}$$

As Ω is assumed to be smooth, there exists some vector field $n \in W^{1,\infty}(\bar{\Omega})$ which coincides with the outward unit normal at the boundary. Thus, choosing

$$\varphi(x,v) = \frac{(v \cdot n(x))}{(1+|v|^2)^{1/2}}$$

we get

$$\begin{aligned} &\left\| f_{|\partial\Omega} \right\|_{L^p(dt d\sigma_x |v \cdot n(x)|^2 (1+|v|)^{-1} dv)} \\ &\leq C \left(\|f\|_{L^p(dt dx dv)} + \|(\mathrm{St} + v \cdot \nabla_x) f\|_{L^p(dt dx dv)} \right), \end{aligned} \tag{B.7}$$

which concludes the proof. □

B.2 Free Transport with Reflection at the Boundary

In order to extend regularity and dispersion results to free transport with reflection at the boundary, we have then to establish a priori estimates on the incoming flux (which is defined in terms of the outgoing flux).

Proposition B.2 *Let Ω be any smooth subset of $\mathbf{R}^3$, and $f \in L^1(\mathbf{R} \times \Omega \times \mathbf{R}^3)$ be a solution to the free-transport equation*

$$\mathrm{St}\partial_t f + v \cdot \nabla_x f = S$$

supplemented with Maxwell's boundary condition

$$f_{|\Sigma_-} = (1-\alpha)Lf_{|\Sigma_+} + \alpha K f_{|\Sigma_+} \quad on\ \Sigma_-$$

where the outgoing/incoming sets Σ_+ *and* Σ_- *at the boundary* $\partial\Omega$ *are defined by*

$$\Sigma_\pm = \{(x,v) \in \partial\Omega \times \mathbf{R}^3, \quad \pm n(x)\cdot v \ > 0\},$$

the local reflection operator L *is given by*

$$Lf(x,v) = f(x, v - 2(v\cdot n(x))n(x)),$$

and the diffuse reflection operator K *is given by*

$$Kf(x,v) = M_w(v) \int_{v'.n(x)>0} f(x,v')\,(v'\cdot n(x))dv'$$

for some normalized Maxwellian distribution M_w *characterizing the state of the wall.*

Then, there exists some nonnegative constant C *(depending on the Lipschitz norm of* n*) such that*

$$\iiint f_{|\Sigma}|v\cdot n(x)|dvdxdt \le \frac{C}{\alpha}(\|f\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)} + \|S\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)}).$$

Proof. The smoothness assumption made on the boundary implies the existence of a vector field n which belongs to $W^{1,\infty}(\bar{\Omega})$ and coincides with the outward unit normal vector at the boundary. Therefore, multiplying the transport equation by $(n(x)\cdot v)/(1+|v|)$ and integrating with respect to all variables, we get

$$\iiint \frac{v\cdot n(x)}{1+|v|}(v\cdot\nabla_x)f dvdxdt = \iiint \frac{v\cdot n(x)}{1+|v|} S dvdxdt$$

Then, using Green's formula, we get

$$\iiint f_{|\Sigma}\frac{(v\cdot n(x))^2}{1+|v|}dvd\sigma_x dt \le C(\|f\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)} + \|S\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)}).$$

In particular

$$\alpha\iiint_{v\cdot n<0} Kf_{|\Sigma_+}\frac{(v\cdot n(x))^2}{1+|v|}dvd\sigma_x dt \le C(\|f\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)} + \|S\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)}).$$

By definition of K, we have the spreading condition

$$\int_{v\cdot n(x)>0} f_{|\Sigma_+}(v\cdot n(x))dv \le \kappa_0 \int_{v\cdot n(x)<0} Kf_{|\Sigma_+}\frac{(v\cdot n(x))^2}{1+|v|}dv.$$

We then deduce that

$$\iiint_{v\cdot n(x)>0} f_{|\Sigma_+}(v\cdot n(x))dvd\sigma_x dt \le \frac{C\kappa_0}{\alpha}(\|f\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)} + \|S\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)}).$$

On the other hand, the normalization condition on M_w implies

$$-\int_{v\cdot n(x)<0} f_{|\Sigma}(v\cdot n(x))dv = \int_{v\cdot n(x)>0} f_{|\Sigma}(v\cdot n(x))dv.$$

