

Burgers Equation with Multiplicative Noise: Dynamics and Stability

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Abstract

The main objective of this article is to analyse the dynamics of Burgers equation on the unit interval, driven by multiplicative white noise. It is shown that the solution field of the stochastic Burgers equation generates a smooth perfect and locally compacting cocycle on the energy space $L^2([0, 1], \mathbf{R})$. Using multiplicative ergodic theory techniques, we compute the discrete non-random Lyapunov spectrum $\{\lambda_i\}_{i=1}^\infty$ of the linearized cocycle. The Lyapunov spectrum characterizes the asymptotics of the cocycle near the zero equilibrium solution. In particular, we construct a countable random family of local asymptotically flow-invariant manifolds $\{\mathcal{S}_i(\omega)\}_{i=1}^\infty$ so that on each manifold $\mathcal{S}_i(\omega)$, the cocycle decays with fixed exponential speed less than or equal to λ_i . Each local manifold $\mathcal{S}_i(\omega)$ is smooth and has finite-codimension $i - 1$ for $i \geq 1$. On a global level, we show the existence of a flow-invariant random flag in the energy space $L^2([0, 1], \mathbf{R})$. The global random flag is characterized by the Lyapunov spectrum of the linearized cocycle. In the presence of a linear drift, we also give sufficient conditions on the parameters of the stochastic Burgers equation which guarantee uniqueness of the stationary solution or its hyperbolicity. In the hyperbolic case, we establish a local stable manifold theorem near the zero equilibrium.

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1 Introduction

Our main interest in this article is to study the dynamics and characterize the almost sure asymptotic stability of the zero equilibrium solution for the following one-dimensional Burgers

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equation with multiplicative white noise:

$$\left. \begin{aligned} du(t) &= \nu \Delta u dt - u \frac{\partial u}{\partial \xi} dt + \gamma u(t) dt + \sum_{k=1}^{\infty} \sigma_k u(t) dW_k(t), \quad t > 0, \quad \xi \in [0, 1], \\ u(t, 0) &= u(t, 1) = 0 \quad \text{for all } t > 0, \\ u(0, \xi) &= f(\xi), \quad \xi \in [0, 1]. \end{aligned} \right\} \quad (1.1)$$

In the above stochastic partial differential equation (spde), the noise coefficients σ_k , $k \geq 1$, are constants such that $\sum_{k=1}^{\infty} \sigma_k^2 < \infty$; the W_k , $k \geq 1$, are independent standard Brownian motions defined on the complete Wiener space (Ω, \mathcal{F}, P) ; $\gamma u(t) dt$ is a deterministic linear drift term with a fixed parameter γ ; the positive constant ν is the viscosity coefficient; and $f \in L^2([0, 1], \mathbf{R})$ is the initial function.

The main objectives of this article are:

- To describe the stochastic dynamics of Burgers spde (1.1) via a perfect locally compacting smooth cocycle (semiflow) generated by mild solutions of the equation. The construction of the cocycle is described in Section 2.
- To characterize the almost sure long-time asymptotics for the cocycle using the Lyapunov spectrum of its linearization. The Lyapunov spectrum is countable and non-random.
- To establish (in the stable case $\gamma = 0$) the existence of local flow-invariant submanifolds as well as a global invariant foliation through the zero equilibrium solution.
- To obtain hyperbolicity of the zero equilibrium and the existence of local stable/unstable manifolds under sufficient conditions on the parameters $\nu, \gamma, \sigma_i, i \geq 1$. These issues are presented in Section 3.

2 The Dynamics

It is well-known that a unique mild solution to Burgers spde (1.1) exists. See [6] and the references therein.

Throughout this article, we will denote by $\theta : \mathbf{R} \times \Omega \rightarrow \Omega$ the standard P -preserving ergodic Wiener shift:

$$\theta(t, \omega)(s) := \omega(t + s) - \omega(t), \quad t, s \in \mathbf{R}, \omega \in \Omega.$$

In this section, our main objective is to show that the random field of mild solutions of (1.1) generates a Fréchet smooth perfect cocycle $U : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega \rightarrow L^2([0, 1], \mathbf{R})$. Furthermore, our construction will show that the cocycle is locally compacting in the sense

that the map $U(t, \cdot, \omega)$ carries bounded sets in $L^2([0, 1], \mathbf{R})$ into relatively compact sets, for each $t > 0$ and almost all $\omega \in \Omega$. The construction also yields Oseledec-type integrability estimates on the cocycle and its Fréchet derivatives (Theorem 2.2).

We start with a reduction of Burgers spde (1.1) to a random pde of Burgers type. To do this, let $Q : [0, \infty) \times \Omega \rightarrow \mathbf{R}$ be the solution of the one-dimensional linear stochastic ordinary differential equation (sode)

$$\left. \begin{aligned} dQ(t) &= \gamma Q(t) dt + \sum_{k=1}^{\infty} \sigma_k Q(t) dW_k(t), \quad t \geq 0, \\ Q(0) &= 1. \end{aligned} \right\} \quad (2.1)$$

Using Itô's formula, it follows that

$$Q(t) = \exp \left\{ \sum_{k=1}^{\infty} \sigma_k W_k(t) - \frac{t}{2} \sum_{k=1}^{\infty} \sigma_k^2 + \gamma t \right\}, \quad t \geq 0. \quad (2.2)$$

Furthermore, (2.2) implies that

$$E\|Q\|_{\infty} < \infty,$$

where

$$\|Q\|_{\infty} \equiv \|Q(\cdot, \omega)\|_{\infty} := \sup_{0 \leq t \leq T} Q(t, \omega), \quad \omega \in \Omega,$$

for any finite positive T .

Write each solution u of Burgers spde (1.1) in the form

$$u(t, \xi) = V(t, \xi)Q(t), \quad t \geq 0, \quad \xi \in [0, 1], \quad (2.3)$$

with $V(t, \xi)$ a suitably chosen random field of bounded variation in t . Therefore, by Itô's formula (the product rule), we have

$$du(t) = Q(t) dV(t) + V(t) dQ(t), \quad t > 0.$$

Hence, substituting from (2.3) into (1.1) gives the following equalities for $t > 0$:

$$\begin{aligned} \nu \Delta u dt - u \frac{\partial u}{\partial \xi} dt + \gamma u dt + \sum_{k=1}^{\infty} \sigma_k u(t) dW_k(t) \\ = dV(t) \cdot Q(t) + \gamma Q(t) V(t) dt + V(t) \sum_{k=1}^{\infty} \sigma_k Q(t) dW_k(t), \\ \left[\nu \Delta (V(t)Q(t)) - V(t)Q(t) \frac{\partial}{\partial \xi} (V(t)Q(t)) \right] dt = dV(t) \cdot Q(t), \\ \nu Q(t) \Delta V(t) dt - V(t)Q(t)^2 \frac{\partial}{\partial \xi} V(t) dt = dV(t) \cdot Q(t). \end{aligned}$$

Therefore, the random field V must satisfy the following random pde

$$\left. \begin{aligned} \frac{\partial V}{\partial t} &= \nu \Delta V(t) - Q(t)V(t) \frac{\partial V(t)}{\partial \xi}, \quad t > 0, \\ V(0, \xi) &= u(0, \xi) = f(\xi), \quad \xi \in [0, 1], \\ V(t, 0) &= Q(t)^{-1}u(t, 0) = 0, \quad t > 0, \\ V(t, 1) &= Q(t)^{-1}u(t, 1) = 0, \quad t > 0. \end{aligned} \right\} \quad (2.4)$$

Let $\phi : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega \rightarrow L^2([0, 1], \mathbf{R})$ be the perfect linear cocycle generated by the linear spde

$$\left. \begin{aligned} d\phi(t) &= \nu \Delta \phi(t) dt + \gamma \phi(t) dt + \sum_{k=1}^{\infty} \sigma_k \phi(t) dW_k(t) \\ \phi(0) &= id_{L^2([0,1], \mathbf{R})}, \quad \phi(t)(0) = \phi(t)(1) = 0, \quad \forall t > 0. \end{aligned} \right\} \quad (2.5)$$

([13, Theorem 1.2.4]).

By Theorem 1.2.5 ([13]), every (\mathcal{F}_t) -adapted solution field $U : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega \rightarrow L^2([0, 1], \mathbf{R})$ of the random integral equation

$$U(t, f, \omega) = \phi(t, f, \omega) - \int_0^t \phi(t-s, \cdot, \theta(s, \omega)) \left[U(s, f, \omega) \frac{\partial}{\partial \xi} U(s, f, \omega) \right] ds, \quad t \geq 0, \quad (2.6)$$

is a mild solution of the stochastic Burgers equation (1.1). The proof follows that of Theorem 1.2.5 ([13]): Interchange Itô and Lebesgue integrals, using the identity

$$\phi(t, f, \cdot) = T_t(f) + \gamma \int_0^t T_{t-s} \phi(s, f, \cdot) ds + \sum_{k=1}^{\infty} \int_0^t \sigma_k T_{t-s} \phi(s, f, \cdot) dW_k(s), \quad t \geq 0, \quad \omega \in \Omega \quad (2.7)$$

where $T_t : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$, $t \geq 0$, is the heat semigroup generated by the Laplacian $\nu \Delta$ with Dirichlet boundary conditions on $[0, 1]$: $T_t = e^{t\nu \Delta}$, $t \geq 0$.

The next proposition gives an a priori bound on solutions of the initial boundary-value problem (2.4). These a priori bounds are needed for the construction of the cocycle (U, θ) .

Proposition 2.1. For $f \in L^2([0, 1], \mathbf{R})$, let $V(t, f, \omega) \in C^1([0, 1], \mathbf{R})$ be a (classical) solution of the initial boundary value problem (2.4) for $0 < t < T$ and some $T > 0$. Then for each $\omega \in \Omega$, the map $[0, T) \ni t \mapsto \|V(t, f, \omega)\|_{L^2} \in \mathbf{R}$ is decreasing. In particular,

$$\|V(t, f, \omega)\|_{L^2([0,1], \mathbf{R})} \leq \|f\|_{L^2([0,1], \mathbf{R})} \quad (2.8)$$

for all $t \in [0, T)$, and all $\omega \in \Omega$. Also

$$\int_0^T \left\| \frac{\partial V(t, f, \omega)}{\partial \xi} \right\|_{L^2([0,1], \mathbf{R})}^2 dt \leq \frac{1}{2\nu} \|f\|_{L^2([0,1], \mathbf{R})}^2 \quad (2.9)$$

for all $\omega \in \Omega$.

Proof. Let $f \in L^2([0, 1], \mathbf{R})$ in (2.4) and $V(t) \equiv V(t, f, \omega)$, $0 < t < T$, be a solution of (2.4). We fix and suppress $\omega \in \Omega$ throughout. Multiply both sides of (2.4) by $V(t)$ to get

$$\frac{\partial}{\partial t} V(t) \cdot V(t) = \nu V(t) \frac{\partial^2 V(t)}{\partial \xi^2} - Q(t) V(t)^2 \frac{\partial V(t)}{\partial \xi}, \quad 0 < t < T. \quad (2.10)$$

Integrate both sides of (2.10) with respect to $\xi \in [0, 1]$ to obtain

$$\frac{1}{2} \int_0^1 \frac{\partial V(t)^2}{\partial t} d\xi = \nu \int_0^1 V(t) \frac{\partial^2 V(t)}{\partial \xi^2} d\xi - Q(t) \int_0^1 V(t)^2 \frac{\partial V(t)}{\partial \xi} d\xi, \quad 0 < t < T, \quad (2.11)$$

because $Q(t)$ is independent of $\xi \in [0, 1]$. Using integration by parts and the boundary conditions $V(t)|_{\xi=1} = V(t)|_{\xi=0} = 0$, we obtain from (2.11):

$$\begin{aligned} \frac{1}{2} \frac{d}{dt} \|V(t)\|_{L^2}^2 &= \nu V(t) \cdot \frac{\partial V(t)}{\partial \xi} \Big|_{\xi=0}^{\xi=1} - \nu \int_0^1 \left(\frac{\partial V(t)}{\partial \xi} \right)^2 d\xi \\ &\quad - Q(t) \cdot \frac{1}{3} V(t)^3 \Big|_{\xi=0}^{\xi=1}, \quad 0 < t < T. \end{aligned}$$

Thus

$$\frac{d}{dt} \|V(t)\|_{L^2}^2 = -2\nu \left\| \frac{\partial V(t)}{\partial \xi} \right\|_{L^2}^2 \leq 0, \quad \text{for all } t \in [0, T). \quad (2.12)$$

Hence the function

$$[0, T) \ni t \longmapsto \|V(t)\|_{L^2}^2 \in \mathbf{R}$$

is non-increasing; i.e.,

$$\|V(t)\|_{L^2}^2 \leq \|V(0)\|_{L^2}^2 = \|f\|_{L^2}^2 \quad \text{for all } t \in [0, T). \quad (2.13)$$

This implies (2.8).

To see (2.9), integrate both sides of (2.12) over $[0, T]$:

$$\|V(T)\|_{L^2}^2 - \|f\|_{L^2}^2 = -2\nu \int_0^T \left\| \frac{\partial V(t)}{\partial \xi} \right\|_{L^2}^2 dt.$$

Hence,

$$\begin{aligned} \int_0^T \left\| \frac{\partial V(t)}{\partial \xi} \right\|_{L^2}^2 dt &= \frac{1}{2\nu} \|f\|_{L^2}^2 - \frac{1}{2\nu} \|V(T)\|_{L^2}^2 \\ &\leq \frac{1}{2\nu} \|f\|_{L^2}^2. \end{aligned}$$

This proves (2.9). □

Next, we show local existence of a unique mild solution of (2.4). Rewrite (2.4) in the mild form

$$V(t) = T_t(f) - \int_0^t Q(s)T_{t-s} \left[V(s) \frac{\partial V(s)}{\partial \xi} \right] ds, \quad t \geq 0. \quad (2.14)$$

We use a contraction mapping argument.

Proposition 2.2 (Local Existence). Let $f \in L^2([0, 1], \mathbf{R})$. Then, for some $a > 0$, the random integral equation (2.14) has a unique (local) solution $V \in C([0, a], L^2([0, 1], \mathbf{R}))$.

Proof. Fix $f_0 \in L^2([0, 1], \mathbf{R})$. Let $a > 0$. Denote by $E := C([0, a], L^2([0, 1], \mathbf{R}))$, the Banach space of all continuous maps $v : [0, a] \rightarrow L^2([0, 1], \mathbf{R})$ with the usual norm

$$\|v\|_E := \sup_{0 \leq t \leq a} \|v(t)\|_{L^2}. \quad (2.15)$$

Fix $\rho > 0$. Denote by $B(f, \rho)$ the closed ball in $L^2([0, 1], \mathbf{R})$, center f and radius ρ . Let $Y \subset E$ denote the set

$$Y := \{v \in E : \|v(t) - f_0\|_{L^2} \leq \rho \text{ for all } t \in [0, a]\}. \quad (2.16)$$

Define the mapping $\psi : B(f_0, \rho_0) \times Y \rightarrow E$ by

$$\psi(f, v)(t) := T_t(f) - \int_0^t Q(s)T_{t-s} \left[v(s) \frac{\partial v(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq a, \quad (2.17)$$

for all $v \in Y, f \in B(f_0, \rho_0)$.

