

Noise-sustained flashing structures in bistable systems[☆]

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ABSTRACT

Fluctuations are an inherent feature of macroscopic systems. Rather than merely disturbing deterministic dynamics, noise can induce well-defined and often counterintuitive behaviors. We investigate noise-sustained flashing domain walls between stable states in convective bistable systems. By anchoring one end of the system in its least favorable stable state, noise persistently generates a pair of domain walls that propagate at different velocities, producing triangular patterns in the space–time diagram. Experimentally, this phenomenon is examined using a liquid crystal light valve with optical feedback, subjected to both fluctuating and controlled illumination. Theoretically, employing a bistable model with drift and noise, exhibiting noise-sustained flashing domain walls, we analyze the average emission time and size of these structures as functions of noise intensity, characterized by escape and relaxation times. The experimental observations align closely with the theoretical predictions.

1. Introduction

Macroscopic systems are typically described by nonlinear equations; their variables are related to microscopic variables through coarse-graining or averaging processes [1–4]. As a consequence of these processes, the dynamics are naturally formulated in terms of stochastic equations [5,6]. In physics, stochastic terms are often viewed as noise in deterministic equations; this perspective is typically linked to the Langevin-type approach. Far from serving solely as a perturbation to deterministic dynamics or a disruptive element of randomness, noise can give rise to well-defined and often counterintuitive dynamical behaviors. Driven by noise, macroscopic systems can exhibit universal phenomena such as Brownian motion [7–10], stochastic resonance [11], noise-induced synchronization [12–14], noise-induced stabilization [15], and noise-induced transitions [16]. For extended systems, noise can induce new universal phenomena such as noise-induced phase transition [17], noise-induced patterns [18–20], stochastic spatiotemporal intermittency [21], noise-induced traveling waves [22], stochastic front dynamics [23], noise-induced front propagation [24–27], noise-induced precursor [28–30], and noise-sustained structures [31–35].

The noise-sustained structure is characterized by the coexistence of stable and unstable equilibria together with advection. The system is configured with one boundary in an unstable state and the opposite boundary constrained to zero flow under a convective regime. Any disturbance around the unstable equilibrium propagates and is subsequently eliminated from the system. When stochastic fluctuations are included, the system exhibits a balance between advection and persistent fluctuations, resulting in an equilibrium structure. This structure manifests as a fluctuating domain wall between equilibrium states. Fig. 1a illustrates the noise-sustained structure between homogeneous states. The symbols B and C represent the stable and unstable states, respectively.

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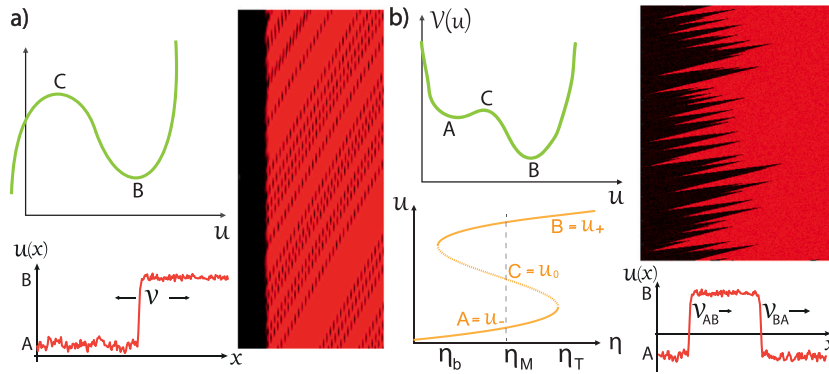


