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Interaction of localized pulses of traveling-wave convection with propagating disturbances

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We study the stability of the stationary, spatially localized states of traveling-wave convection recently described by Niemela, Ahlers, and Cannell [Phys. Rev. Lett. **64**, 1365 (1990)] and by Anderson and Behringer [Phys. Lett. A **145**, 323 (1990)] by bombarding them with propagating wave packets. At sufficiently large incident amplitude, this can lead to the destruction of the localized state and to a transition to a new state. Sufficiently far above the onset of convection, this process is triggered by spontaneously arising propagating fluctuations, causing convection to fill the experimental cell.

Niemela, Ahlers, and Cannell[1] have recently described a localized state of one-dimensional traveling waves (TW) in experiments on convection in binary fluid mixtures in rectangular and annular containers. In these experiments, TW are confined to narrow, stationary regions, while the rest of the system remains quiescent. Anderson and Behringer[2] have reported complementary observations. These confined states bear a strong resemblance to the pulses discovered numerically by Thual and Fauve[3] (we reserve the use of the work "pulse" in this paper to denote only these stationary, nonlinear TW structures). Experimentally, pulses exhibit several intriguing features. First, apart from an initial transient, they are truly stationary in space. This defies the theory of Ref. 3, in which pulses travel at the group velocity of the underlying TW. Second, they are found to persist well above the onset of convection with little change in shape, despite the prediction of van Saarloos and Hohenberg[4] that pulse solutions of the complex Ginzburg-Landau equation should be stable only below onset, and even though the nonconvecting part of the system is linearly unstable to the growth of propagating disturbances.[5,6] Finally, at a fractional distance $\epsilon_f \sim 0.01$ above onset, a transition to a full-cell TW state occurs. This transition has not been explored.

In this paper, we study the stability of pulses by launching propagating disturbances at them. Weak disturbances are totally absorbed. Thus, the reason that the conductive part of the cell is not convectively unstable to propagating waves is that this instability is completely suppressed by absorption. Stronger disturbances, however, undergo a complicated interaction with a pulse which can lead to its destruction and thence to a new state. We find that propagating disturbances arise spontaneously, so that this process can happen without external intervention, if the system is far enough above onset that convective amplification can bring spontaneous fluctuations to sufficient amplitude. This leads to an estimate of the cell-filling threshold ϵ_f which is in reasonable agreement with experimental observations.

We have described our apparatus elsewhere.[7] The cell is an annular channel formed by a plastic disk and ring that are clamped between a rhodium-plated, mirror-polished copper bottom plate and a sapphire top plate. The dimensions are 0.301 cm ($=d$) height $\times 1.73d$ radial width $\times 80.1d$ mean circumference. Cooling water circulates azimuthally over the top plate, and the bottom plate is heated electrically. The temperature difference applied across the fluid layer, ΔT, is typically 4.1 K and is regulated with a stability of ± 0.3 mK. We employed a 1.4-wt.% ethanol-waver solution at a mean temperature of 27.1 °C, which has separation ratio $\psi = -0.069$, Prandtl number $P = 6.62$, and Lewis number $L = 0.009$.[8] Shadowgraphic visualization is used to record the pattern of the TW.[9] The convection is always observed to be one-dimensional, consisting of superpositions of waves which propagate azimuthally around the cell in opposite directions (here called "left" and "right"). During an experimental run, we record the shadowgraph intensity as a function of time with an annular array of 720 photodiodes aligned along the mean diameter of the image of the cell. We perform a spatial demodulation of the data at each time step, in order to obtain the profile of the total wave amplitude. In addition, the separate profiles of the left and right TW components can be extracted by complex demodulation.[9]

Launching small-amplitude disturbances in this apparatus is as easy as tapping a finger. Two thin tubes are used to fill the cell through diametrically opposite holes in its outer plastic ring. These holes are located at positions 90° and 270° in Figs. 1–4. The fill tube connected to the hole at 270° is terminated with a sealed metal bellows for pressure equalization with the atmosphere. Tapping this bellows caused fluid to be squirted into and out of the cell, causing a localized disturbance at that location and a weaker disturbance at the opposite hole. This is illustrated in Fig. 1. For reproducibility, we tap the bellows not with a finger but with a small ball which is dropped from a measured height inside a transparent, graduated tube. Because this system is convectively unstable,[5,6] the disturbances at the fill-tube inlet holes quickly decompose into TW which propagate around the cell, as illustrated in Fig. 1. The frequency, group velocity, dispersion, and growth rate of the TW are consistent with the theory of the linear TW instability[6] and with previous experiments.[10] These propagating disturbances are properly referred to as linear (or, at large amplitudes, quasilinear) wave packets. The amplitude of the wave packets, as measured by the area under the wave-packet amplitude profile, experiences temporal growth at a rate which is proportional to ϵ, the frac-

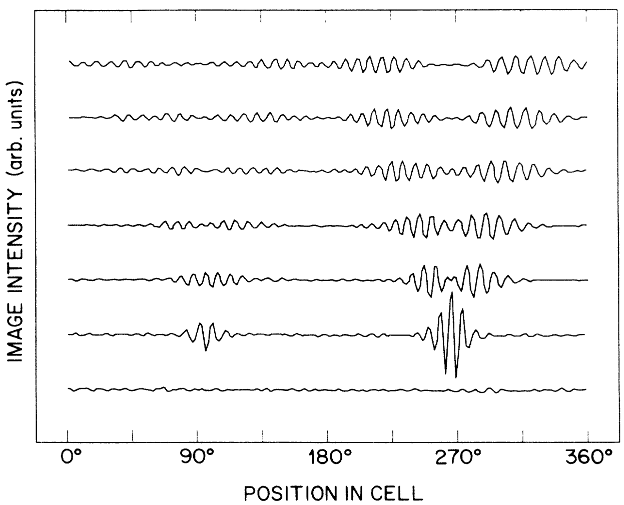

FIG. 1. Shadowgraph intensity as a function of position in the cell at several successive times (time step 200 sec) following the creation of a disturbance just above the onset of convection. Time proceeds upwards in this and subsequent figures, and the disturbance was created between the first two traces. Initially, a narrow region of standing waves is created at the location of each of the fill holes. These then separate into TW components which propagate around the cell in a manner consistent with the linear TW instability.