Let $f \in B(f_0, \rho_0)$ and $v \in Y$. Then, for all $s \in [0, a]$,

$$\|v(s)\|_{L^2} \leq \|v(s) - f_0\|_{L^2} + \|f_0\|_{L^2} \leq \rho + \|f_0\|_{L^2}. \quad (2.18)$$

In the computations below, C denotes positive deterministic constants which may change from line to line. Let $p(t, \xi, y)$ denote the heat kernel for the heat equation

$$\begin{aligned} \frac{\partial u_0}{\partial t} &= \Delta u_0(t), \quad t > 0, \\ u_0(0, \cdot) &= f \in L^2([0, 1], \mathbf{R}), \\ u_0(t, 0) &= u_0(t, 1) = 0, \quad \text{for all } t \geq 0, \end{aligned}$$

with Dirichlet boundary conditions. Thus,

$$u_0(t, \xi) = \int_0^1 p(t, \xi, y) f(y) dy, \quad t > 0, \xi \in [0, 1]. \quad (2.19)$$

The following estimates on the heat kernel $p(t, \xi, y)$ are well-known:

$$\left| \frac{\partial p(t, \xi, y)}{\partial y} \right| \leq \frac{c_1}{t} e^{-\frac{(\xi-y)^2}{2c_2 t}}, \quad t > 0, \xi, y \in [0, 1], \quad (2.20)$$

$$\int_{-\infty}^{\infty} e^{-\frac{y^2}{2c_2 t}} dy \leq c_3 \sqrt{t}, \quad t > 0. \quad (2.21)$$

where c_1, c_2, c_3 are positive constants.

Using (2.17), (2.19) and the estimates (2.20), (2.21), we have

$$\begin{aligned}
& \|\psi(f, v)(t) - f_0\|_{L^2}^2 \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + 2\|Q\|_{\infty}^2 \frac{1}{4} \int_0^1 \left(\int_0^t \int_0^1 p(t-s, \xi, y) \frac{\partial}{\partial y} [v^2(s)(y)] dy ds \right)^2 d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + \frac{1}{2} \|Q\|_{\infty}^2 \cdot \int_0^1 \left(\int_0^t \int_0^1 \left| \frac{\partial}{\partial y} p(t-s, \xi, y) \right| v^2(s)(y) dy ds \right)^2 d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + C_1 \|Q\|_{\infty}^2 \cdot \int_0^1 \left[\int_0^t \frac{1}{(t-s)^{3/8}} \times \right. \\
& \quad \left. \times \int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} v^2(s)(y) dy \frac{1}{(t-s)^{1/8}} ds \right]^2 d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + C_1 \|Q\|_{\infty}^2 \int_0^1 \left\{ \int_0^t \frac{ds}{(t-s)^{3/4}} \int_0^t \frac{1}{(t-s)^{1/4}} \times \right. \\
& \quad \left. \times \left(\int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} v^2(s)(y) dy \right)^2 ds \right\} d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + C \|Q\|_{\infty}^2 \cdot t^{1/4} \int_0^1 \int_0^t \frac{1}{(t-s)^{3/4}} \int_0^1 e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} \cdot v^2(s)(y) dy \\
& \quad \times \int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} v^2(s)(y) dy ds d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + C \|Q\|_{\infty}^2 \cdot t^{1/4} \int_0^1 \int_0^t \frac{1}{(t-s)^{3/4}} \left(\int_0^1 v^2(s)(y) dy \right) \times \\
& \quad \times \int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} v^2(s)(y) dy ds d\xi \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + \\
& + C \|Q\|_{\infty}^2 \cdot t^{1/4} \sup_{0 \leq s \leq a} \|v(s)\|_{L^2}^2 \int_0^t \frac{1}{(t-s)^{3/4}} \times \\
& \quad \times \int_0^1 \left(\int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} d\xi \right) \times v^2(s)(y) dy ds \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 +
\end{aligned}$$

$$\begin{aligned}
& + C\|Q\|_\infty^2 \cdot t^{1/4} \sup_{0 \leq s \leq a} \|v(s)\|_{L^2}^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|v(s)\|_{L^2}^2 ds \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + C\|Q\|_\infty^2 \sup_{0 \leq s \leq a} \|v(s)\|_{L^2}^4 \cdot t^{1/2} \\
& \leq 2\|T_t(f) - f_0\|_{L^2}^2 + C\|Q\|_\infty^2 (\rho + \|f_0\|_{L^2})^4 t^{1/2}, \quad 0 \leq t \leq a,
\end{aligned} \tag{2.22}$$

where $\|Q\|_\infty := \sup_{0 \leq t \leq a} Q(t)$.

By the strong continuity of the (bounded linear) heat semigroup $T_t : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$, $t \geq 0$, choose $a \in (0, 1)$ and $\rho_0 > 0$ sufficiently small such that

$$\|T_t(f) - f_0\|_{L^2}^2 < \frac{\rho^2}{4} \quad \text{and} \quad C\|Q\|_\infty^2 (\rho + \|f_0\|_{L^2})^4 t^{1/2} < \frac{\rho^2}{2} \tag{2.23}$$

for all $0 \leq t \leq a$, and all $f \in B(f_0, \rho_0)$.

Using (2.22) and (2.23), we get

$$\|\psi(f, v)(t) - f_0\|_{L^2}^2 < \frac{\rho^2}{2} + \frac{\rho^2}{2} = \rho^2, \quad 0 \leq t \leq a.$$

Thus

$$\|\psi(f, v)(t) - f_0\|_{L^2}^2 < \rho$$

for all $t \in [0, a]$ and all $v \in Y$, all $f \in B(f_0, \rho_0)$. Hence $\psi(f, v) \in Y$ for all $f \in B(f_0, \rho_0)$ and $v \in Y$.

We must show that a and ρ_0 can be chosen sufficiently small so that

$$\begin{aligned}
\psi : B(f_0, \rho_0) \times Y & \longrightarrow Y \\
(f, v) & \longmapsto \psi(f, v)
\end{aligned}$$

is a uniform contraction on Y . Let $v_1, v_2 \in Y$ and use (2.17) to get

$$\begin{aligned}
\|\psi(f, v_1)(t) - \psi(f, v_2)(t)\|_{L^2}^2 & \leq \|Q\|_\infty^2 \int_0^1 \left(\int_0^t \int_0^1 \left| \frac{\partial}{\partial y} p(t-s, \xi, y) \right| \times \right. \\
& \quad \left. \times |v_1^2(s)(y) - v_2^2(s)(y)| dy ds \right)^2 d\xi \\
& \leq \|Q\|_\infty^2 \int_0^1 \left[\int_0^t \frac{1}{\sqrt{t-s}} \int_0^1 \frac{1}{\sqrt{t-s}} e^{-\frac{(\xi-y)^2}{2c_2(t-s)}} \times \right. \\
& \quad \left. \times |v_1^2(s)(y) - v_2^2(s)(y)| dy ds \right]^2 d\xi \\
& = \|Q\|_\infty^2 \int_0^1 \left[\int_0^1 \frac{1}{(t-s)^{3/8}} \int_0^1 \frac{1}{\sqrt{t-s}} e^{-\frac{(\xi-y)^2}{2c_2(t-s)}} \times \right.
\end{aligned}$$

$$\begin{aligned}
& \times \left| v_1^2(s)(y) - v_2^2(s)(y) \right| dy \frac{1}{(t-s)^{1/8}} ds \Big]^2 d\xi \\
\leq & \|Q\|_\infty^2 \int_0^1 \left\{ \int_0^t \frac{ds}{(t-s)^{3/4}} \int_0^t \frac{1}{(t-s)^{1/4}} \times \right. \\
& \left. \times \left(\int_0^1 \frac{1}{\sqrt{t-s}} e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} |v_1^2(s)(y) - v_2^2(s)(y)| dy \right)^2 ds \right\} d\xi \\
= & \|Q\|_\infty^2 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \left(\int_0^1 |v_1^2(s)(y) - v_2^2(s)(y)| dy \right) \times \\
& \times \int_0^1 \int_0^1 \frac{e^{\frac{-(\xi-y)^2}{2c_2(t-s)}}}{\sqrt{t-s}} d\xi |v_1^2(s)(y) - v_2^2(s)(y)| dy ds \\
\leq & C \|Q\|_\infty^2 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \left(\int_0^1 |v_1^2(s)(y) - v_2^2(s)(y)| dy \right)^2 ds \\
\leq & C \|Q\|_\infty^2 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \left\{ \int_0^1 [v_1(s)(y) + v_2(s)(y)]^2 dy \right\} \\
& \times \left\{ \int_0^1 |v_1(s)(y) - v_2(s)(y)|^2 dy \right\} ds \\
\leq & C \|Q\|_\infty^2 (\rho + \|f_0\|_{L^2})^2 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \|v_1(s) - v_2(s)\|_{L^2}^2 ds \\
= & C \|Q\|_\infty^2 (\rho + \|f_0\|_{L^2})^2 t^{1/4} \sup_{0 \leq s \leq a} \|v_1(s) - v_2(s)\|_{L^2}^2 \int_0^t \frac{1}{(t-s)^{3/4}} ds \\
\leq & C \|Q\|_\infty^2 (\rho + \|f_0\|_{L^2})^2 t^{1/2} \|v_1 - v_2\|_E^2, \quad 0 \leq t \leq a. \tag{2.24}
\end{aligned}$$

Now choose $a > 0$ sufficiently small such that

$$L := C \|Q\|_\infty (\rho + \|f_0\|_{L^2}) a^{1/4} < 1. \tag{2.25}$$

Therefore by (2.24) and (2.25), we get

$$\|\psi(f, v_1) - \psi(f, v_2)\|_E \leq L \|v_1 - v_2\|_E \tag{2.26}$$

for all $v_1, v_2 \in Y$, all $f \in B(f_0, \rho_0)$, where $L < 1$. Hence for each $f \in B(f_0, \rho_0)$, $\psi(f, \cdot) : Y \rightarrow Y$ is a uniform contraction on Y . By the contraction mapping theorem, $\psi(f, \cdot)$ has a unique fixed point $V(f) \in Y$; i.e.,

$$\psi(f, V(f))(t) = V(f)(t), \quad 0 \leq t \leq a. \tag{2.27}$$

Thus $V(f)$ is a unique local mild solution of Burgers spde

$$V(f)(t) = T_t(f) - \int_0^t Q(s) T_{t-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq a$$

for all $f \in B(f_0, \rho_0)$. Note that in (2.27), a is independent of the choice of the initial condition $f \in B(f_0, \rho_0)$ (although a is random and may still depend on the choice of $f_0 \in L^2([0, 1], \mathbf{R})$). \square

The following proposition gives regularity of the local mild solution

$$L^2([0, 1], \mathbf{R}) \supset B(f_0, \rho_0) \ni f \longmapsto V(f) \in C([0, a], L^2([0, 1], \mathbf{R}))$$

of (2.14).

Proposition 2.3 (Uniform Contraction Principle). Let E, F be real Banach spaces. Suppose $B \subset F$ is an open set and $Y \subset E$ a closed ball in E . Let $\psi : B \times Y \rightarrow Y$ be a C^k map such that $\psi(f, \cdot) : Y \rightarrow Y$, $f \in B$, is a uniform contraction; i.e., there exists $L \in (0, 1)$ such that

$$\|\psi(f, v_1) - \psi(f, v_2)\|_E \leq L\|v_1 - v_2\|_E \quad (2.28)$$

for all $v_1, v_2 \in Y$ and all $f \in B$. Then for each $f \in B$, there is a unique $v(f) \in Y$ such that $\psi(f, v(f)) = v(f)$. Moreover, the map $B \ni f \longmapsto v(f) \in Y \subset E$ is C^k with bounded Fréchet derivatives on bounded subsets of B .

Proof. See the proof of Lemma 2.7 in ([12]). \square

Theorem 2.1 (Global existence). For each $f \in L^2([0, 1], \mathbf{R})$, Burgers spde (1.1) has a unique pathwise solution $U(f, \omega) \in C([0, \infty), L^2([0, 1], \mathbf{R}))$ such that the map

$$L^2([0, 1], \mathbf{R}) \ni f \longmapsto U(f, \omega)(t) \in L^2([0, 1], \mathbf{R})$$

is C^∞ for a.a. $\omega \in \Omega$ and all $t \geq 0$, and has bounded Fréchet derivatives on bounded sets in $L^2([0, 1], \mathbf{R})$.