We therefore have

$$\iiint f_{|\Sigma}|v\cdot n(x)|dvd\sigma_x dt \leq \frac{2C\kappa_0}{\alpha}(\|f\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)} + \|S\|_{L^1(\mathbf{R}\times\Omega\times\mathbf{R}^3)}).$$

which is the expected inequality. □

Remark B.3 *Note that, in the case of a purely specular reflection, we do not obtain such a bound on the trace. Nevertheless, because the specular reflection is completely transparent in the weak formulation of the transport equation (by obvious symmetry properties), the study is actually much easier (very similar to the case when there is no boundary). We refer to the work [63] by Hamdache for a careful treatment of that case.*

C Some Consequences of Chacon's Biting Lemma

Let us first recall the statement of Chacon's Biting Lemma [21]:

Theorem C.1 *Let (X,μ) be some measure space with finite positive measure. Consider a sequence (g_n) bounded in $L^1(X)$. Then, there exists a subsequence (g'_n) of (g_n) and some function $g\in L^1(X)$ such that $g'_n\to g$ in the sense of Chacon, meaning that for each $\varepsilon>0$, there exists a measurable $E\subset X$ such that $\mu(X\setminus E)\leq\varepsilon$ and*

$$g'_n \to g \text{ in } L^1(E).$$

C.1 From Renormalized Convergence to Chacon's Convergence

We now give an extension of Chacon's Biting Lemma to the space of measurable and almost everywhere finite functions, established by Mischler [85] to study the traces of kinetic equations in the framework of renormalized solutions.

This requires the following definition of *renormalized convergence* (see [85] and the references therein for basic results concerning renormalized convergence) :

Definition C.2 *A sequence (g_n) of measurable and almost everywhere finite functions is said to converge in renormalized sense to some measurable and almost everywhere finite function g, if for any increasing sequence $\Gamma_M\in C\cap L^\infty(\mathbf{R}^+)$ converging simply to $\mathrm{Id}_{|\mathbf{R}^+}$ as $M\to\infty$, and any subsequence (g'_n) of (g_n), there exists a sequence γ_M and a subsequence (g''_n) of (g'_n) such that*

$$\Gamma_M(g''_n) \rightharpoonup \gamma_M \text{ weakly-* in } L^\infty(X) \text{ and } \gamma_M\to g \text{ a.e. in } X.$$

We have then the following relation between renormalized convergence and convergence in the sense of Chacon (see [85]) :

Proposition C.3 *Let (X, μ) be some measure space with finite positive measure. Consider a sequence (g_n) of measurable and almost everywhere finite functions, such that*

$$g_n \to g \text{ in renormalized sense,}$$

where g is some measurable and almost everywhere finite function. Then,

$$\lim_{M\to+\infty} \sup_n \mu(\{g_n \geq M\}) = 0,$$

and there exists a subsequence (g'_n) of (g_n) such that $g'_n \to g$ in the sense of Chacon.

Proof. Without loss of generality, we can restrict our attention to nonnegative functions.

• We first prove the L^0 bound, arguing by contradiction. Since g is a measurable and almost everywhere finite function, for any arbitrary $\varepsilon > 0$, there exists $E \subset X$ such that $\mu(X \setminus E) < \varepsilon$ and $g \in L^1(E)$.

If there is no m such that

$$\sup_n \mu(\{g_n \geq m\}) < \varepsilon$$

there exists an increasing sequence (n_m) such that

$$\forall m \in \mathbf{N}, \quad \mu(\{g_{n_m} \geq m\}) \geq \varepsilon.$$

Therefore, for any $l \in \mathbf{N}$ and any $m \geq l$,

$$\int_E \Gamma_l(g_{n_m}) d\mu \geq l\varepsilon,$$

where Γ_l is some smooth version of the truncation $x \mapsto \min(x, l)$. Passing to the limit $m \to \infty$ leads to

$$\int_E g d\mu \geq \int_E \gamma_l d\mu \geq \varepsilon l,$$

by definition of the renormalized convergence. Thus

$$\int_E g d\mu \geq \lim_{l\to\infty} \varepsilon l,$$

which gives the expected contradiction.

• We have then to prove the convergence in the sense of Chacon. Given $\varepsilon > 0$, one can choose $E \subset X$ such that $\mu(X \setminus E) < \varepsilon$ and $g \in L^1(E)$.