Fig. 1. Noise-sustained domain walls between homogeneous stable states in convective regimes. (a) Schematic representation of noise-sustained structures. The top left panel illustrates the potential for coexistence between two states: C (unstable) and B (stable). The bottom left panel shows the induced domain wall when the system is fixed at the left edge in A and free-flowing at the right edge in the convective regime. The right panel shows a spatiotemporal diagram illustrating how the noise-sustained structure evolves, with black and red regions representing the stable and unstable states, respectively. (b) Schematic representation of noise-sustained flashing structures. The top-left panel illustrates a bistable potential with three states: A (stable), C (unstable), and B (stable). The bottom panel shows the bifurcation diagram. This is characterized by three critical points: the bistability (η_b), the Maxwell (η_M), and the transition (η_T). The transition point η_T (bistability point η_b) corresponds to the value of the control parameter at which the lower stable state A (upper B) transitions to the higher state B (lower A). The Maxwell point η_M corresponds to the value of the control parameter at which both states are energetically equivalent. The right panel shows a spatiotemporal diagram illustrating how noise-sustained the flashing structure, where the black and red regions represent the least and most favorable stable states, respectively. The bottom-right panel shows a typical induced domain wall, where two fronts propagate with velocities determined by the energy difference between the stable states A and B and by the system's advection. The front velocities take the form $V_{AB} = V_0 - \alpha'$ and $V_{BA} = V_0 + \alpha'$, where V_0 and α' are set by the energy difference and advection, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The space–time diagram illustrates the evolution of the noise-induced structure, with black and red regions representing the stable and unstable states, respectively. The size of this wall (black region) is of the order of the logarithm of the noise intensity level [36], and the fluctuations in this length are of the order of the noise intensity. The concept of noise-sustained structures was introduced to analyze how traveling patterns emerge in the presence of absolute convective instability. Initially predicted in various fields, such as open flows, optics, and traffic flow [37]. These phenomena were later experimentally observed in hydrodynamics [38] and optical systems [39,40]. One of the main experimental challenges in studying noise-sustained structures is that the system must be anchored in an unstable state at one boundary. This constraint complicates the exploration of parameter dependence, since the equilibria themselves vary with system parameters. Noise-sustained structures represent a universal phenomenon in nature, which requires the coexistence of equilibrium, advection, tunable boundary conditions, and noise. To our knowledge, the extension of this phenomenon to noise-sustained domain walls between stable states, and in particular, the universal laws governing its properties, has not yet been investigated. Fig. 1 illustrates the difference between these types of noise-sustained domain walls. The spatiotemporal diagrams highlight clear differences between these domain walls.

In optics, numerous monostable systems are observed; that is, systems that, when their parameters are modified, exhibit only one equilibrium point. In high-intensity regimes or in optically strongly nonlinear media, optical bistability is observed [41–43]. That is, for fixed parameters, multiple equilibria can be observed. It is in this type of system that noise-sustained structure studies can be performed.

This work aims to investigate noise-sustained flashing domain walls between stable states in bistable systems, through both experimental and theoretical approaches. In this context, within the convective regime and accounting for inherent fluctuations, one end of the system is fixed in its least-favorable stable state. Due to noise, the system continuously generates a pair of domain walls between homogeneous states with different propagation velocities, resulting in a triangular structure in the spatiotemporal diagram. Note that this behavior is completely different from that observed in noise-sustained structures for domain walls between stable and unstable states, where the wall exhibits slight fluctuations around its equilibrium position. We have coined the term “flashing structures” to describe this observed triangular behavior in the spatiotemporal diagram. Fig. 1(b) depicts a noise-sustained flashing structure. These triangular structures observed in the spatiotemporal diagram arise from two fronts propagating at different velocities, a consequence of the energy difference between the equilibrium states and the system's advection. In a noisy optical bistability experiment, we employ a liquid crystal light valve (LCLV) with shifted optical feedback and controllable fluctuating forcing; the resulting noise-induced flashing structures between stable states are observed in a quasi-one-dimensional configuration.

Theoretically, based on a bistable model with drift and noise, exhibiting noise-sustained flashing domain walls, we analyze the average emission time and size of these structures as functions of noise intensity, characterized by escape and relaxation times. Experimentally, we found a fair agreement with the theoretical findings.