Proof. In view of the relation (2.3), it is sufficient to prove the theorem for the random Burgers equation (2.4). Fix and suppress $\omega \in \Omega$. Also fix $f_0 \in L^2([0, 1], \mathbf{R})$. By Proposition 1.2, there exists $\rho_0, a > 0$ such that if $f \in B(f_0, \rho_0)$ and

$$\psi(f, v)(t) := T_t(f) - \int_0^t Q(s)T_{t-s} \left[v(s) \frac{\partial v(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq a, \quad (2.29)$$

then $\psi(f, \cdot)$ has a fixed point $V(f) \in Y \subset C([0, a], L^2([0, 1], \mathbf{R}))$ which gives a unique local mild solution $V(f)$ of (2.4). Since ψ satisfies

$$\|\psi(f_1, v) - \psi(f_2, v)\|_E \leq \sup_{0 \leq t \leq a} \|T_t\|_{L(L^2)} \|f_1 - f_2\|_{L^2}$$

it follows (from the proof of Proposition 2.3) that the solution map

$$B(f_0, \rho_0) \ni f \longmapsto V(f) \in Y \subset C([0, a], L^2([0, 1], \mathbf{R})) \quad (2.30)$$

of (2.4) is Lipschitz. In fact, we will show that the above solution map (2.30) is C^∞ (Fréchet). In view of Proposition 2.3, it is sufficient to prove that the map $\psi : B(f_0, \rho_0) \times Y \rightarrow E$ in (2.17) is C^k for all $k \geq 1$. Consider

$$\psi(f, v)(t) := T_t(f) - \int_0^t Q(s)T_{t-s} \left[v(s) \frac{\partial v(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq a \quad (2.17)$$

for $f \in B(f_0, \rho_0)$, $v \in Y$, where

$$Y := \left\{ v \in C([0, a], L^2([0, 1], \mathbf{R})) : \|v(t) - f_0\|_{L^2} \leq \rho \quad \forall t \in [0, a] \right\}. \quad (2.31)$$

Note first that the map

$$L^2([0, 1], \mathbf{R}) \ni f \longmapsto T_{(\cdot)} f \in C([0, a], L^2([0, 1], \mathbf{R}))$$

is continuous linear (and hence C^∞). So it remains to show that the map $\phi : Y \rightarrow C([0, a], L^2([0, 1], \mathbf{R}))$, where

$$\begin{aligned} \phi(v)(t) &:= \int_0^t Q(s)T_{t-s} \left[v(s) \frac{\partial v(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq a, \\ &v \in C([0, a], L^2([0, 1], \mathbf{R})), \end{aligned} \quad (2.32)$$

is C^∞ . To do this, consider the map

$$A : E \times E \longrightarrow E$$

defined by

$$A(v_1, v_2)(t) := \int_0^t Q(s)T_{t-s} \left[\frac{\partial}{\partial \xi} (v_1(s)v_2(s)) \right] ds \quad (2.33)$$

for $0 \leq t \leq a$, $v_1, v_2 \in E$. Clearly,

$$\phi(v) = \frac{1}{2} A(v, v), \quad v \in C([0, a], L^2([0, 1], \mathbf{R})). \quad (2.34)$$

We will show that A is continuous bilinear. By (2.34), this implies that ϕ is C^∞ . Rewrite (2.33) in the form

$$A(v_1, v_2)(t)(\xi) = \int_0^t Q(s) \int_0^1 \frac{\partial}{\partial y} p(t-s, \xi, y) v_1(s)(y) v_2(s)(y) dy ds \quad (2.35)$$

for all $\xi \in [0, 1]$, $t \in [0, a]$, $v_1, v_2 \in E$. Then

$$\begin{aligned}
\|Av_1, v_2(t)\|_{L^2}^2 &\leq C\|Q\|_\infty^2 \int_0^1 \left(\int_0^t \frac{1}{\sqrt{t-s}} \int_0^1 e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} |v_1(s)(y)| |v_2(s)(y)| dy ds \right)^2 d\xi \\
&\leq C\|Q\|_\infty^2 \int_0^1 \left[\int_0^t \frac{1}{(t-s)^{3/8}} \int_0^1 \frac{e^{\frac{-(\xi-y)^2}{2c_2(t-s)}}}{\sqrt{t-s}} |v_1(s)(y)| |v_2(s)(y)| dy \frac{1}{(t-s)^{1/8}} ds \right]^2 d\xi \\
&\leq C\|Q\|_\infty^2 \int_0^1 \left\{ \int_0^t \frac{ds}{(t-s)^{3/4}} \int_0^t \frac{1}{(t-s)^{1/4}} \left(\int_0^1 e^{\frac{-(\xi-y)^2}{2c_2(t-s)}} \times \right. \right. \\
&\quad \left. \left. \times |v_1(s)(y)| |v_2(s)(y)| dy \right)^2 ds \right\} d\xi \\
&= C\|Q\|_\infty^2 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \left| \int_0^1 |v_1(s)(y)| |v_2(s)(y)| dy \right| \times \\
&\quad \times \left| \int_0^1 \int_0^1 \frac{e^{\frac{-(\xi-y)^2}{2c_2(t-s)}}}{\sqrt{t-s}} d\xi \cdot |v_1(s)(y)| |v_2(s)(y)| dy \right| ds \\
&\leq C\|Q\|_\infty^2 t^{1/4} \int_0^t \frac{\|v_1(s)\|_{L^2}^2 \|v_2(s)\|_{L^2}^2}{(t-s)^{3/4}} ds \\
&\leq C\|Q\|_\infty^2 t^{1/2} \left(\sup_{0 \leq t \leq a} \|v_1(s)\|_{L^2} \right)^2 \left(\sup_{0 \leq t \leq a} \|v_2(s)\|_{L^2} \right)^2 \\
&\leq C\|Q\|_\infty^2 a^{1/2} \|v_1\|_E^2 \cdot \|v_2\|_E^2 .
\end{aligned}$$

for all $t \in [0, a]$ and $v_1, v_2 \in E$. Therefore,

$$\|A(v_1, v_2)\|_E = \sup_{0 \leq t \leq a} \|A(v_1, v_2)(t)\|_{L^2} \leq C\|Q\|_\infty a^{1/4} \|v_1\|_E \cdot \|v_2\|_E$$

for all $v_1, v_2 \in E$. Hence A is continuous bilinear, ϕ and ψ are C^∞ maps.

By the uniform contraction principle (Proposition 2.3), it follows that the solution map

$$L^2([0, 1], \mathbf{R}) \supset B(f_0, \rho_0) \ni f \longmapsto V(f) \in C([0, a], L^2([0, 1], \mathbf{R})) \quad (2.36)$$

is C^∞ for some $a > 0$.

We now prove existence of a global solution of (2.4). Let $\tau = \tau(\omega) > 0$ denote the supremum of all $a > 0$ such that a C^∞ solution map (2.36) exists on $[0, a]$ (for fixed f_0, ρ_0). We will show $\tau = \infty$ a.s.. Suppose, if possible, that $\tau = \tau(\omega) < \infty$ for some $\omega \in \Omega$. We claim that

$$V(f)(\tau) = \lim_{t \rightarrow \tau^-} V(f)(t) = T_\tau(f) - \int_0^\tau Q(s) T_{\tau-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \quad (2.37)$$

for all $f \in B(f_0, \rho_0)$, where the limit is taken in $L^2([0, 1], \mathbf{R})$. Since $\lim_{t \rightarrow \tau^-} T_t(f) = T_\tau(f)$ by strong continuity of the heat semigroup $T_t : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$, (2.37) will follow if we show that

$$\begin{aligned} \lim_{t \rightarrow \tau^-} \left\| \int_0^\tau Q(s) T_{\tau-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \right. \\ \left. - \int_0^t Q(s) T_{t-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \right\|_{L^2} = 0. \end{aligned} \quad (2.38)$$

Denote

$$\begin{aligned} B(t)(\xi) &:= - \int_0^t Q(s) T_{t-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \\ &= \int_0^t Q(s) \int_0^1 \frac{\partial}{\partial y} p(t-s, \xi, y) V(f)^2(s)(y) dy ds, \\ &0 \leq t < \tau, \quad \xi \in [0, 1]. \end{aligned} \quad (2.39)$$

Consider

$$\begin{aligned} B(\tau)(\xi) - B(t)(\xi) &= \int_t^\tau Q(s) \int_0^1 \frac{\partial}{\partial y} p(\tau-s, \xi, y) V(f)^2(s)(y) dy ds + \\ &+ \int_0^t Q(s) \int_0^1 \left[\frac{\partial}{\partial y} p(\tau-s, \xi, y) - \frac{\partial}{\partial y} p(t-s, \xi, y) \right] V(f)^2(s)(y) dy ds \\ &= B_1(t)(\xi) + B_2(t)(\xi), \quad \xi \in [0, 1], \quad 0 \leq t < \tau, \end{aligned} \quad (2.40)$$

where

$$B_1(t)(\xi) := \int_t^\tau Q(s) \int_0^1 \frac{\partial}{\partial y} p(\tau-s, \xi, y) V(f)^2(s)(y) dy ds, \quad (2.41)$$

and

$$B_2(t)(\xi) := \int_0^t \int_0^1 Q(s) \left[\frac{\partial}{\partial y} p(\tau-s, \xi, y) - \frac{\partial}{\partial y} p(t-s, \xi, y) \right] V(f)^2(s)(y) dy ds. \quad (2.42)$$

for $\xi \in [0, 1]$, $0 \leq t < \tau$. We will show that

$$\lim_{t \rightarrow \tau^-} \|B_i(t)\|_{L^2} = 0, \quad i = 1, 2. \quad (2.43)$$

Using the estimates (2.20), (2.21) and an argument similar to that used in deriving (2.22), we obtain

$$\|B_1(t)\|_{L^2}^2 \leq C \|Q\|_\infty^2 \sup_{0 \leq s \leq \tau} \|V(f)(s)\|_{L^2}^4 (\tau-t)^{1/2}, \quad 0 \leq t < \tau. \quad (2.44)$$

Note that in (2.44), we have used the fact that

$$\sup_{0 \leq s < \tau} \|V(f)(s)\|_{L^2}^4 \leq \|f\|_{L^2}^4 < \infty \quad (2.45)$$

which follows from Proposition 2.1 ((2.8)). Thus (2.44) implies

$$\lim_{t \rightarrow \tau^-} \|B_1(t)\|_{L^2} = 0.$$

Employing similar estimates as in (2.44), the dominated convergence theorem and the fact that

$$\lim_{t \rightarrow \tau^-} \left[\frac{\partial}{\partial y} p(\tau - s, \xi, y) - \frac{\partial}{\partial y} p(t - s, \xi, y) \right] = 0 \quad (2.46)$$

a.e., it follows that

$$\lim_{t \rightarrow \tau^-} \|B_2(t)\|_{L^2} = 0. \quad (2.47)$$

This proves (2.43), (2.38) and (2.37).

By local existence, the random pde (2.4) (with Q replaced by $Q(\tau + \cdot)$) admits a local mild solution $y : [0, \epsilon] \rightarrow L^2([0, 1], \mathbf{R})$ with initial condition $V(f)(\tau) \in L^2([0, 1], \mathbf{R})$; that is

$$\begin{aligned} y(t) &= T_t[V(f)(\tau)] - \int_0^t Q(\tau + s)T_{t-s} \left[y(s) \frac{\partial y(s)}{\partial \xi} \right] ds, \\ &= T_{t+\tau}(f) - \int_0^\tau Q(s)T_{t+\tau-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \\ &\quad - \int_0^t Q(\tau + s)T_{t-s} \left[y(s) \frac{\partial y(s)}{\partial \xi} \right] ds \\ &= T_{t+\tau}(f) - \int_0^\tau Q(s)T_{t+\tau-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \\ &\quad - \int_\tau^{t+\tau} Q(s)T_{t+\tau-s} \left[y(s - \tau) \frac{\partial y(s - \tau)}{\partial \xi} \right] ds, \quad 0 \leq t < \epsilon. \end{aligned} \quad (2.48)$$

Define $\theta \in C([0, \tau + \epsilon], L^2([0, 1], \mathbf{R}))$ by

$$\theta(t) := \begin{cases} V(f)(t) & 0 \leq t \leq \tau \\ y(t - \tau) & \tau < t \leq \tau + \epsilon. \end{cases} \quad (2.49)$$

Therefore (2.48) implies

$$\theta(t + \tau) = T_{t+\tau}(f) - \int_0^{t+\tau} Q(s)T_{t+\tau-s} \left[\theta(s) \frac{\partial \theta(s)}{\partial \xi} \right] ds, \quad 0 \leq t \leq \epsilon. \quad (2.50)$$

For $0 \leq t \leq \tau$, we have

$$\begin{aligned} \theta(t) &= V(f)(t) = T_t(f) - \int_0^t Q(s)T_{t-s} \left[V(f)(s) \frac{\partial V(f)(s)}{\partial \xi} \right] ds \\ &= T_t(f) - \int_0^t Q(s)T_{t-s} \left[\theta(s) \frac{\partial \theta(s)}{\partial \xi} \right] ds. \end{aligned} \quad (2.51)$$

Therefore, from (2.50) and (2.51), it follows that $\theta : [0, \tau + \epsilon] \rightarrow L^2([0, 1], \mathbf{R})$ is a mild solution of (2.4) on $[0, \tau + \epsilon]$ with $\theta(0) = f$. This contradicts the maximality of τ . So $\tau(\omega) = \infty$ for all $\omega \in \Omega$.

From the relation

$$U(f, \omega)(t) = V(f, \omega)(t)Q(t, \omega), \quad t \geq 0, \omega \in \Omega, \quad (2.52)$$

we conclude that the solution map

$$L^2([0, 1], \mathbf{R}) \ni f \mapsto U(f, \omega) \in C([0, T], L^2([0, 1], \mathbf{R}))$$

of (1.1) is C^∞ for all $\omega \in \Omega$, all $T > 0$ and has bounded Fréchet derivatives on bounded subsets of $L^2([0, 1], \mathbf{R})$. This completes the proof of Theorem 2.1. \square

The next result shows that mild solutions of the stochastic Burgers equation (1.1) generate a C^∞ jointly measurable perfect cocycle

$$\begin{aligned} U : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega &\longrightarrow L^2([0, 1], \mathbf{R}) \\ (t, f, \omega) &\longmapsto U(t, f, \omega) \equiv U(f, \omega)(t) \end{aligned}$$

which maps bounded sets in $L^2([0, 1], \mathbf{R})$ into relatively compact sets.

Theorem 2.2 (The cocycle). *Let $U(t, f, \omega)$ be the unique global mild solution of Burgers spde (1.1) for $t \geq 0$, $f \in L^2([0, 1], \mathbf{R})$, $\omega \in \Omega$. Recall that $\theta : \mathbf{R} \times \Omega \rightarrow \Omega$ is the standard Brownian shift*

$$\theta(t, \omega)(s) := \omega(t + s) - \omega(t), \quad t, s \in \mathbf{R}, \omega \in \Omega, \quad (2.53)$$

on Wiener space (Ω, \mathcal{F}, P) . Then $U : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega \rightarrow L^2([0, 1], \mathbf{R})$ is jointly measurable and has the following properties:

(i) (U, θ) is a C^∞ perfect cocycle; viz.

$$Ut_2, U(t_1, f, \omega), \theta(t_1, \omega)) = U(t_1 + t_2, f, \omega) \quad (2.54)$$

for all $t_1, t_2 \geq 0$, $f \in L^2([0, 1], \mathbf{R})$, $\omega \in \Omega$.

(ii) For fixed $t > 0$ and $\omega \in \Omega$, the map $U(t, \cdot, \omega) : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$ takes bounded sets into relatively compact sets in $L^2([0, 1], \mathbf{R})$.

(iii) For each $(t, f, \omega) \in \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega$, the Fréchet derivative $DU(t, f, \omega) \in L(L^2([0, 1], \mathbf{R}))$ is compact linear, and the map

$$\begin{aligned} \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega &\longrightarrow L(L^2([0, 1], \mathbf{R})) \\ (t, f, \omega) &\longmapsto DU(t, f, \omega) \end{aligned}$$

is strongly measurable.

(iv) For fixed $\rho, a > 0$ and any integer $k \geq 1$,

$$E \log^+ \sup_{\substack{0 \leq t_1, t_2 \leq a \\ \|f\|_2 \leq \rho}} \left\{ \|U(t_2, f, \theta(t_1, \cdot))\|_{L^2} + \|D^{(k)}U(t_2, f, \theta(t_1, \cdot))\|_{L^{(k)}(L^2)} \right\} < \infty \quad (2.55)$$

where $L^{(k)}(L^2)$ denotes the space of all continuous k -multilinear maps $(L^2)^k \rightarrow L^2$ given the uniform operator norm $\|\cdot\|_{L^{(k)}(L^2)}$.