We construct a first subsequence (n_l) such that

$$\int_E \Gamma_l(g_{n_l})d\mu \leq \int_E g d\mu + \frac{1}{l}.$$

Then, for any $m \leq l$, $\Gamma_m(g_{n_l}) \leq \Gamma_l(g_{n_l})$ so that

$$g = \limsup_{m\to\infty} \gamma_m \leq \limsup_{m\to\infty} \liminf_{l\to\infty} \Gamma_l(g_{n_l}),$$

where the lim inf is taken in the sense of Chacon. By Fatou's lemma and the definition of the renormalized convergence, we also have

$$\forall A \subset X, \quad \int_A \limsup_{l\to\infty} \Gamma_l(g_{n_l})d\mu \leq \limsup_{l\to\infty} \int_A \Gamma_l(g_{n_l})d\mu \leq \int_A g d\mu.$$

Combining all these results show that

$$\Gamma_l(g_{n_l}) \to g \text{ in the sense of Chacon on } E.$$

In other words, there exists E' such that $\mu(E \setminus E') < \varepsilon$ and

$$\Gamma_l(g_{n_l}) \rightharpoonup g \text{ weakly in } L^1(E').$$

Furthermore, since (g_n) is bounded in L^0, one can choose a second subsequence (still denoted (g_{n_l})) such that the sets Z_L defined by

$$Z_L = \{\exists l \geq L \,/\, g_{n_l} \neq \Gamma_l(g_{n_l})\}$$

satisfy

$$\mu(Z_L) \leq \sum_{l\geq L} \mu(\{g_{n_l} > l\}) \to 0 \text{ as } L \to \infty.$$

Finally, choosing L large enough such that $\mu(Z_L) < \varepsilon$, and setting $E'' = E' \setminus Z_L$, we obtain

$$\mu(X \setminus E'') < 3\varepsilon \text{ and } g_{n_l} \rightharpoonup g \text{ weakly in } L^1(E'').$$

We conclude thanks to a diagonal process. □

C.2 A Result of Partial Equiintegrability

In order to characterize the limiting incoming flux in Maxwell's boundary condition, we also need the following variant of the previous result, also established in [85].

Proposition C.4 *Let (X, μ_X) be some measure space with finite positive measure, and $(\mu_Y(x))_{x\in X}$ a family of probability measures on the space Y, and denote $\langle g\rangle_Y = \int g d\mu_Y$.*

Let $h \in C(\mathbf{R}^+, \mathbf{R}^+)$ be some convex function of class $C^2(\mathbf{R}^+_*)$ with superlinear growth at infinity, and such that $H(s,t) \equiv (h(t) - h(s))(t-s)$ is convex.

Consider a sequence (g_n) of measurable nonnegative and almost everywhere finite functions on $X \times Y$, such that

$$\begin{aligned} &\int \Big(\langle h(g_n) \rangle_Y - h\left(\langle g_n \rangle_Y \right) \Big) d\mu_X \leq C, \\ &\langle g_n \rangle_Y \to \bar{g} \textit{ in renormalized sense on } X \end{aligned} \tag{C.8}$$

Then there exists $g \in L^1(X \times Y, d\mu_X(x) d\mu_Y(x,y))$ and a subsequence (g'_n) of (g_n) such that, for every $\varepsilon > 0$, one can find some $E \subset X$ with

$$\mu_X(X \setminus E) < \varepsilon \textit{ and } g'_n \rightharpoonup g \textit{ weakly in } L^1(E \times Y).$$

In particular, $\bar{g}(x) = \langle g \rangle_Y$ almost everywhere.

Furthermore

$$\int \Big(\langle h(g) \rangle_Y - h\left(\langle g \rangle_Y \right) \Big) d\mu_X \leq C.$$

Proof. The point to be understood here is how the (convex) functional which generalizes the Darrozès-Guiraud information allows to gain some equiintegrability with respect to y, and thus to establish the convergence of some integral quantities.

• By Proposition C.3, we deduce from the renormalized convergence in (C.8) that, up to extraction of a subsequence,

$$\langle g_n \rangle_Y \to \bar{g} \text{ in the sense of Chacon.}$$

In particular, for any $\varepsilon > 0$, there exists $A \subset X$ such that

$$\mu_X(X \setminus A) < \varepsilon \quad \text{ and } \langle g_n \rangle_Y \to \bar{g} \text{ weakly in } L^1(A).$$

Thanks to Dunford-Pettis' lemma, there is therefore a (nonnegative increasing) convex function Φ with superlinear growth at infinity such that $\Phi(0) = 0$, $\Phi'(0) > 0$ and

$$\int_A \Phi(\langle g_n \rangle_Y) d\mu_X \leq C_1.$$

We are then able to build some (nonnegative increasing) convex function Ψ with superlinear growth at infinity such that $\Psi(0) = 0$, $\Psi'(0) > 0$ and

$$\begin{aligned} &\Psi \leq \Phi, \\ &h - \Psi \text{ is convex.} \end{aligned}$$