2. Experimental setup

To investigate noise-sustained structures, we consider an experimental setup based on an LCLV with optical feedback and fluctuating illumination, as illustrated in Fig. 2(a). The LCLV contains a nematic liquid crystal, specifically LC-654 (NIOPIK), a mixture of cyano-biphenyls characterized by a dielectric anisotropy of $\epsilon_a = 10.7 \epsilon_0$ and an optical birefringence of $\Delta n = 0.2$. This liquid crystal layer is confined between two glass substrates, separated by a gap of $d = 15 \mu\text{m}$. Transparent indium tin oxide (ITO) electrodes and a photoconductive layer are deposited onto the glass substrate to apply a controlled voltage across the liquid crystal. Additionally, a dielectric Bragg mirror, optimized for high reflectivity at 632.8 nm, is integrated into the rear layer of the liquid crystal cell to enhance optical feedback. The liquid crystal has planar anchoring. The LCLV is electrically addressed by applying an oscillatory voltage V_0 rms and frequency $f_0 = 1.0 \text{ kHz}$ across the liquid crystal layer. The optical valve is optically forced with a He-Ne laser (wavelength $\lambda = 632.8 \text{ nm}$). The LCLV is placed in a $4f$ optical configuration ($f = 25 \text{ cm}$). The optical feedback circuit is closed using an optical fiber bundle (FB) located $4f$ from the LCLV front face. The optical fiber bundle injects the light into the photoconductive layer, applying an additional voltage to the liquid crystal layer depending on the local light intensity. The optical feedback loop is designed so that light simultaneously presents polarization interference induced by the polarizing beam splitter (PBS). A spatial light modulator (SLM) is considered to implement one-dimensional configurations of bistable optical chains. The experiment is monitored by a complementary metal–oxide–semiconductor (CMOS) camera. Likewise, the SLM serves a dual purpose: it both induces the target configuration and regulates the noise intensity by modulating the light intensity. Noise control via the SLM is achieved by assigning random intensity values to each pixel within a predefined range. Increasing this range results in a higher noise level. For a given intensity interval, 10,000 distinct masks are generated and cycled at 10 Hz using the HOLOEYE Slideshow Player, which enables precise control over the temporal frequency of the applied noise. Fig. 2(c) illustrates how the intensity distribution behaves as the range of pixel fluctuations in the spatial light modulator increases. Note that the intensity without pixel fluctuations does not follow a Gaussian distribution (see upper-left chart), whereas including pixel fluctuations yields a distribution closer to Gaussian.

3. Experimental results

To study the noise-sustained structure, we investigated the LCLV in the bistability region, where the lowest-intensity state is less stable. This state corresponds to the lower one in the bifurcation diagram of Fig. 2b. By displacing the optical fiber bundle by a distance α , we induce a convective effect in the system (shifted optical feedback), and, in turn, the left edge of the system is fixed in the lower state by means of the illumination and the voltage we apply. When we increased the illumination fluctuations on the system using the SLM, we observed the emergence of noise-sustained dynamic domains.

Figs. 2a and 3a illustrate snapshots of the observed domains and their dynamics, respectively. Domains are systematically emitted from the left edge, propagating and expanding (see Fig. 3). This flashing phenomenon persists across different noise intensity levels. To illustrate this dynamic, we have plotted the respective spatiotemporal diagrams for different noise levels. Fig. 3b summarizes the observed result. The chart indicates that as the noise level increases, the frequency of domain flashing also increases. In other words, the waiting time for a front to appear at an intermediate position decreases. As a result, the emission of pairs of fronts occurs more often.