Proof. Note first that Q has the cocycle property

$$Q(t_1 + t_2, \omega) = Q(t_2, \theta(t_1, \omega))Q(t_1, \omega), \quad t_1, t_2 \geq 0, \omega \in \Omega. \quad (2.56)$$

Secondly, (2.54) will follow from the following identity

$$V(f)(t_1 + t_2, \omega) = Q(t, \omega)^{-1}V[Q(t_1, \omega)V(f)(t_1, \omega)](t_2, \theta(t_1, \omega)) \quad (2.57)$$

for $t_1, t_2 \geq 0, \omega \in \Omega, f \in L^2([0, 1], \mathbf{R})$. To see this, we use the relation

$$U(t, f, \omega) = Q(t, \omega)V(f)(t, \omega), \quad t \geq 0, \omega \in \Omega, f \in L^2([0, 1], \mathbf{R}) \quad (2.58)$$

and uniqueness of the mild solution of (2.4). Indeed, assume that (2.57) holds. Fix $\omega \in \Omega$ and $t_1 \geq 0$ throughout this proof. Then, for $t \geq 0$, we have

$$\begin{aligned} & U(t, U(t_1, f, \omega), \theta(t_1, \omega)) \\ &= Q(t, \theta(t_1, \omega))V[Q(t_1, \omega)V(f)(t_1, \omega)](t, \theta(t_1, \omega)) \\ &= Q(t_1 + t, \omega)Q(t_1, \omega)^{-1}V[Q(t_1, \omega)V(f)(t_1, \omega)](t, \theta(t_1, \omega)) \\ &= Q(t_1 + t, \omega)V(f)(t_1 + t, \omega) \\ &= U(t_1 + t, f, \omega). \end{aligned}$$

Hence the cocycle property (2.54) holds. We now show (2.57). Define the processes

$$\left. \begin{aligned} z(t) &:= Q(t_1, \omega)^{-1}V[Q(t_1, \omega)V(f)(t_1, \omega)](t, \theta(t_1, \omega)) \\ \bar{z}(t) &:= V(f)(t + t_1, \omega), \end{aligned} \right\} \quad (2.59)$$

for all $t \geq 0$. Thus

$$\begin{aligned} z(t) &= Q(t_1, \omega)^{-1}[T_t\{Q(t_1, \omega)V(f)(t_1, \omega)\} \\ &\quad - \int_0^t Q(s, \theta(t_1, \omega))T_{t-s}\{V(Q(t_1, \omega)V(f)(t_1, \omega))(s, \theta(t_1, \omega))\} \\ &\quad \frac{\partial V}{\partial \xi}(Q(t_1, \omega)V(f)(t_1, \omega))(s, \theta(t_1, \omega))\} ds] \\ &= T_{t+t_1}(f) - \int_0^{t_1} Q(s, \omega)T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \end{aligned}$$

$$\begin{aligned}
& - \int_0^t Q(s, \theta(t_1, \omega)) Q(t_1, \omega) T_{t-s} \{ Q(t_1, \omega)^{-1} \cdot \\
& \quad V(Q(t_1, \omega) V(f)(t_1, \omega))(s, \theta(t_1, \omega)) \cdot \\
& \quad \frac{\partial}{\partial \xi} [Q(t_1, \omega)^{-1} V(Q(t_1, \omega)) V(f)(t_1, \omega)(s, \theta(t_1, \omega))] \} ds \\
& = T_{t+t_1}(f) - \int_0^{t_1} Q(s, \omega) T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \\
& \quad - \int_0^t Q(s+t_1, \omega) T_{t-s} \left[z(s) \frac{\partial z(s)}{\partial \xi} \right] ds, \quad t \geq 0. \tag{2.60}
\end{aligned}$$

On the other hand,

$$\begin{aligned}
\bar{z}(t) & = T_{t+t_1}(f) - \int_0^{t+t_1} Q(s, \omega) T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \\
& = T_{t+t_1}(f) - \int_0^{t_1} Q(s, \omega) T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \\
& \quad - \int_{t_1}^{t+t_1} Q(s, \omega) T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \\
& = T_{t+t_1}(f) - \int_0^{t_1} Q(s, \omega) T_{t+t_1-s} \left[V(f)(s, \omega) \frac{\partial V(f)}{\partial \xi}(s, \omega) \right] ds \\
& \quad - \int_0^t Q(s+t_1, \omega) T_{t-s} \left[\bar{z}(s) \frac{\partial \bar{z}(s)}{\partial \xi} \right] ds, \quad t \geq 0. \tag{2.61}
\end{aligned}$$

Subtracting (2.61) from (2.60), taking L^2 -norms and using estimates similar to those to derive (2.24), we obtain

$$\begin{aligned}
\|z(t) - \bar{z}(t)\|_{L^2}^2 & \leq \|Q\|_\infty^2 \int_0^1 \left(\int_0^t \int_0^1 \left| \frac{\partial}{\partial y} p(t-s, \xi, y) \right| \times \right. \\
& \quad \left. |z^2(s)(y) - \bar{z}^2(s)(y)| dy ds \right)^2 d\xi \\
& \leq C \|Q\|_\infty^2 \sup_{0 \leq t \leq a} [\|z(t)\|_{L^2}^2 + \|\bar{z}(t)\|_{L^2}^2] \cdot \\
& \quad t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \|z(s) - \bar{z}(s)\|_{L^2}^2 ds \\
& = C_1 t^{1/4} \int_0^t \frac{1}{(t-s)^{3/4}} \|z(s) - \bar{z}(s)\|_{L^2}^2 ds, \quad 0 \leq t \leq a, \tag{2.62}
\end{aligned}$$

where

$$C_1 := C \|Q\|_\infty^2 \sup_{0 \leq t \leq a} [\|z(t)\|_{L^2}^2 + \|\bar{z}(t)\|_{L^2}^2]. \tag{2.63}$$

Iterating (2.62), we get

$$\begin{aligned}
\|z(t) - \bar{z}(t)\|_{L^2}^2 &\leq C_1^2 t^{1/4} \int_0^t \int_0^s \frac{s^{1/4}}{(t-s)^{3/4}(s-r)^{3/4}} \|z(r) - \bar{z}(r)\|_{L^2}^2 dr ds \\
&= C_1^2 t^{1/4} \int_0^t \left[\int_r^t \frac{s^{1/4}}{(t-s)^{3/4}(s-r)^{3/4}} ds \right] \|z(r) - \bar{z}(r)\|_{L^2}^2 dr \\
&\leq C_2 t^{1/4} \int_0^t \frac{1}{(t-r)^{1/2}} \|z(r) - \bar{z}(r)\|_{L^2}^2 dr, \quad 0 \leq t \leq a.
\end{aligned} \tag{2.64}$$

Again, iterating the above inequality, we obtain

$$\begin{aligned}
\|z(t) - \bar{z}(t)\|_{L^2}^2 &\leq C_2 t^{1/4} \int_0^t \int_0^s \frac{s^{1/4}}{(t-s)^{1/2}(s-r)^{1/2}} \|z(r) - \bar{z}(r)\|_{L^2}^2 dr ds \\
&\leq C_3 \int_0^t \left[\int_r^t \frac{1}{(t-s)^{1/2}(s-r)^{1/2}} ds \right] \|z(r) - \bar{z}(r)\|_{L^2}^2 dr \\
&= C_3 \int_0^t \int_0^{t-r} \frac{ds}{(t-r-s)^{1/2}s^{1/2}} \|z(r) - \bar{z}(r)\|_{L^2}^2 dr \\
&\leq C_4 \int_0^t \|z(r) - \bar{z}(r)\|_{L^2}^2 dr, \quad 0 \leq t \leq a.
\end{aligned} \tag{2.65}$$

Now (2.65) implies that $\|z(t) - \bar{z}(t)\|_{L^2} = 0$ for all $t \geq 0$ (because a is arbitrary). Hence $z(t) = \bar{z}(t)$ for all $t \geq 0$. Therefore (2.57) holds for all t_1, ω and $t_2 = t$. Thus the cocycle property (2.54) is satisfied for all $\omega \in \Omega$, $t_1, t_2 \geq 0$, $f \in L^2([0, 1], \mathbf{R})$.

To prove assertion (ii) of the theorem, it is sufficient to show that the solution map

$$L^2([0, 1], \mathbf{R}) \ni f \longmapsto V(f, \omega)(t) \in L^2([0, 1], \mathbf{R}) \tag{2.66}$$

takes bounded sets to relatively compact sets for fixed $t > 0$, $\omega \in \Omega$. In order to do this, we establish the following claim.

Claim:

Let X be a real Banach space and $S_t : X \rightarrow X$, $t \in [0, a]$, a strongly continuous semigroup of continuous linear operators on X such that $S_t : X \rightarrow X$ is compact for each $t \in (0, a]$. If $\{x_n\}_{n=1}^\infty \subset X$ is a bounded sequence in X , then there is a subsequence $\{x'_n\}_{n=1}^\infty$ of $\{x_n\}_{n=1}^\infty$ such that $\{S_t(x'_n)\}_{n=1}^\infty$ converges for each $t \in (0, a]$. (The subsequence $\{x'_n\}_{n=1}^\infty$ does not depend on the choice of $t \in (0, a]$.)

Proof of Claim. Suppose $\{x_n\}_{n=1}^\infty \subset X$ is any bounded sequence in X . Let $\{t_m\}_{m=1}^\infty$ be a decreasing sequence in $(0, a]$ converging to 0, i.e. $t_m \searrow 0$, $t_1 = a$. By compactness of $S_{t_1} : X \rightarrow X$, there is a subsequence $\{x_n^1\}_{n=1}^\infty$ of $\{x_n\}_{n=1}^\infty$ such that $\{S_{t_1}(x_n^1)\}_{n=1}^\infty$ is convergent. Similarly, by compactness of S_{t_2} , there is a subsequence $\{x_n^2\}_{n=1}^\infty \subset \{x_n^1\}_{n=1}^\infty$ such that $\{S_{t_2}(x_n^2)\}_{n=1}^\infty$ converges. By induction there is a subsequence $\{x_n^m\}_{n=1}^\infty$, $m \geq 1$,

of $\{x_n\}_{n=1}^\infty$ such that $\{S_{t_m}(x_n^m)\}_{n=1}^\infty$ converges and $\{x_n^{m+1}\}_{n=1}^\infty \subset \{x_n^m\}_{n=1}^\infty$ for each $m \geq 1$. Denote by $\tilde{x}_n := x_n^n$, $n \geq 1$, the diagonal subsequence of $\{x_n\}_{n=1}^\infty$ with the property that $\{S_{t_m}(\tilde{x}_n)\}_{n=1}^\infty$ converges for each $m \geq 1$. We now check that $\{S_t(\tilde{x}_n)\}_{n=1}^\infty$ converges for any $t \in (0, a]$. Let $0 < t \leq a$. Since $t_m \searrow 0$, then there exists $m \geq 1$ such that $0 < t_m < t$. Since $\{S_{t_m}(\tilde{x}_n)\}_{n=1}^\infty$ converges, then by continuity of $S_{t-t_m} : X \rightarrow X$ and the semigroup property, it follows that the sequence $S_t(\tilde{x}_n) = S_{t-t_m}[S_{t_m}(\tilde{x}_n)]$, $n \geq 1$, converges. This proves the claim.

We next show that the solution map

$$L^2([0, 1], \mathbf{R}) \ni f \longmapsto V(f, \omega)(t) \in L^2([0, 1], \mathbf{R})$$

is compact for each $t > 0$, $\omega \in \Omega$. To do so, let $\{f_n\}_{n=1}^\infty$ be any bounded sequence in $L^2([0, 1], \mathbf{R})$. Then by compactness and strong continuity of the heat semigroup $T_t : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$, $t > 0$, the above claim gives a subsequence $\{\tilde{f}_n\}_{n=1}^\infty$ of $\{f_n\}_{n=1}^\infty$ such that $\{T_t(\tilde{f}_n)\}_{n=1}^\infty$ is convergent for each $t \in (0, a]$. Now, using estimates similar to (2.24), we get

$$\begin{aligned} & \|V(\tilde{f}_n, \omega)(t) - V(\tilde{f}_m, \omega)(t)\|_{L^2}^2 \\ & \leq 2\|T_t(\tilde{f}_n) - T_t(\tilde{f}_m)\|_{L^2}^2 + \\ & \quad + \frac{1}{2}\|Q_\infty^2 \int_0^1 \left(\int_0^t \int_0^1 \left| \frac{\partial p}{\partial y}(t-s, \xi, y) \right| \times \right. \\ & \quad \left. \times |V(\tilde{f}_n)^2(s)(y) - V(\tilde{f}_m)^2(s)(y)| dy ds \right)^2 d\xi \\ & \leq 2\|T_t(\tilde{f}_n) - T_t(\tilde{f}_m)\|_{L^2}^2 + \\ & \quad + C \int_0^t \frac{1}{(t-s)^{3/4}} \|V(\tilde{f}_n)(s) - V(\tilde{f}_m)(s)\|_{L^2}^2 ds \end{aligned} \quad (2.67)$$

for all $0 < t \leq a$, $\omega \in \Omega$. Set

$$\phi(t) := \limsup_{m, n \rightarrow \infty} \|V(\tilde{f}_n)(t) - V(\tilde{f}_m)(t)\|_{L^2}, \quad 0 < t \leq a.$$

Taking $\limsup_{m, n \rightarrow \infty}$ on both sides of (2.67) and using the fact that

$$\limsup_{m, n \rightarrow \infty} \|T_t(\tilde{f}_n) - T_t(\tilde{f}_m)\|_{L^2}^2 = 0, \text{ we get}$$

$$\phi(t) \leq C \int_0^t \frac{1}{(t-s)^{3/4}} \phi(s) ds, \quad 0 < t \leq a. \quad (2.68)$$

Iterating (2.68) twice as in the proof of (2.65), it follows that $\phi(t) = 0$ for all $t \in (0, a]$. Therefore, for each $t \in (0, a]$, $\{V(\tilde{f}_n)(t)\}_{n=1}^\infty$ is a Cauchy sequence in $L^2([0, 1], \mathbf{R})$ and hence

it converges. This proves compactness of the solution map (2.66) of (2.4), and completes the proof of assertion (ii) of the theorem.