Jensen's inequality, written for the function $h - \Psi$, combined with the uniform bound in (C.8), gives therefore

$$\int \Big(\langle \Psi(g_n) \rangle_Y - \Psi\left(\langle g_n \rangle_Y \right) \Big) d\mu_X \leq C,$$

and thus

$$\iint_{A \times Y} \Psi(g_n) d\mu_Y d\mu_X \leq C + C_1.$$

By Dunford-Pettis' lemma, we obtain that (g_n) belongs to a weak compact subset of $L^1(A \times Y)$.

We conclude, by a diagonal process, that there is a function g in $L^1(X \times Y)$ and a subsequence of (g_n) which converges to g in the sense stated in Proposition C.4. In particular, for any $\varepsilon > 0$, there exists $A \subset X$ such that

$$\mu_X(X \setminus A) < \varepsilon \quad \text{and } \langle g_n \rangle_Y \to \langle g \rangle_Y \text{ in } L^1(A).$$

Identifying the limit leads to $\bar{g} = \langle g \rangle_Y$ for almost every $x \in X$.

• It remains then to take limits in the uniform bound in (C.8).

We start by proving that, for all $x \in X$,

$$E : g \in L^1(Y) \mapsto E(g) = \Big\langle h(g) \Big\rangle_Y - h\Big(\langle g(y) \rangle_Y \Big)$$

is a convex functional. We proceed indeed by approximation replacing h by $h_\varepsilon : z \mapsto h(z + \varepsilon) - h(\varepsilon)$. As $h_\varepsilon \in C^2(\mathbf{R}^+)$,

$$DE_\varepsilon(g_1) \cdot g_2 = \Big\langle h'_\varepsilon(g_1).g_2 \Big\rangle_Y - h'_\varepsilon\Big(\langle g_1 \rangle_Y \Big) \langle g_2 \rangle_Y.$$

Therefore, by Jensen's inequality, we have for $g_1, g_2 \in L^\infty(Y)$

$$\begin{aligned} &\Big(DE_\varepsilon(g_1) - DE_\varepsilon(g_2) \Big) \cdot (g_1 - g_2) \\ &= \Big\langle H(g_1, g_2) \Big\rangle_Y - H\Big(\langle g_1 \rangle_Y, \langle g_2 \rangle_Y \Big) \geq 0, \end{aligned}$$

so that DE_ε is monotone and E_ε is convex on $L^\infty(Y)$. Passing to the limit $\varepsilon \to 0$, we then obtain that E is convex on $L^\infty(Y)$:

$$\forall t \in [0,1], \quad E(tg_1 + (1-t)g_2)) \leq tE(g_1) + (1-t)E(g_2).$$

Now let $g_1, g_2 \in L^1(Y)$. If $h(g_1)$ or $h(g_2)$ does not belong to $L^1(Y)$ the convex inequality obviously holds. In the other case, we choose two sequences $(g_{1\varepsilon})$ and $(g_{2\varepsilon})$ of $L^\infty(Y)$ such that $g_{1\varepsilon} \nearrow g_1$ and $g_{2\varepsilon} \nearrow g_2$ almost everywhere, and passing to the limit $\varepsilon \to 0$ in the convex inequality written for $g_{1\varepsilon}$ and $g_{2\varepsilon}$, we get by Lebesgue's theorem and Fatou's lemma that

$$\forall t \in [0,1], \quad E(tg_1 + (1-t)g_2)) \leq tE(g_1) + (1-t)E(g_2).$$

Now, if $g_1, g_2 \in L^1(X \times Y)$, then $g_1(x,.)$, $g_2(x,.) \in L^1(Y)$ for almost all $x \in X$ and, integrating the previous convex inequality, we obtain that the functional

$$g \in L^1(X \times Y) \mapsto \int E(g) d\mu_X$$

is convex. Furthermore, by Fatou's Lemma, this functional is lower semi-continuous.

From the convergence stated in Proposition C.4 and established previously, we then deduce that

$$\int \Big(\langle h(g) \rangle_Y - h\left(\langle g \rangle_Y\right) \Big) d\mu_X \leq C,$$

which concludes the proof. □

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Edited by J.-M. Morel, F. Takens, B. Teissier, P.K. Maini

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