4. Theoretical description

To shed light on the observed dynamics, we consider an LCLV close to a nascent of bistability with shifted optical feedback, which is described by the following dimensionless model equation [44]

$$\partial_t u = \eta + \mu u - u^3 + \partial_{xx} u - \alpha' \partial_x u + \sqrt{\zeta} \xi(x, t), \quad (1)$$

where the scalar field $u(x, t)$ accounts for the deviation of the average orientation angle of the molecules from their critical angle, exhibiting bistability, μ and η are the bifurcation parameters that control the bistability region, both proportional to the critical voltage and light intensity. The cubic term stands for the nonlinear response of the system; the term proportional to the Laplacian $\partial_{xx} u$ accounts for the elastic coupling of the liquid crystal. α' stands for the nonreciprocal optical coupling, which is proportional to α . ζ is the noise level intensity. $\xi(x, t)$ accounts for the inherent fluctuations to the system, which we model using white noise with a mean value of $\langle \xi \rangle = 0$ and correction $\langle \xi(x, t) \xi(x', t') \rangle = \delta(x - x') \delta(t - t')$, where the symbol $\langle \cdot \rangle$ stands for the average of the noise realization. Notice we study the system with a fixed condition on the left flank and zero flow on the right flank.

In the bistability region without advection ($\alpha' = 0$), model Eq. (1) exhibits two stable states that satisfy the relation $\eta + \mu u_{\pm} - u_{\pm}^3 = 0$, characterized by positive and negative values, respectively (see Fig. 1). The bistability region is bounded by the bistability point $\eta_b = -2(\mu/3)^{3/2}$ and the transition point $\eta_T = 2(\mu/3)^{3/2}$. These states are energetically equivalent at the Maxwell point, when $\eta_M = 0$ [45]. At the Maxwell point, the front connecting both equilibrium states is motionless. For η positive, the more stable state is the positive one. Hence, the system exhibits fronts between the two states, with the more stable state invading the less stable one. This occurs even when one of the flanks is fixed in the less-stable state, the *absolute regime*.