To prove assertion (iv) of the theorem, use the definition (2.17) of ψ , and linearize the fixed-point relation

$$V(f)(t) = \psi(f, V(f))(t), \quad 0 \leq t \leq a \quad (2.69)$$

to obtain

$$\begin{aligned} DV(f)(t)(g) &= D_1\psi(f, V(f))(t)(g) + D_2\psi(f, V(f))(t)(g) \\ &= T_t(g) - \int_0^t Q(s) \int_0^1 \frac{\partial}{\partial y} p(t-s, \xi, y) [DV(f)(s)(g)(y)V(f)(s)(y)] dy ds \end{aligned} \quad (2.70)$$

for all $t \in [0, a]$, $f, g \in L^2([0, 1], \mathbf{R})$. Let $\rho > 0$ and suppose $g, f \in L^2([0, 1], \mathbf{R})$ are such that $\|f\|_{L^2} \leq \rho$ and $\|g\|_{L^2} \leq 1$. Take L^2 -norms of (2.70) and use C as a generic deterministic constant that could change from line to line. This gives

$$\begin{aligned} \|DV(f)(t)(g)\|_{L^2}^2 &\leq 2\|T_t\|_{L(L^2)}^2 \|g\|_{L^2}^2 + \\ &\quad + C\|Q\|_\infty^2 \int_0^1 \left(\int_0^t \left| \frac{\partial}{\partial y} p(t-s, \xi, y) \right| \times \right. \\ &\quad \left. \times |DV(f)(s)(g)(y)V(f)(s)(y)| dy ds \right)^2 d\xi \\ &\leq 2 + C\|Q\|_\infty^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|V(f)(s)\|_{L^2}^2 \|DV(f)(s)(g)\|_{L^2}^2 ds \\ &\leq 2 + C\|Q\|_\infty^2 \|f\|_{L^2}^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|DV(f)(s)\|_{L(L^2)}^2 \|g\|_{L^2}^2 ds \\ &\leq 2 + C\|Q\|_\infty^2 \rho^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|DV(f)(s)\|_{L(L^2)}^2 ds \\ &\leq 2 + C\|Q\|_\infty^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|DV(f)(s)\|_{L(L^2)}^2 ds, \quad 0 \leq t \leq a. \end{aligned}$$

Hence,

$$\|DV(f)(t)\|_{L(L^2)}^2 \leq 2 + C\|Q\|_\infty^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|DV(f)(s)\|_{L(L^2)}^2 ds, \quad (2.71)$$

for $0 \leq t \leq a$ and $f \in L^2([0, 1], \mathbf{R})$ with $\|f\| \leq \rho$. Define

$$\eta(t) := \sup_{\substack{0 \leq s \leq t \\ \|f\| \leq \rho}} \|DV(f)(s)\|_{L(L^2)}^2, \quad 0 \leq t \leq a. \quad (2.72)$$

Then (2.71) and (2.86) give

$$\eta(t) \leq 2 + C\|Q\|_\infty^2 \int_0^t \frac{1}{(t-s)^{3/4}} \eta(s) ds, \quad 0 \leq t \leq a. \quad (2.73)$$

Iterating (2.73) yields

$$\eta(t) \leq 1 + C\|Q\|_\infty^2 + C\|Q\|_\infty^4 \int_0^t \frac{1}{(t-s)^{1/2}} \eta(s) ds, \quad 0 \leq t \leq a. \quad (2.74)$$

Again iterate (2.74) to obtain

$$\begin{aligned} \eta(t) &\leq 1 + C[\|Q\|_\infty^2 + \|Q\|_\infty^4 + \|Q\|_\infty^6] + C\|Q\|_\infty^8 \int_0^t \eta(s) ds \\ &\leq 1 + C\|Q\|_\infty^6 + C\|Q\|_\infty^8 \int_0^t \eta(s) ds, \quad 0 \leq t \leq a. \end{aligned} \quad (2.75)$$

By Gronwall's lemma, (2.75) implies

$$\eta(t) \leq [1 + C\|Q\|_\infty^6] e^{C\|Q\|_\infty^8 t}, \quad 0 \leq t \leq a.$$

Therefore,

$$\log^+ \sup_{\substack{0 \leq s \leq a \\ \|f\| \leq \rho}} \|DV(f)(s)\|_{L(L^2)} \leq \log^+ [1 + C\|Q\|_\infty^6] + C\|Q\|_\infty^8. \quad (2.76)$$

By the proof of the contraction mapping theorem (via successive approximation) and using the joint measurability of

$$\begin{aligned} \psi : \Omega \times B(f_0, \rho_0) \times Y &\longrightarrow E \\ (\omega, f, v) &\longmapsto \psi(f, v, \omega)(t) \\ &= T_t(f) - \int_0^t Q(s, \omega) T_{t-s} \left[v(s) \frac{\partial v(s)}{\partial \xi} \right] ds \end{aligned}$$

it follows that the maps

$$\begin{aligned} [0, a] \times L^2([0, 1], \mathbf{R}) \times \Omega &\longrightarrow L^2([0, 1], \mathbf{R}) \\ (t, f, \omega) &\longmapsto V(f, \omega)(t) \end{aligned}$$

and

$$\begin{aligned} [0, a] \times L^2([0, 1], \mathbf{R}) \times \Omega &\longrightarrow L^2([0, 1], \mathbf{R}) \\ (t, f, \omega) &\longmapsto DV(f, \omega)(t)(g) \end{aligned}$$

are jointly measurable (for each $g \in L^2([0, 1], \mathbf{R})$). This proves the strong measurability assertion in (iii) of the theorem. The proof of the first part of assertion (iii) follows from the Fréchet smoothness of U and assertion (ii) of the theorem.

Using the martingale property of Q and the relation

$$Q(t) = \exp \left\{ \gamma t + \sum_{k=1}^{\infty} (\sigma_k W_k(t) - \frac{1}{2} \sigma_k^2 t) \right\}, \quad t \geq 0,$$

it is easy to see that

$$E\|Q\|_\infty^p < \infty \quad (2.77)$$

for all $p \geq 1$. Taking expectations on both sides of (2.76), we get

$$E \log^+ \sup_{\substack{0 \leq s \leq a \\ \|f\|_2 \leq \rho}} \|DV(f)(t)\|_{L(L^2)} < \infty. \quad (2.78)$$

Now by (2.58), we have

$$DU(t, f, \omega) = Q(t, \omega)DV(f, \omega)(t). \quad (2.79)$$

Assertion (iv) of the theorem, for $k = 1$, now follows from (2.78) and (2.79). To complete the proof of the theorem, we indicate the proof of the estimate (2.55) for $k \geq 2$. From the proof of Theorem 2.1, recall that $E := C([0, a], L^2([0, 1], \mathbf{R}))$ and $\psi : L^2([0, 1], \mathbf{R}) \times E \rightarrow E$ is given by

$$\psi(f, v)(t) := T_t(f) - \frac{1}{2}A(v, v)(t), \quad f \in E, \quad 0 \leq t \leq a, \quad (2.80)$$

where $A : E \times E \rightarrow E$ is the continuous bilinear map

$$A(v_1, v_2)(t) := \int_0^t Q(s)T_{t-s} \left[\frac{\partial}{\partial \xi}(v_1(s)v_2(s)) \right] ds, \quad v_1, v_2 \in E, \quad 0 \leq t \leq a. \quad (2.81)$$

Therefore, (2.69) becomes

$$V(f)(t) := T_t(f) - \frac{1}{2}A(V(f), V(f))(t), \quad f \in L^2([0, 1], \mathbf{R}), \quad 0 \leq t \leq a. \quad (2.82)$$

Fix $t \in [0, a]$ and take Fréchet derivatives on both sides of the above equation to obtain

$$DV(f)(t) := T_t - \frac{1}{2}A(\cdot, V(f))(t) \circ DV(f)(t), \quad f \in L^2([0, 1], \mathbf{R}). \quad (2.83)$$

Since V is C^∞ , then using the fact that A is continuous symmetric bilinear, we can differentiate the above equation once more to obtain

$$D^{(2)}V(f)(\cdot, \cdot)(t) = A(DV(f)(\cdot), DV(f)(\cdot))(t) - A(\cdot, V(f)) \circ D^{(2)}V(f)(\cdot, \cdot)(t) \quad (2.84)$$

for all $f \in L^2([0, 1], \mathbf{R})$ and $t \in [0, a]$.

In the remaining estimates we will denote by C a generic deterministic positive constant that may change from line to line.

Taking $L^{(2)}(L^2)$ -norms on both sides of (2.84) and using an argument similar to the proof of (2.71), we get

$$\|D^{(2)}V(f)(t)\|^2 \leq C\|Q\|_\infty^2 \sup_{0 \leq t \leq a} \|DV(f)(\cdot)(t)\|_{L(L^2)}$$

$$+ C[\|Q\|_\infty^2 \int_0^t \frac{1}{(t-s)^{3/4}} \|V(f)(s)\|_{L^2}^2 \cdot \|D^{(2)}V(f)(s)\|^2 ds, \quad (2.85)$$

for all $f \in L^2([0, 1], \mathbf{R})$ and $t \in [0, a]$. Let $\eta(t)$, $t \in [0, a]$, be defined as in (2.72). Define

$$\beta(t) := \sup_{\substack{0 \leq s \leq t \\ \|f\| \leq \rho}} \|D^{(2)}V(f)(s)\|_{L^{(2)}(L^2)}^2, \quad 0 \leq t \leq a. \quad (2.86)$$

From (2.75), we know that

$$\eta(t) \leq [1 + C\|Q\|_\infty^6] e^{C\|Q\|_\infty^8 t}, \quad 0 \leq t \leq a. \quad (2.87)$$

Hence (2.85) implies

$$\beta(t) \leq C\|Q\|_\infty^8 e^{C\|Q\|_\infty^8 t} + C\|Q\|_\infty^2 \int_0^t \frac{\beta(s)}{(t-s)^{3/4}} ds, \quad 0 \leq t \leq a. \quad (2.88)$$

Iterating the above inequality gives

$$\beta(t) \leq C\|Q\|_\infty^{10} e^{C\|Q\|_\infty^8 t} + C\|Q\|_\infty^4 \int_0^t \frac{\beta(s)}{(t-s)^{1/2}} ds, \quad 0 \leq t \leq a, \quad (2.89)$$

and iterating once more, we obtain

$$\beta(t) \leq C\|Q\|_\infty^{14} e^{C\|Q\|_\infty^8 t} + C\|Q\|_\infty^8 \int_0^t \beta(s) ds, \quad 0 \leq t \leq a, \quad (2.90)$$

Then Gronwall's lemma implies

$$\beta(t) \leq C\|Q\|_\infty^{14} e^{C\|Q\|_\infty^8 t}, \quad 0 \leq t \leq a. \quad (2.91)$$

Since Q has finite moments of all orders, the above inequality implies

$$E \log^+ \sup_{\substack{0 \leq t \leq a \\ \|f\| \leq \rho}} \|D^{(2)}V(f)(s)\|_{L^{(2)}(L^2)}^2 < \infty. \quad (2.92)$$

To complete the proof of (2.55), one may take higher-order Fréchet derivatives of (2.84) and then repeat the above argument to obtain

$$E \log^+ \sup_{\substack{0 \leq t \leq a \\ \|f\| \leq \rho}} \|D^{(k)}V(f)(s)\|_{L^{(k)}(L^2)}^2 < \infty, \quad k \geq 1, \quad (2.93)$$

by induction on k . This completes the proof of assertion (iv) of the theorem. \square

3 Stability

Our objective in this section is to characterize the local behavior of solutions of Burgers spde (1.1) near its zero stationary point.

A trivial stationary solution of (1.1) is $U(t, 0, \omega) \equiv 0$ corresponding to the zero initial function $f \equiv 0 \in L^2([0, 1], \mathbf{R})$. Linearizing the cocycle $U : \mathbf{R}^+ \times L^2([0, 1], \mathbf{R}) \times \Omega \rightarrow L^2([0, 1], \mathbf{R})$ at $f = 0$ gives a solution of the linearized Burgers equation:

$$DU(t, 0, \omega) = Q(t, \omega)DV(0, \omega)(t)$$

where

$$DV(0, \omega)(t) = T_t - \int_0^t Q(s, \omega)T_{t-s} \left[V(0)(s) \frac{\partial}{\partial \xi} DV(0)(s) + DV(0)(s) \frac{\partial}{\partial \xi} V(0)(s) \right] ds$$

i.e.

$$DV(0, \omega)(t) = T_t, \quad t > 0,$$

because $V(0)(s) = 0$ for all $s > 0$. Hence,

$$DU(t, 0, \omega) = Q(t, \omega)T_t \tag{3.1}$$

$$= \exp \left\{ \gamma t + \sum_{i=1}^{\infty} (\sigma_i W_i(t, \omega) - \frac{1}{2} \sigma_i^2 t) \right\} T_t, \quad t \geq 0. \tag{3.2}$$

Recall that $T_t : L^2([0, 1], \mathbf{R}) \rightarrow L^2([0, 1], \mathbf{R})$, $t \geq 0$, is the heat semigroup of the Laplacian $\nu\Delta$ with Dirichlet boundary condition on $[0, 1]$. Now $\nu\Delta$ has a discrete spectrum of simple eigenvalues $\mu_n := -\nu\pi^2 n^2$, $n = 1, 2, 3, \dots$ and a complete orthonormal system of corresponding eigenfunctions $e_n(\xi) := \sqrt{2} \sin(n\pi\xi)$, $\xi \in [0, 1]$, $n \geq 1$. Let F_n be the one-dimensional eigenspace of $\nu\Delta$ corresponding to the eigenvalue μ_n , viz. $F_n := \{\sqrt{2}r \sin(n\pi(\cdot)) : r \in \mathbf{R}\}$. We now apply the Oseledec-Ruelle spectral theorem to the compact linear cocycle $(DU(t, 0, \omega), \theta(t, \omega))$, $t \geq 0$, $\omega \in \Omega$. This gives

Theorem 3.1 (The Lyapunov spectrum). *Let $(U(t, \cdot, \omega), \theta(t, \omega))$ be the smooth cocycle on $L^2([0, 1], \mathbf{R})$ generated by the stochastic Burgers equation (1.1). Then the following limit*

$$\exp \left\{ \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right\} T_1 = \lim_{t \rightarrow \infty} \{ [DU(t, 0, \omega)]^* \circ [DU(t, 0, \omega)] \}^{1/2t} \tag{3.3}$$

exists in the uniform operator norm in $L(L^2([0, 1], \mathbf{R}))$. The operator in (3.3) is compact, self-adjoint and non-negative with discrete simple spectrum

$$e^{\lambda_1} > e^{\lambda_2} > e^{\lambda_3} > \dots > e^{\lambda_n} > \dots \tag{3.4}$$

The Lyapunov exponents $\{\lambda_n := \gamma - \nu\pi^2 n^2 - \frac{1}{2} \sum_{i=1}^{\infty} \sigma_i^2\}_{n=1}^{\infty}$ correspond to values of the almost sure limit

$$\lim_{t \rightarrow \infty} \frac{1}{t} \log \|DU(t, 0, \omega)(g)\|_{L^2} \in \left\{ \gamma - \nu\pi^2 n^2 - \frac{1}{2} \sum_{i=1}^{\infty} \sigma_i^2 \right\}_{n=1}^{\infty}$$

for $g \in L^2([0, 1], \mathbf{R})$. Indeed, set

$$E_1 := L^2([0, 1], \mathbf{R}), \quad E_n := \left[\bigoplus_{j=1}^{n-1} F_j \right]^{\perp}, \quad n > 1.$$

Then $\text{codim } E_n = n - 1$,

$$E_n \subset E_{n-1} \subset \cdots \subset E_2 \subset E_1, \quad n > 1,$$

$$\lim_{t \rightarrow \infty} \frac{1}{t} \log \|DU(t, 0, \omega)(g)\|_{L^2} = \gamma - \nu\pi^2 n^2 - \frac{1}{2} \sum_i \sigma_i^2 \quad (3.5)$$

for $g \in E_n \setminus E_{n+1}$,

$$\lim_{t \rightarrow \infty} \frac{1}{t} \log \|DU(t, 0, \omega)\|_{L(L^2)} = \gamma - \nu\pi^2 - \frac{1}{2} \sum_{i=1}^{\infty} \sigma_i^2 \quad (3.6)$$

$$DU(t, 0, \omega)(E_n) \subseteq E_n \quad (3.7)$$

for all $t \geq 0$, $\omega \in \Omega$, $n \geq 1$.