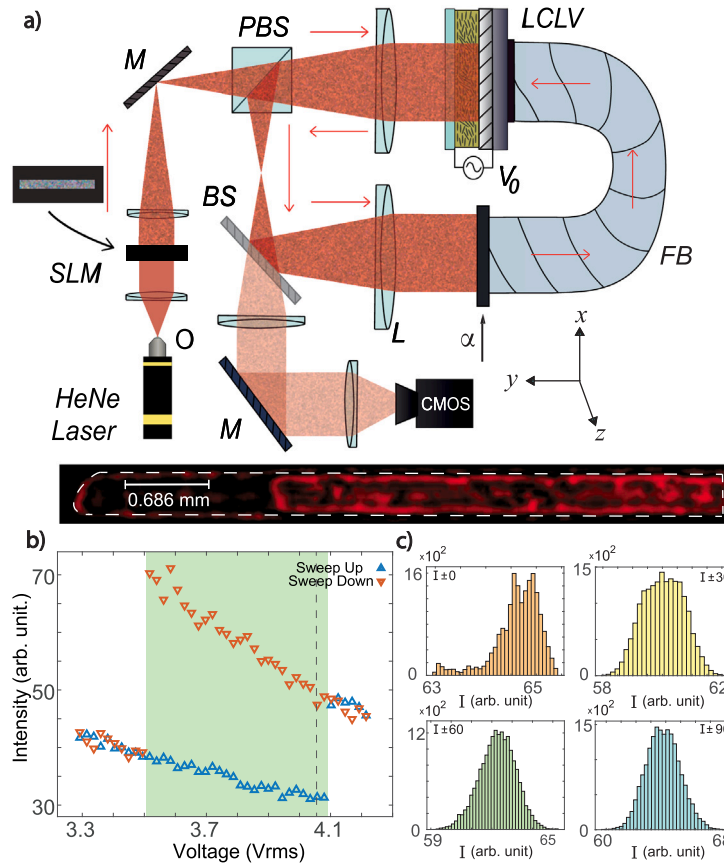


Fig. 2. Liquid crystal light valve with shifted optical feedback and fluctuating illumination. (a) Schematic representation of an experimental LCLV with optical feedback and fluctuating illumination. He-Ne laser accounts for a helium-neon laser light source with a wavelength $\lambda = 632.8$ nm. O stands for an optical objective with magnification $\times 20$, SLM is a spatial light modulator that has a twofold role: creating a quasi-one-dimensional configuration and providing fluctuating lighting, M is a mirror, PBS stands for a polarizing beam splitter, V_0 is the intensity of an alternative voltage applied to the LCLV, BS is a beam splitter, L stands for lens, FB is a high-resolution optical fiber bundle, which is responsible for the shifted optical feedback, α accounts for spatial light shift, and CMOS stands for a complementary metal–oxide–semiconductor camera. The top left inset indicates the type of mask used in the SLM. The bottom inset shows the typical snapshot of noise-sustained flashing structures. (b) Experimental bifurcation diagram of the total intensity as a function of the applied voltage V_0 . The upward-pointing and downward-pointing triangles represent the intensity obtained by increasing and decreasing the voltage, respectively. The colored area represents the bistability region. The studies presented were conducted for the voltage indicated by the vertical dashed line. (c) Histograms of light intensities generated with the spatial light modulator for different grayscales that vary randomly in a range of $\{I \pm 0, I \pm 30, I \pm 60, I \pm 90\}$ in arbitrary intensity units and $I = 128$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Including the advective term $\alpha' \partial_x u$, the above scenario changes radically: for sufficiently large α' , the system exhibits a convective regime. Namely, the less stable state u_- invades the more stable one, since any disturbance is advected out of the system. Including stochastic fluctuations, the noise sustains a flashing structure. Fig. 3(c) illustrates the typical observed dynamical behaviors, which show excellent qualitative agreement with experimental observations. These results were obtained from numerical simulations of Eq. (1), integrated using a fourth-order Runge–Kutta scheme combined with first-order finite differences ($dx = 1$, 700 grid points). The boundary conditions were fixed on the left at -0.9 and Neumann on the right, with a time step of $\Delta t = 0.01$. Uniform noise was generated using the standard pseudo-random number generator `rand()` in C++. Through a linear rescaling, the values were transformed to produce noise uniformly distributed in the interval $[-\sqrt{\zeta}, \sqrt{\zeta}]$. Noise was incorporated following the Itô prescription, where the random variable is sampled from a Gaussian distribution with variance equal to the noise intensity.

For noise to induce advected domains, it must be such that fluctuations from the less stable state cross the nucleation barrier and subsequently relax to the more stable equilibrium. The time it takes for fluctuations to cross the nucleation barrier is characterized by the mean time of first passage or escape time $\tau_{AC} \approx 2\pi e^{\Delta U/\zeta} / \sqrt{U''(A)|U''(C)|}$ where $\Delta U = U(C) - U(A)$ [5]. The relaxation time to equilibrium, given a perturbation of the unstable state, is given by the expression $\tau_{CB} = \ln(B/\zeta)/|U''(C)|$ [36]. Then the

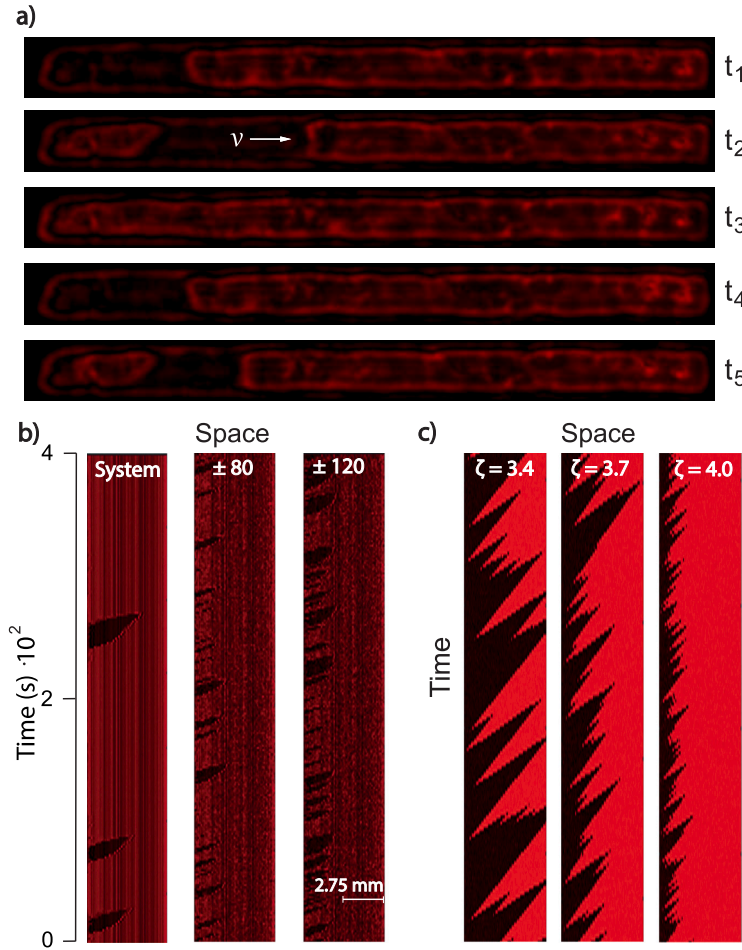


Fig. 3. Noise-sustained flashing structure: experimentally and numerically. (a) Time sequence of snapshots of the dynamics of the domain induced by noise ($t_1 < t_2 < t_3 < t_4 < t_5$). (b) Experimental spatiotemporal diagrams for the light intensity profile obtained on the intermediate line, for different noise levels. (c) Numerical results of noise-sustained flashing structure from the model Eq. (1) by $\eta = 0.95$, $\mu = 2$, $\alpha = -3$, noise intensity level $\zeta = 3.4$, $\zeta = 3.7$, and $\zeta = 4.0$. The black and red regions correspond to the lower and upper stable states in the bifurcation diagram, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

average emission time of front pairs is $\langle \tau \rangle = \tau_{AC} + \tau_{CB}$. To measure the above quantity, both experimentally and numerically, at a distance close to the edge, one estimates the time it takes for a front to pass. Note that this result does not depend on the choice of the observation point. Fig. 4 shows a comparison of this time $\langle \tau \rangle$ and those obtained experimentally and numerically by varying the noise level. This chart shows excellent agreement between the theoretical formula and the experimental and numerical observations. Likewise, we measured the average size of the fronts $\langle x \rangle$ emitted at each instant of time and compared it with the theoretical average time given by the formula $\langle x \rangle = v \langle \tau \rangle$ where v is a speed. We compared v with velocities derived from the energy difference [46] and from advection (α'); however, it does not coincide with either characteristic velocity, nor with their sum or difference. We therefore interpret v as the velocity that transports the separation between successive events. we found excellent agreement, both experimentally and numerically, with this expression, as illustrated in Fig. 4. Note that to account for the observations of noise-sustained flashing structures, it is necessary to consider both the escape time and the relaxation time.

5. Conclusions

Our findings demonstrate that noise, far from being a mere disturbance, can generate well-defined structures in macroscopic convective and bistable systems. By fixing one end of the system in its least favorable stable state, noise induces the persistent