Proof. Recall the Oseledec integrability condition

$$E \log^+ \sup_{0 \leq t_1, t_2 \leq a} \|DU(t_2, 0, \theta(t_1, \cdot))\|_{L(L^2)} < \infty. \quad (3.8)$$

for any $0 < a < \infty$, which follows directly from (3.66) in Theorem 3.2. Using the above integrability condition and the Ruelle-Oseledec theorem (Theorem 2.1.1, [M-Z-Z]), there is a random family of compact self-adjoint positive operators $\Lambda(\omega) \in L(L^2)$, defined perfectly in ω , and satisfies

$$\Lambda(\omega) := \lim_{t \rightarrow \infty} \left\{ [DU(t, 0, \omega)]^* \circ [DU(t, 0, \omega)] \right\}^{1/2t} \quad (3.9)$$

The above almost sure limit exists in the uniform operator norm in $L(L^2)$, perfectly in ω . The operator $\Lambda(\omega)$ has in discrete non-random spectrum

$$e^{\lambda_1} > e^{\lambda_2} > e^{\lambda_3} > \cdots > e^{\lambda_n} > \cdots \quad (3.10)$$

due to the ergodicity of the Brownian shift θ .

In order to evaluate the Lyapunov spectrum $\{\lambda_n : n \geq 1\}$ of the linearized cocycle $(DU(t, 0, \omega), \theta(t, \omega))$, we first compute the Oseledec operators $\Lambda(\omega)$. To do this, use relation (4.2) to obtain

$$\begin{aligned}
\Lambda(\omega) &= \lim_{t \rightarrow \infty} \{[DU(t, 0, \omega)]^* \circ [DU(t, 0, \omega)]\}^{1/2t} \\
&= \lim_{t \rightarrow \infty} \left[\exp \left\{ 2\gamma t + \sum_{k=1}^{\infty} (2\sigma_k W_k(t) - \sigma_k^2 t) \right\} (T_t^* \circ T_t) \right]^{1/2t} \\
&= \lim_{t \rightarrow \infty} \exp \left\{ \gamma + \sum_{k=1}^{\infty} \left(\sigma_k \frac{W_k(t)}{t} - \frac{\sigma_k^2}{2} \right) \right\} \lim_{t \rightarrow \infty} (T_t^* \circ T_t)^{1/2t} \\
&= \exp \left\{ \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right\} \lim_{t \rightarrow \infty} (T_t^* \circ T_t)^{1/2t}. \tag{3.11}
\end{aligned}$$

Now, it is easy to see that

$$(T_t^* \circ T_t)(e_n) = \exp\{-2\nu\pi^2 n^2 t\} e_n, \quad n \geq 1$$

for all $n \geq 1$. Therefore,

$$(T_t^* \circ T_t)^{1/2t} = T_1 \tag{3.12}$$

for all $t > 0$. By (3.11) and (3.12), we get (3.3) and (3.5). In particular, (4.3) implies that the Oseledec-Ruelle operator $\exp \left\{ \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right\} T_1$ is *non-random*. Consequently, the Oseledec spaces $\{E_n : n \geq 1\}$ are also non-random.

The assertions (3.6) and (3.7) of the theorem follow from the Oseledec-Ruelle spectral theorem (Theorem 2.1.1, [M-Z-Z]). Cf.[11, Thm. 3.1]. \square

Remark.

- (i) The Oseledec spaces $\{E_n\}_{n=1}^{\infty}$ in Theorem 2.1 are non-random because the Oseledec-Ruelle operator

$$\Lambda(\omega) = \exp \left\{ \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right\} T_1, \quad \omega \in \Omega, \tag{3.13}$$

is deterministic.

- (ii) When the top Lyapunov exponent $\lambda_1 = \gamma - \nu\pi^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2$ of the linearized cocycle $(DU(t, 0, \omega), \theta(t, \omega))$ of Burgers equation (1.1) is negative, this suggests that the zero solution of (1.1) is globally a.s. asymptotically stable with exponential decay rate λ_1 (for solutions starting with deterministic initial functions in $L^2([0, 1], \mathbf{R})$).

For the remainder of the article we will adopt the following convention:

Definition 3.1 (Perfection). A family of propositions $\{P(\omega) : \omega \in \Omega\}$ is said to **hold perfectly in ω** if there is a sure event $\Omega^* \in \mathcal{F}$ such that $\theta(t, \cdot)(\Omega^*) = \Omega^*$ for all $t \in \mathbf{R}$ and $P(\omega)$ is true **for every** $\omega \in \Omega^*$.

We next describe the concepts of a stationary point and hyperbolicity for the Burgers spde (1.1).

Definition 3.2 (Stationary point/equilibrium). An \mathcal{F} -measurable random variable $Y : \Omega \rightarrow L^2([0, 1], \mathbf{R})$ is said to be a **stationary random point** or **equilibrium** for the cocycle (U, θ) if

$$U(t, Y(\omega), \omega) = Y(\theta(t, \omega)) \quad (3.14)$$

for all $t \in \mathbf{R}^+$, and $\omega \in \Omega$.

Let $Y : \Omega \rightarrow L^2([0, 1], \mathbf{R})$ be a stationary random point for the cocycle (U, θ) of (1.1) with $E \log^+ \|Y\|_{L^2} < \infty$. It is easy to see that $(DU(t, Y(\omega), \omega), \theta(t, \omega))$ is a compact linear cocycle. So by the integrability condition (2.55) and the Ruelle-Oseledec theorem, it has a discrete fixed Lyapunov spectrum

$$\{\dots < \tilde{\lambda}_{i+1} < \tilde{\lambda}_i < \dots < \tilde{\lambda}_2 < \tilde{\lambda}_1\}.$$

The stationary point Y is said to be *hyperbolic* if $\tilde{\lambda}_i \neq 0$ for all $i \geq 1$.

Our next result gives necessary and sufficient conditions for hyperbolicity of the zero equilibrium $Y \equiv 0$. It is a consequence of the nonlinear multiplicative ergodic theorem ([13, Theorem 4.1]).

Theorem 3.2 (Hyperbolicity of equilibrium). *In Burgers spde (1.1), the zero equilibrium is hyperbolic if and only if the following conditions hold*

- (i) $-\nu\pi^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 > 0$;
- (ii) $-\nu\pi^2 n^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \neq 0$ for all $n \geq 2$.

Proof. The result follows immediately from the formula $\lambda_n = -\nu\pi^2 n^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2$, $n \geq 1$, for the Lyapunov exponents of the linearized cocycle $(DU(t, 0, \omega), \theta(t, \omega))$ (Theorem 3.1). \square

Theorem 3.3 below is a consequence of the nonlinear multiplicative ergodic theorem ([13, Theorem 2.2.1]). It establishes a saddle-point property for the random semiflow near a hyperbolic zero equilibrium.

Recall that $B(0, \rho)$ denotes the closed ball in $L^2([0, 1], \mathbf{R})$ with center 0 and radius $\rho > 0$.

Theorem 3.3 (The local stable manifold theorem). *In Burgers spde (1.1), assume that the zero equilibrium is hyperbolic. Define $i_0 := \min\{i : -\nu\pi^2 i^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 < 0\}$.*

Fix $\epsilon_1 \in (0, \nu\pi^2 i_0^2 - \gamma + \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2)$ and $\epsilon_2 \in (0, -\nu\pi^2 (i_0 - 1)^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2)$. Then there exist

- (i) a sure event $\Omega^* \in \mathcal{F}$ with $\theta(t, \cdot)(\Omega^*) = \Omega^*$ for all $t \in \mathbf{R}$,
- (ii) \mathcal{F} -measurable random variables $\rho_i, \beta_i : \Omega^* \rightarrow (0, 1)$, $\beta_i > \rho_i > 0$, $i = 1, 2$, such that for each $\omega \in \Omega^*$, the following is true:

There are C^∞ submanifolds $\tilde{\mathcal{S}}(\omega), \tilde{\mathcal{U}}(\omega)$ of $B(0, \rho_1(\omega))$ and $B(0, \rho_2(\omega))$ (resp.) with the following properties:

- (a) $\tilde{\mathcal{S}}(\omega)$ is the set of all $f \in B(0, \rho_1(\omega))$ such that

$$\|U(n, f, \omega)\|_{L^2} \leq \beta_1(\omega) \exp \left\{ \left(-\nu\pi^2 i_0^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 + \epsilon_1 \right) n \right\}$$

for all integers $n \geq 0$. Furthermore,

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq -\nu\pi^2 i_0^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \quad (3.15)$$

for all $f \in \tilde{\mathcal{S}}(\omega)$. The stable subspace \mathcal{S} of the linearized cocycle $(DU(t, 0, \cdot), \theta(t, \cdot))$ is tangent at 0 to the submanifold $\tilde{\mathcal{S}}(\omega)$, viz. $T_0 \tilde{\mathcal{S}}(\omega) = \mathcal{S}$. In particular, $\text{codim } \tilde{\mathcal{S}}(\omega) = \text{codim } \mathcal{S} = \sum_{j=1}^{i_0-1} \dim F_j$ is fixed and finite.

$$(b) \limsup_{t \rightarrow \infty} \frac{1}{t} \log \left[\sup \left\{ \frac{\|U(t, f_1, \omega) - U(t, f_2, \omega)\|_{L^2}}{\|f_1 - f_2\|_{L^2}} : f_1 \neq f_2, f_1, f_2 \in \tilde{\mathcal{S}}(\omega) \right\} \right] \\ \leq -\nu\pi^2 i_0^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2.$$

- (c) (Cocycle-invariance of the stable manifolds):

There exists $\tau_1(\omega) \geq 0$ such that

$$U(t, \cdot, \omega)(\tilde{\mathcal{S}}(\omega)) \subseteq \tilde{\mathcal{S}}(\theta(t, \omega)) \quad (3.16)$$

for all $t \geq \tau_1(\omega)$. Also

$$DU(t, 0, \omega)(\mathcal{S}) \subseteq \mathcal{S}, \quad t \geq 0. \quad (3.17)$$

- (d) $\tilde{\mathcal{U}}(\omega)$ is the set of all $f \in B(0, \rho_2(\omega))$ with the property that there is a discrete-time "history" process $y(\cdot, \omega) : \{-n : n \geq 0\} \rightarrow L^2([0, 1], \mathbf{R})$ such that $y(0, \omega) = f$ and for each integer $n \geq 1$, one has $U(1, y(-n, \omega), \theta(-n, \omega)) = y(-(n-1), \omega)$ and

$$\|y(-n, \omega)\|_{L^2} \leq \beta_2(\omega) \exp \left\{ - \left(-\nu\pi^2 (i_0 - 1)^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 - \epsilon_2 \right) n \right\}.$$

Furthermore, for each $f \in \tilde{\mathcal{U}}(\omega)$, there is a unique continuous-time “history” process also denoted by $y(\cdot, \omega) : (-\infty, 0] \rightarrow L^2([0, 1], \mathbf{R})$ such that $y(0, \omega) = f$, $U(t, y(s, \omega), \theta(s, \omega)) = y(t + s, \omega)$ for all $s \leq 0, 0 \leq t \leq -s$, and

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \|y(-t, \omega)\|_{L^2} \leq - \left(-\nu\pi^2(i_0 - 1)^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right).$$

Each unstable subspace \mathcal{U} of the linearized cocycle $(DU(t, 0, \cdot), \theta(t, \cdot))$ is tangent at 0 to $\tilde{\mathcal{U}}(\omega)$, viz. $T_0\tilde{\mathcal{U}}(\omega) = \mathcal{U}$. In particular, $\dim \tilde{\mathcal{U}}(\omega) = \sum_{j=1}^{i_0-1} \dim F_j$ is finite and non-random.

- (e) Let $y(\cdot, f_i, \omega), i = 1, 2$, be the history processes associated with $f_i = y(0, f_i, \omega) \in \tilde{\mathcal{U}}(\omega), i = 1, 2$. Then

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \left[\sup \left\{ \frac{\|y(-t, f_1, \omega) - y(-t, f_2, \omega)\|_{L^2}}{\|f_1 - f_2\|_{L^2}} : f_1 \neq f_2, f_i \in \tilde{\mathcal{U}}(\omega), i = 1, 2 \right\} \right] \leq - \left(-\nu\pi^2(i_0 - 1)^2 + \gamma - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \right).$$

- (f) (Cocycle-invariance of the unstable manifolds):

There exists $\tau_2(\omega) \geq 0$ such that

$$\tilde{\mathcal{U}}(\omega) \subseteq U(t, \cdot, \theta(-t, \omega))(\tilde{\mathcal{U}}(\theta(-t, \omega))) \quad (3.18)$$

for all $t \geq \tau_2(\omega)$. Also

$$DU(t, 0, \theta(-t, \omega))(\mathcal{U}) = \mathcal{U}, \quad t \geq 0;$$

and the restriction

$$Du(t, 0, \theta(-t, \omega))|_{\mathcal{U}} : \mathcal{U} \rightarrow \mathcal{U}, \quad t \geq 0,$$

is a linear homeomorphism onto.

- (g) The submanifolds $\tilde{\mathcal{U}}(\omega)$ and $\tilde{\mathcal{S}}(\omega)$ are transversal, viz.

$$L^2([0, 1], \mathbf{R}) = T_0\tilde{\mathcal{U}}(\omega) \oplus T_0\tilde{\mathcal{S}}(\omega).$$

We will only give an outline of the proof of Theorem 4.3. Full details of the proof may be obtained by adapting the arguments in [12] and [13].