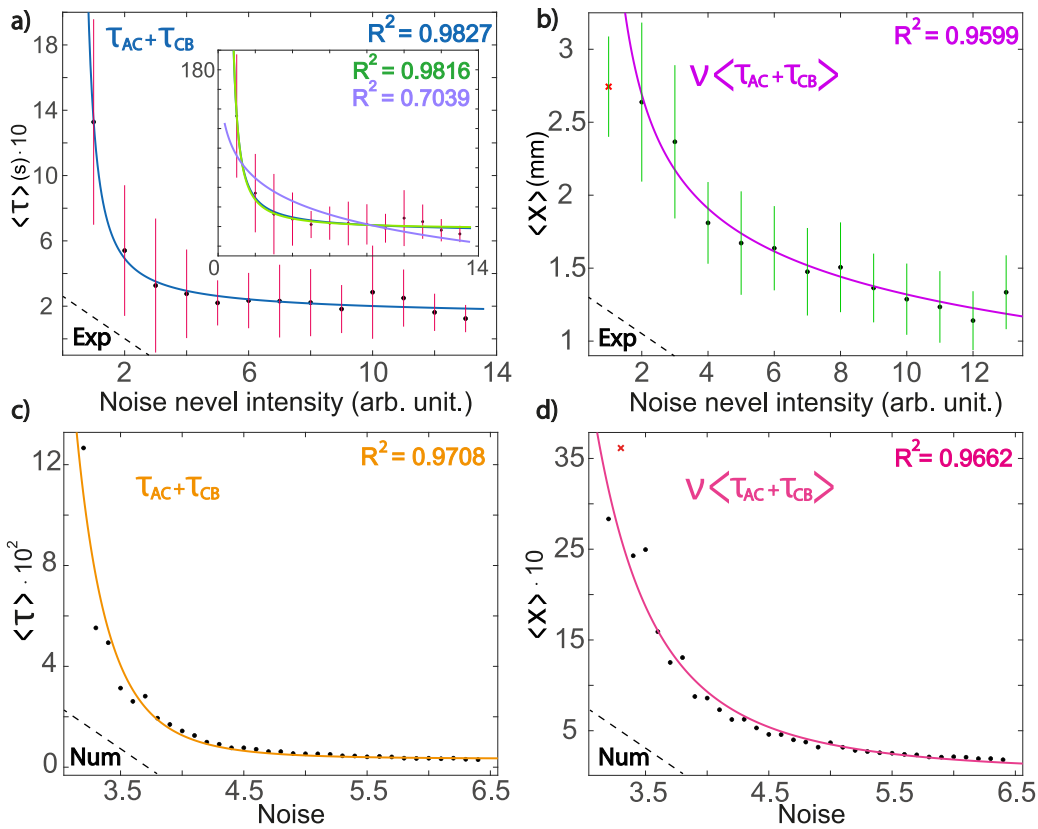


Fig. 4. Average emission time $\langle \tau \rangle$ and size $\langle x \rangle$ of fronts as a function of noise intensity. (a) Average experimental emission time. The points and their respective error bars correspond to the experimental observations. The solid line corresponds to the theoretical curve using $\langle \tau \rangle = \tau_{AC} + \tau_{CB}$, with $\tau_{AC} = 15.49e^{2.1/\zeta}$ and $\tau_{CB} = 2.465 \ln(14.9/\zeta)$. R^2 stands for the coefficient of determination. The inset shows the same experimental data compared with the escape time τ_{AC} , relaxation time τ_{CB} , and emission time $\tau_{AC} + \tau_{CB}$, respectively. (b) Average size $\langle x \rangle$ of front as a function of noise intensity. The points and their respective error bars correspond to the experimental observations. The solid line corresponds to the theoretical curve using $\langle x \rangle = v \langle \tau \rangle$, where v is the front speed. (c) and (d) are numerical, the average emission time $\langle \tau \rangle$ and size $\langle x \rangle$ of fronts as a function of noise intensity. The points correspond to numerical simulations and the solid lines to analytical formulas.

formation of domain wall pairs between two uniform states that propagate with different velocities, resulting in triangular patterns and flashing structures in the space–time diagram. Experiments performed with an optical valve under controllable fluctuating illumination and optical feedback confirm this behavior. Theoretical analysis further allows us to characterize the average emission time and size of these structures as functions of noise intensity, defined by escape and relaxation times. The close agreement between experimental and theoretical results underscores the relevance of these findings for understanding the constructive role of noise in complex systems.