An outline of the proof of Theorem 3.3:

- Develop perfect continuous-time versions of Kingman's subadditive ergodic theorem as well as the ergodic theorem ([13], Lemma 2.3.1 (ii), (iii)). The linearized cocycle $(DU(t, 0, \cdot), \theta(t, \cdot))$ at the zero equilibrium can be shown to satisfy the hypotheses of these perfect ergodic theorems. As a consequence of the perfect ergodic theorems, one obtains stable/unstable subspaces for the linearized cocycle, which will constitute tangent spaces to the local stable and unstable manifolds of the nonlinear cocycle (U, θ) .
- We use hyperbolicity of the zero equilibrium, the continuous-time integrability condition (2.55) on the cocycle and perfect versions of the ergodic and subadditive ergodic theorems to show the existence of local stable/unstable manifolds for the discrete cocycle $(U(n, \cdot, \omega), \theta(n, \omega))$ near 0 (cf. [14], Theorems 5.1 and 6.1). These manifolds are random objects and are perfectly defined for $\omega \in \Omega$. Using interpolation between discrete times and the (continuous-time) integrability condition (3.66), it can be shown that the above manifolds for the discrete-time cocycle $(U(n, \cdot, \omega), \theta(n, \omega)), n \geq 1$, also serve as perfectly defined local stable/unstable manifolds for the *continuous-time* cocycle $(U(t, \cdot, \omega), \theta(t, \omega)), t \geq 0$, near 0 (see [12],[13], [14]).
- Again, by using the integrability condition (2.55) on the nonlinear cocycle and its Fréchet derivatives, it is possible to control the excursions of the continuous-time cocycle $(U(t, \cdot, \omega), \theta(t, \omega)), t \geq 0$, between discrete times. In view of the perfect subadditive ergodic theorem, these estimates show that the local stable manifolds are asymptotically invariant under the non-linear cocycle. The asymptotic invariance of the unstable manifolds is obtained via the concept of a *stochastic history process* for the cocycle. The existence of a stochastic history process is needed because the (locally compact) cocycle is *not invertible*.

This completes the outline of the proof of Theorem 3.3. □

Our next result gives sufficient conditions on the parameters of Burgers spde (1.1) to guarantee that the zero equilibrium is its only stationary point.

Theorem 3.4 (Uniqueness of the stationary solution). *Suppose that*

$$\pi^2\nu > \gamma + \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2. \tag{3.19}$$

Then the zero equilibrium $u \equiv 0$ is the only stationary solution of Burgers spde (1.1).

Proof. Assume that Burgers spde (1.1) admits a non-zero stationary solution $u_0(t)$. By stationarity, $a := E[\|u_0(t)\|_{L^2}^2] > 0$ and $b := E\left[\left\|\frac{\partial u_0(t)}{\partial \xi}\right\|_{L^2}^2\right] > 0$ are independent of t .

Suppose $t > s > 0$. Then from (1.1) and Ito's formula, we have

$$\begin{aligned} \|u_0(t)\|_{L^2}^2 &= \|u_0(s)\|_{L^2}^2 - 2\nu \int_s^t \left\| \frac{\partial u_0(r)}{\partial \xi} \right\|_{L^2}^2 dr + 2 \sum_{k=1}^{\infty} \int_s^t \sigma_k \|u_0(r)\|_{L^2}^2 dW_k(r) \\ &\quad + 2\gamma \int_s^t \|u_0(r)\|_{L^2}^2 dr + \sum_{k=1}^{\infty} \int_s^t \sigma_k^2 \|u_0(r)\|_{L^2}^2 dr. \end{aligned} \quad (3.20)$$

Taking expectations on both sides of the above identity, we obtain

$$a = a - 2\nu(t-s)b + \sum_{k=1}^{\infty} \sigma_k^2(t-s)a + 2\gamma(t-s)a. \quad (3.21)$$

Hence

$$2\nu b = \left[\sum_{k=1}^{\infty} \sigma_k^2 + 2\gamma \right] a. \quad (3.22)$$

Combining the above equality with Wirtinger's inequality:

$$a \leq \frac{b}{\pi^2}, \quad (3.23)$$

it follows that

$$\pi^2 \nu \leq \gamma + \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2. \quad (3.24)$$

This proves the theorem. □

We conclude this section by stating the *Local Invariant Manifold Theorem* and the *Global Invariant Foliation Theorem* for Burgers spde (1.1) when $\gamma = 0$ (Theorems 3.5 and 3.6 below). These results are also consequences of the nonlinear multiplicative ergodic theorem ([13, Theorem 2.2.1]). The *Local Invariant Manifold Theorem* (Theorem 3.5) characterizes the almost sure asymptotic stability of the random flow of Burgers spde (1.1) in the neighborhood of the zero equilibrium, in the special case when the linear drift vanishes ($\gamma = 0$). On the other hand, the *Global Invariant Foliation Theorem* (Theorem 3.6) gives a random cocycle-invariant foliation in $L^2([0, 1], \mathbf{R})$. The invariant global foliation is characterized by the Lyapunov exponents $\{\lambda_i : i \geq 1\}$ of the cocycle (U, θ) .

Theorem 3.5 (Local invariant manifolds). *Let (U, θ) be the cocycle generated by Burgers spde (1.1) with $\gamma = 0$. Fix $\epsilon_1 \in (0, \nu\pi^2 + \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2)$. Then there exist*

- (i) *a sure event $\Omega^* \in \mathcal{F}$ with $\theta(t, \cdot)(\Omega^*) = \Omega^*$ for all $t \in \mathbf{R}$,*

(ii) \mathcal{F} -measurable random variables $\rho_i, \beta_i : \Omega^* \rightarrow (0, 1)$, $\beta_i > \rho_i \geq \rho_{i+1} > 0$, $i \geq 1$, such that for each $\omega \in \Omega^*$, the following is true:

For each $i \geq 1$, there is a C^∞ submanifold $\mathcal{S}_i(\omega)$ of $B(0, \rho_i(\omega))$ with the following properties:

(a) $\mathcal{S}_i(\omega)$ is the set of all $f \in B(0, \rho_i(\omega))$ such that

$$\|U(n, f, \omega)\|_{L^2} \leq \beta_i(\omega) \exp \left\{ \left(-\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 + \epsilon_i \right) n \right\}$$

for all integers $n \geq 0$. Furthermore,

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \quad (3.25)$$

for all $f \in \mathcal{S}_i(\omega)$. Each $\mathcal{S}_{i+1}(\omega)$ is a submanifold of $\mathcal{S}_i(\omega)$. Furthermore, each Oseledec space E_i of the linearized cocycle $(DU(t, 0, \cdot), \theta(t, \cdot))$ is tangent at 0 to the submanifold $\mathcal{S}_i(\omega)$, viz. $T_0 \mathcal{S}_i(\omega) = E_i$. In particular, $\text{codim} \mathcal{S}_i(\omega) = \text{codim} E_i = i - 1$ (fixed and finite).

$$\begin{aligned} \text{(b)} \quad \limsup_{t \rightarrow \infty} \frac{1}{t} \log \left[\sup \left\{ \frac{\|U(t, f_1, \omega) - U(t, f_2, \omega)\|_{L^2}}{\|f_1 - f_2\|_{L^2}} : f_1 \neq f_2, f_1, f_2 \in \mathcal{S}_i(\omega) \right\} \right] \\ \leq -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2. \end{aligned}$$

(c) (Cocycle-invariance):

There exists $\tau_i(\omega) \geq 0$ such that

$$U(t, \cdot, \omega)(\mathcal{S}_i(\omega)) \subseteq \mathcal{S}_i(\theta(t, \omega)) \quad (3.26)$$

for all $t \geq \tau_i(\omega)$. Also

$$DU(t, 0, \omega)(E_i) \subseteq E_i, \quad t \geq 0. \quad (3.27)$$

Conjecture:

Burgers spde (1.1) has a family of cocycle-invariant (one-dimensional) smooth curves $\{\Gamma_n(\omega)\}_{n=1}^{\infty}$ foliating $B(0, \rho_1(\omega))$ and passing through 0 with tangents $\{F_n\}_{n=1}^{\infty}$ at 0. On each $\Gamma_n(\omega)$, the mild solution of Burgers spde (1.1) decays exponentially fast with rate

$$\lambda_n = -\nu\pi^2 n^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2.$$

Proof of Theorem 3.5. Let $\epsilon_1 \in \left(0, \nu\pi^2 + \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2\right)$. Then there exists $\Omega^* \in \mathcal{F}$ such that $\theta(t, \cdot)(\Omega^*) = \Omega^*$ for all $t \in \mathbf{R}$, and \mathcal{F} -measurable random variables $\rho_i, \beta_i : \Omega^* \rightarrow (0, 1)$ such that $\beta_i(\omega) > \rho_i(\omega) > 0$, and C^∞ stable local submanifolds $S_i(\omega) \subset B(0, \rho_i(\omega))$ given by

$$S_i(\omega) := \left\{ f : f \in B(0, \rho_i(\omega)), \|U(n, f, \omega)\|_{L^2} \leq \beta_i(\omega) e^{(-\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 + \epsilon_1)n} \quad \forall n \geq 1 \right\}. \quad (3.28)$$

Furthermore,

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2 \quad (3.29)$$

for all $f \in S_i(\omega)$.

Also, $T_0 S_i(\omega) = E_i$, the Oseledec space for the linearized cocycle $(DU(t, 0, \omega), \theta(t, \omega))$ corresponding to the Lyapunov exponent $\lambda_i := -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2$, $i \geq 1$.

Following the argument in [12] and [14], the random variables $\rho_i(\omega)$, $\beta_i(\omega)$ may be selected such that

$$\rho_i(\omega) e^{(\lambda_i + \epsilon_1)t} \leq \rho_i(\theta(t, \omega)) \quad (3.30)$$

and

$$\beta_i(\omega) e^{(\lambda_i + \epsilon_1)t} \leq \beta_i(\theta(t, \omega)) \quad (3.31)$$

for all $t \geq 0$ and $\omega \in \Omega^*$ (where $\lambda_i := -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2$). We now show that there exists $\tau_i(\omega) > 0$ such that

$$U(t, \cdot, \omega)(S_i(\omega)) \subseteq S_i(\theta(t, \omega)) \quad \forall t \geq \tau_i(\omega) \quad (3.32)$$

and all $\omega \in \Omega^*$.

Let $f \in S_i(\omega)$, $t \geq 0$ and let $n \geq 0$ be any integer. Consider (by the cocycle property):

$$\|U(n, U(t, f, \omega), \theta(t, \omega))\|_{L^2} = \|U(n+t, f, \omega)\|_{L^2}. \quad (3.33)$$

From [12] and [14], we have

$$\limsup_{t \rightarrow \infty} \frac{1}{t} \log \left[\sup_{\substack{f \in S_i(\omega) \\ f \neq 0}} \frac{\|U(t, f, \omega)\|_{L^2}}{\|f\|_{L^2}} \right] \leq \lambda_i. \quad (3.34)$$

From the above estimate, for any $\epsilon' \in (0, \epsilon_1)$, there exists $N_0 = N_0(\epsilon') > 0$ such that

$$\sup_{t \geq N} \frac{1}{t} \log \left[\sup_{\substack{f \in S_i(\omega) \\ f \neq 0}} \frac{\|U(t, f, \omega)\|_{L^2}}{\|f\|_{L^2}} \right] \leq \lambda_i + \epsilon', \quad \forall N \geq N_0.$$

Thus

$$\sup_{\substack{f \in S_i(\omega) \\ f \neq 0}} \frac{\|U(t, f, \omega)\|_{L^2}}{\|f\|_{L^2}} \leq e^{(\lambda_i + \epsilon')t}, \quad t \geq N_0.$$

Define

$$\beta_i^{\epsilon'}(\omega) := \sup_{0 \leq t \leq N_0} \sup_{\substack{f \in S_i(\omega) \\ f \neq 0}} \frac{\|U(t, f, \omega)\|_{L^2}}{\|f\|_{L^2}} \cdot e^{-(\lambda_i + \epsilon')N_0}.$$

Therefore,

$$\sup_{\substack{f \in S_i(\omega) \\ f \neq 0}} \frac{\|U(t, f, \omega)\|_{L^2}}{\|f\|_{L^2}} \leq \beta_i^{\epsilon'}(\omega) \cdot e^{(\lambda_i + \epsilon')t} \quad \forall t \geq 0.$$

Since $f \in S_i(\omega) \subset B(0, 1)$, then $\|f\| \leq 1$ and

$$\|U(t, f, \omega)\|_{L^2} \leq \beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t} \quad (3.35)$$

for all $t \geq 0$. Therefore, from (3.33) and (3.35),

$$\begin{aligned} \|U(n, U(t, f, \omega), \theta(t, \omega))\|_{L^2} &\leq \beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')(n+t)} \\ &\leq \beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t} \cdot e^{(\lambda_i + \epsilon_1)n}. \end{aligned} \quad (3.36)$$

Consider

$$\lim_{t \rightarrow \infty} \frac{\beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t}}{\beta_i(\omega) e^{(\lambda_i + \epsilon_1)t}} = \lim_{t \rightarrow \infty} \frac{\beta_i^{\epsilon'}(\omega)}{\beta_i(\omega)} \cdot e^{(\epsilon' - \epsilon_1)t} = 0$$

because $\epsilon' < \epsilon_1$. Thus there exists $\tilde{\tau}_i(\omega) > 0$ such that

$$\beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t} \leq \beta_i(\omega) e^{(\lambda_i + \epsilon_1)t}, \quad \forall t \geq \tilde{\tau}_i(\omega). \quad (3.37)$$

By (3.36), (3.37) and (3.31), we get

$$\begin{aligned} \|U(n, U(t, f, \omega), \theta(t, \omega))\| &\leq \beta_i(\omega) e^{(\lambda_i + \epsilon_1)t} \cdot e^{(\lambda_i + \epsilon_1)n} \\ &\leq \beta_i(\theta(t, \omega)) e^{(\lambda_i + \epsilon_1)n} \end{aligned} \quad (3.38)$$

for all $n \geq 1$ and all $t \geq \tilde{\tau}_i(\omega)$. Furthermore,

$$\lim_{t \rightarrow \infty} \frac{\beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t}}{\rho_i(\theta(t, \omega))} \leq \lim_{t \rightarrow \infty} \frac{\beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t}}{\beta_i(\omega) e^{(\lambda_i + \epsilon_1)t}} = 0. \quad (3.39)$$

Therefore, there exists $\tilde{\tilde{\tau}}_i(\omega) > 0$ such that

$$\beta_i^{\epsilon'}(\omega) e^{(\lambda_i + \epsilon')t} \leq \rho_i(\theta(t, \omega)) \quad (3.40)$$

for all $t \geq \tilde{\tilde{\tau}}_i(\omega)$. Hence $U(t, f, \omega) \in B(0, \rho_i(\theta(t, \omega)))$ for all $t \geq \tilde{\tilde{\tau}}_i(\omega)$.

Define $\tau_i(\omega) := \tilde{\tau}_i(\omega) \vee \tilde{\tilde{\tau}}_i(\omega)$. Then $U(t, f, \omega) \in B(0, \rho_i(\theta(t, \omega)))$ and satisfies (3.38) for all $n \geq 0$ and all $t \geq \tau_i(\omega)$. By definition of $S_i(\theta(t, \omega))$, it follows that $U(t, f, \omega) \in S_i(\theta(t, \omega))$ for all $t \geq \tau_i(\omega)$. Thus $U(t, \cdot, \omega)(S_i(\omega)) \subseteq S_i(\theta(t, \omega))$ for all $t \geq \tau_i(\omega)$. Note that $\tau_i(\omega)$, $\tilde{\tau}_i(\omega)$, $\tilde{\tilde{\tau}}_i(\omega)$ are all independent of $f \in S_i(\omega)$ because $\beta_i(\omega)$, $\beta_i^{\varepsilon'}(\omega)$ and $\rho_i(\omega)$ are independent of $f \in S_i(\omega)$. This completes the proof of asymptotic invariance of $S_i(\omega)$, $i \geq 1$. \square

In Theorem 3.6 below, we use the Lyapunov spectrum $\{\lambda_i\}_{i=1}^{\infty}$ of the linearized cocycle to establish the existence of global invariant flag manifolds for the (nonlinear) cocycle (U, θ) .

Theorem 3.6 (Global invariant flag). *Consider Burgers spde (1.1) with $\gamma = 0$. Define the random family of sets $\{M_i(\omega) : \omega \in \Omega^*, i \geq 1\}$ by*

$$M_i(\omega) := \left\{ f \in L^2([0, 1], \mathbf{R}) : \overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq \lambda_i \right\} \quad (3.41)$$

for $i \geq 1$, $\omega \in \Omega^*$, where $\lambda_i := -\nu\pi^2 i^2 - \frac{1}{2} \sum_{k=1}^{\infty} \sigma_k^2$. For fixed $i \geq 1$, $\omega \in \Omega^*$, define the sequence $\{S_i^n(\omega)\}_{n=1}^{\infty}$, inductively by:

$$S_i^1(\omega) := S_i(\omega) \quad (3.42)$$

$$S_i^n(\omega) := \begin{cases} U(n, \cdot, \omega)^{-1}[S_i(\theta(n, \omega))], & \text{if } S_i^{n-1}(\omega) \subseteq U(n, \cdot, \omega)^{-1}[S_i(\theta(n, \omega))] \\ S_i^{n-1}(\omega), & \text{otherwise,} \end{cases} \quad (3.43)$$

for all $n \geq 2$. In (3.42) and (3.43), the $S_i(\omega)$ are the local invariant C^∞ Hilbert submanifolds of $L^2([0, 1], \mathbf{R})$ constructed in Theorem 3.5.

Then the following is true for each $i \geq 1$ and $\omega \in \Omega^*$:

(i) The sets $\{M_i(\omega) : \omega \in \Omega^*, i \geq 1\}$ are cocycle-invariant:

$$U(t, \cdot, \omega)(M_i(\omega)) \subseteq M_i(\theta(t, \omega)) \quad (3.44)$$

for all $t \geq 0$.

(ii) $S_i^n(\omega) \subseteq S_i^{n+1}(\omega)$ for all $n \geq 1$, and

$$M_i(\omega) = \bigcup_{n=1}^{\infty} S_i^n(\omega), \quad i \geq 1, \quad (3.45)$$

(perfectly in ω).

(iii) $M_{i+1}(\omega) \subseteq M_i(\omega)$.

(iv) For any $f \in M_i(\omega) \setminus M_{i+1}(\omega)$,

$$\overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \in (\lambda_{i+1}, \lambda_i]. \quad (3.46)$$

Proof. Fix $\omega \in \Omega^*$, where Ω^* is defined as in Theorem 3.5.

(i) To prove the cocycle invariance property (3.44), let $f \in M_i(\omega)$ and $t_1 > 0$. Then by definition (3.41) of $M_i(\omega)$, we have

$$\overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq \lambda_i. \quad (3.47)$$

By the cocycle property of (U, θ) , we have

$$\begin{aligned} \overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, U(t_1, f, \omega), \theta(t_1, \omega))\|_{L^2} &= \overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t + t_1, f, \omega)\|_{L^2} \\ &= \overline{\lim}_{t \rightarrow \infty} \frac{1}{t + t_1} \log \|U(t + t_1, f, \omega)\|_{L^2} \cdot \lim_{t \rightarrow \infty} \frac{t + t_1}{t} \\ &= \overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \\ &\leq \lambda_i. \end{aligned}$$

The above inequality implies that $U(t_1, f, \omega) \in M_i(\theta(t_1, \omega))$. Hence $U(t_1, \cdot, \omega)(M_i(\omega)) \subseteq M_i(\theta(t_1, \omega))$ and so (3.44) holds for all $t \geq 0$.

(ii) To prove assertion (ii) of the theorem, observe first that (3.43) implies that $S_i^n(\omega) \subseteq S_i^{n+1}(\omega)$ for all $n \geq 1$. Next, we show that

$$S_i^n(\omega) \subset M_i(\omega) \quad (3.48)$$

for all $n \geq 1$. We prove (3.48) by induction on $n \geq 1$.

Let $f \in S_i^1(\omega) = S_i(\omega)$. By Theorem 3.5 and assertion (3.25), it follows that

$$\overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq \lambda_i \quad (3.49)$$

perfectly in ω . Therefore, $f \in M_i(\omega)$. Hence $S_i^1(\omega) = S_i(\omega) \subset M_i(\omega)$. Assume, by induction, that

$$S_i^k(\omega) \subset M_i(\omega)$$

for all $1 \leq k \leq n$. If $S_i^{n+1}(\omega) \not\subseteq U(n+1, \cdot, \omega)^{-1}[S_i(\theta(n+1, \omega))]$, then $S_i^{n+1}(\omega) = S_i^n(\omega) \subset M_i(\omega)$, by inductive hypothesis. Otherwise, $S_i^{n+1}(\omega) = U(n+1, \cdot, \omega)^{-1}[S_i(\theta(n+1, \omega))]$. Let $f \in S_i^{n+1}(\omega) = U(n+1, \cdot, \omega)^{-1}[S_i(\theta(n+1, \omega))]$. Then by the cocycle property and the definition of $S_i(\theta(n+1, \omega))$, it follows that

$$\|U(n' + n + 1, f, \omega)\|_{L^2} \leq \beta_i(\theta(n+1, \omega)) e^{n' \lambda_i} \quad (3.50)$$

for all $n' \geq 1$. This implies that

$$\overline{\lim}_{n' \rightarrow \infty} \frac{1}{n'} \log \|U(n' + n + 1, f, \omega)\|_{L^2} \leq \lambda_i.$$

Hence

$$\begin{aligned} & \overline{\lim}_{n'' \rightarrow \infty} \frac{1}{n''} \log \|U(n'', f, \omega)\|_{L^2} \\ &= \overline{\lim}_{n' \rightarrow \infty} \frac{1}{n' + n + 1} \log \|U(n' + n + 1, f, \omega)\|_{L^2} \\ &= \overline{\lim}_{n' \rightarrow \infty} \frac{n'}{n' + n + 1} \cdot \overline{\lim}_{n' \rightarrow \infty} \frac{1}{n'} \log \|U(n' + n + 1, f, \omega)\|_{L^2} \\ &\leq \lambda_i. \end{aligned}$$

Therefore, $f \in M_i(\omega)$, and $S_i^{n+1}(\omega) \subset M_i(\omega)$. So, by induction, it follows that

$$S_i^n(\omega) \subset M_i(\omega) \tag{3.51}$$

for all $n \geq 1$. Thus

$$\bigcup_{n=1}^{\infty} S_i^n(\omega) \subseteq M_i(\omega). \tag{3.52}$$

In order to prove the converse inclusion

$$M_i(\omega) \subseteq \bigcup_{n=1}^{\infty} S_i^n(\omega), \tag{3.53}$$

we establish the following:

Claim:

There exist an increasing (random) sequence of integers $n^k \uparrow \infty$ such that

$$S_i^{n^k}(\omega) = U(n^k, \cdot, \omega)^{-1}[S_i(\theta(n^k, \omega))]$$

for all $k \geq 1$.

Proof of Claim. Define $n^1 := \inf \{n > 1 : S_i^{n-1}(\omega) \subseteq U(n, \cdot, \omega)^{-1}[S_i(\theta(n^k, \omega))]\}$. Then

$$S_i^{n^1-1}(\omega) \subseteq U(n^1, \cdot, \omega)^{-1}[S_i(\theta(n^1, \omega))],$$

and by definition (3.43),

$$S_i^{n^1}(\omega) = U(n_1, \cdot, \omega)^{-1}[S_i(\theta(n_1, \omega))]. \tag{3.54}$$

Furthermore, $S_i^{n-1}(\omega) \not\subseteq U(n, \cdot, \omega)^{-1}[S_i(\theta(n, \omega))]$ for all $1 < n < n^1$, and so by definition (3.43),

$$S_i^n(\omega) = S_i^{n-1}(\omega) = S_i^{n-2}(\omega) = \dots = S_i^1(\omega) = S_i(\omega)$$

for all $1 < n < n^1$. In particular,

$$S_i(\omega) = S_i^{n^1-1}(\omega) \subseteq U(n^1, \cdot, \omega)^{-1}[S_i(\theta(n^1, \omega))].$$

Therefore,

$$U(n^1, \cdot, \omega)(S_i(\omega)) \subseteq S_i(\theta(n^1, \omega)).$$

Hence

$$n^1 = \inf \{n > 1 : U(n, \cdot, \omega)(S_i(\omega)) \subseteq S_i(\theta(n, \omega))\}. \quad (3.55)$$

Since $S_i(\omega)$ is asymptotically cocycle invariant (Theorem 3.5(c), (3.26)), it follows from (3.55) that $1 < n^1 < \infty$. Next, define $n^2 > n^1$ by

$$n^2 := \inf \{n > n^1 : S_i^{n-1}(\omega) \subseteq U(n, \cdot, \omega)^{-1}[S_i(\theta(n, \omega))]\}. \quad (3.56)$$

As before, the definition (3.43) implies that

$$S_i^{n^2-1}(\omega) = S_i^{n^1+1}(\omega) = U(n^1, \cdot, \omega)^{-1}[S_i(\theta(n^1, \omega))] \quad (3.57)$$

and

$$S_i^{n^2}(\omega) = U(n^2, \cdot, \omega)^{-1}[S_i(\theta(n^2, \omega))]. \quad (3.58)$$

Since

$$S_i^{n^2-1}(\omega) \subseteq U(n^2, \cdot, \omega)^{-1}[S_i(\theta(n^2, \omega))], \quad (3.59)$$

it follows from (3.57) that

$$U(n^1, \cdot, \omega)^{-1}[S_i(\theta(n^1, \omega))] \subseteq U(n^2, \cdot, \omega)^{-1}[S_i(\theta(n^2, \omega))].$$

Therefore,

$$\{U(n^2, \cdot, \omega)^{-1} \circ U(n^1, \cdot, \omega)^{-1}\}[S_i(\theta(n^1, \omega))] \subseteq S_i(\theta(n^2, \omega)). \quad (3.60)$$

Using the cocycle property (Theorem 3.2(iii)), (3.60) implies

$$U(n^2 - n^1, \cdot, \theta(n^1, \omega))[S_i(\theta(n^1, \omega))] \subseteq S_i(\theta(n^2 - n^1, \theta(n^1, \omega))). \quad (3.61)$$

By the asymptotic cocycle invariance of $S_i(\theta(n^1, \omega))$, it follows from (3.61) that $n^1 < n^2 < \infty$. Hence by induction, there exists an increasing sequence of integers $\{n^k\}_{k=1}^\infty$ such that $n^k \uparrow \infty$ as $k \rightarrow \infty$ and

$$S_i^{n^k}(\omega) = U(n^k, \cdot, \omega)^{-1}[S_i(\theta(n^k, \omega))] \quad (3.62)$$

for all integers $k \geq 1$. This completes the proof of our claim.

We now proceed to prove the inclusion (3.53). Let $f \in M_i(\omega)$. Then by definition of $M_i(\omega)$, we have

$$\overline{\lim}_{t \rightarrow \infty} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} \leq \lambda_i. \quad (3.63)$$

Fix $\epsilon_1 \in (0, -\lambda_1)$ as in Theorem 3.5. Let $0 < \epsilon < \epsilon_1$. Then, using (3.63), there exists a positive integer n_0 such that

$$\sup_{t \geq n} \frac{1}{t} \log \|U(t, f, \omega)\|_{L^2} < \lambda_i + \epsilon$$

for all $n \geq n_0$. In particular,

$$\|U(n, f, \omega)\|_{L^2} < e^{n(\lambda_i + \epsilon)}$$

for all $n \geq n_0$. Define

$$K(\omega) := \max_{1 \leq k < n_0} \|U(k, f, \omega)\|_{L^2}.$$

Therefore,

$$\|U(n, f, \omega)\|_{L^2} \leq K(\omega) e^{n(\lambda_i + \epsilon)} \quad (3.64)$$

for all $n \geq 1$.

Pick m_0 sufficiently large such that

$$K(\omega) e^{n(\epsilon - \epsilon_1)} \leq \beta_i(\theta(n, \omega)) \quad (3.65)$$

for all $n \geq m_0$. Let $n \geq m_0$, $n' \geq 0$. Using the cocycle property and (3.64), we obtain

$$\begin{aligned} \|U(n', U(n, f, \omega), \theta(n, \omega))\|_{L^2} &= \|U(n' + n, f, \omega)\|_{L^2} \\ &\leq K(\omega) e^{(n+n')(\lambda_i + \epsilon)} \\ &\leq K(\omega) e^{n(\epsilon - \epsilon_1)} \cdot e^{n'(\lambda_i + \epsilon_1)}. \end{aligned} \quad (3.66)$$

Pick $m_1 \geq m_0$ and sufficiently large such that

$$K(\omega) e^{n(\epsilon - \epsilon_1)} \leq \beta_i(\theta(n, \omega)) \quad (3.67)$$

for all $n \geq m_1$. From (3.66) and (3.67), we get

$$\|U(n', U(n, f, \omega), \theta(n, \omega))\|_{L^2} \leq \beta_i(\theta(n, \omega)) e^{n'(\lambda_i + \epsilon_1)} \quad (3.68)$$

for all $n' \geq 0$ and $n \geq m_1$. Since $U(n, f, \omega) \rightarrow 0$ as $n \rightarrow \infty$, then there exists $m_2 > 0$ such that $U(n, f, \omega) \in B(0, \rho_i(\omega))$ for all $n \geq m_2$. Thus (3.68) implies that

$$U(n, f, \omega) \in S_i(\theta(n, \omega))$$

for all $n \geq \max(m_1, m_2)$; i.e. $f \in U(n, \cdot, \omega)^{-1}[S_i(\theta(n, \omega))]$, for all $n \geq \max(m_1, m_2)$. Now pick k sufficiently large such that $n^k \geq \max(m_1, m_2)$ and $f \in U(n^k, \cdot, \omega)^{-1}[S_i(\theta(n^k, \omega))] = S_i^{n^k}(\omega)$. This proves that $f \in \bigcup_{n=1}^{\infty} S_i^n(\omega)$; and so the inclusion (3.53) holds. The proof of (3.45) is complete; hence assertion (ii) of the theorem holds.

Assertions (iii) and (iv) of the theorem follow directly from the definition (3.41) of the flag $M_i(\omega)$, $i \geq 1$. \square

Remarks:

It is not clear if the $M_i(\omega)$, $i \geq 1$, in Theorem 3.6 are C^∞ immersed submanifolds in $L^2([0, 1], \mathbf{R})$. This would require transversality of the global semiflow $U(n, \cdot, \omega)$ versus the local stable manifold $S_i(\theta(n, \omega))$.

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