The phenomenon of noise-sustained structures arises from the coexistence of unstable and stable states in the presence of noise within a convective regime. As we have shown, the connection between two stable states under these conditions profoundly alters the dynamics of domain walls in the space–time diagram. Moreover, since stable states are more accessible to experimental control, the emergence of noise-sustained flashing structures becomes both easier to realize and more broadly observable.

To illustrate the universality of the observed phenomenon, we have examined a specific region of parameter space in which the system exhibits bistability between a patterned and a homogeneous state. In this parameter regime, we also observe noise-sustained flashing structures. Fig. 5 illustrates the noise-sustained flashing structures between a homogeneous stable state and a pattern stable state. Note that a similar dynamics can be seen in the absolute and convective instabilities of patterns. Additionally, the phenomenon of noise-sustained flashing structures can be observed in two dimensions; ongoing research in this area.

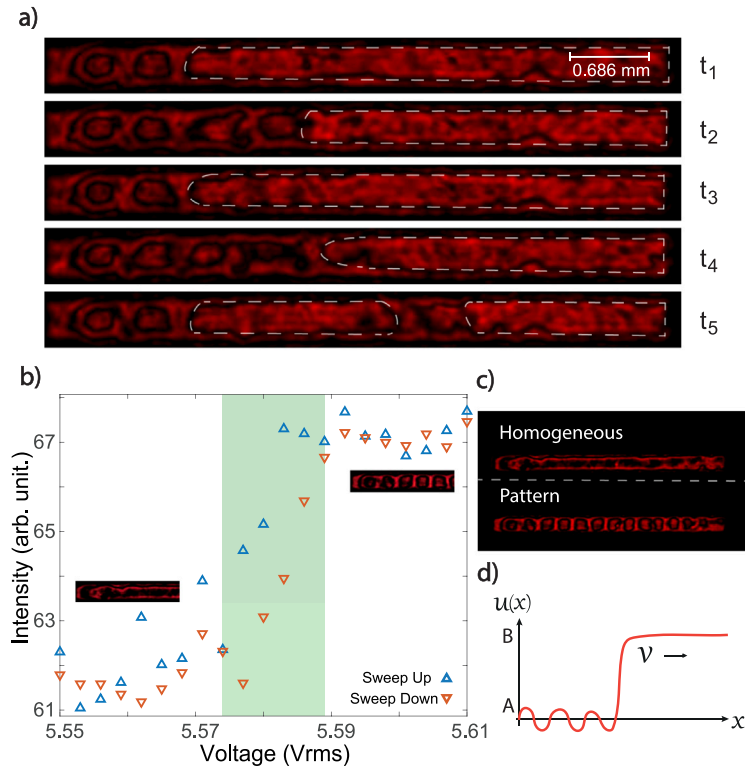


Fig. 5. Noise-sustained domain walls between pattern and homogeneous stable states in convective regimes. (a) Time sequence of snapshots of the dynamics of the domain induced by noise ($t_1 < t_2 < t_3 < t_4 < t_5$). (b) Experimental bifurcation diagram of the total intensity as a function of the applied voltage V_0 . The upward- and downward-pointing triangles represent the intensity obtained by increasing and decreasing the voltage, respectively. The colored area accounts for the bistability region. The insets stand for the extended states. (c) Snapshots of the extended homogeneous and pattern state. (d) Schematic representation of noise-sustained structures between pattern and homogeneous stable states. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since noise in our experimental system can be controlled optically, this opens the possibility of investigating counterintuitive noise phenomena such as stochastic resonance in extended systems [47] and noise-induced propagation of nonlinear waves, among others.

CRediT authorship contribution statement

L.B. Ramirez-Moya: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.G. Clerc:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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