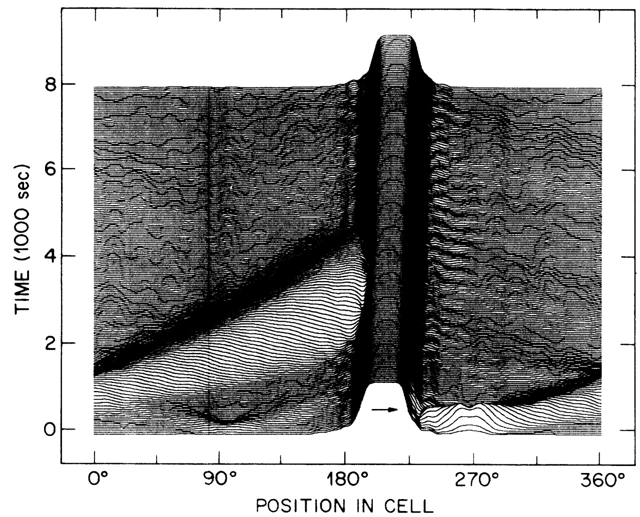

FIG. 2. Interaction of a small-amplitude wave packet with a stationary pulse of right-going TW at a distance $\epsilon = 2.9\times10^{-3}$ above onset. In this hidden-line plot, each trace shows the total demodulated spatial amplitude profile at one instant in time, with time proceeding upwards. In order to suppress the contrast between the pulse and the much weaker wave packet, we plot the hyperbolic tangent of the wave amplitude, which gives a flat-top appearance to the pulse. In this and subsequent figures, the horizontal arrow underneath or above the pulse indicates the direction of the phase velocity of the waves inside the pulse. In this run, the wave packet propagates around the cell and is totally absorbed by the pulse.

tional distance above onset. In Fig. 1, the system is just above onset; although the peak amplitudes of the wave packets initially decay in time, their integrated amplitudes are actually increasing slowly.

Above onset, whether triggered by injected disturbances or by spontaneous fluctuations, the system ultimately organizes itself into one or two localized pulses. As in Refs. 1 and 2, these pulses have a characteristic, narrow spatial profile, and the confined TW have a frequency which is about half that of the linear TW. Once this state is stable, we can launch a wave packet as in Fig. 1 and study the resulting interaction. Figure 2 shows a typical result for small incident amplitude (as measured by the area under the wave-packet amplitude profile, extrapolated to the time of the collision with the pulse): the wave packet is absorbed. In this run, the system was set above onset by a fraction $\epsilon = 2.9\times10^{-3}$, and the round-trip gain for the propagating component was 61. Thus, casual inspection of Fig. 2 shows that the wave packet is attenuated by the pulse by a factor α of at least 100. A more careful search of the data, employing complex demodulation and filtering to isolate the transmitted and reflected components, gives a lower bound $\alpha \gtrsim 400$ for the attenuation of both transmitted and reflected wave packets. This implies that, in the presence of the pulse, the linear convective instability is suppressed above the onset measured with no pulse present by $\epsilon_c = s\tau_0\Gamma^{-1}\ln\alpha \gtrsim 0.013$, where s is the linear group velocity, τ_0 is the time scale of the growth of linear TW, and $\Gamma = 80.1$ is the length of the system.[5,6] In fact, we consider it likely that the absorption is total, and that the pulse suppresses the TW instability completely.

Larger-amplitude wave packets interact with pulses in a different manner. As shown in Fig. 3, a small fraction of a sufficiently large wave packet "burns through" the stationary pulse. This fraction ranges from 0.002 to 0.005, depending nonmonotonically on amplitude. Thus, the growth of convectively unstable waves is no longer completely suppressed by absorption. Furthermore, wave packets of sufficient amplitude can actually destroy the pulse, as is done by the transmitted wave packet in Fig. 3. This leaves the system above onset with no extra absorption, and convective instability can mediate a transition to another state. In the case shown in Fig. 3, since the system was below ϵ_f, the transition was not to a full-cell state but to one consisting of two stationary pulses. We have also been able to trigger the transition to a full-cell state in this manner.

Above onset, we observe that propagating disturbances appear spontaneously even if they are not injected artificially.[11] As illustrated in Fig. 4, these fluctuations can trigger a transition to a full-cell state. We hypothesize that the threshold ϵ_f for the cell-filling transition is determined by the condition that such spontaneous fluctuations experience so much gain as they travel over the length of the system that their amplitude upon collision with the stationary pulse is sufficient to destroy it. On this basis, we can arrive at a reasonable estimate for ϵ_f: The wave-packet amplitude required to destroy a pulse, whether injected or spontaneous, is measured to be 3–8 times smaller than that of the full-cell state, which in turn exhibits a temperature modulation of amplitude 0.08 K $\pm$ 50%.[5] The level of fluctuations in this system has been measured to be approximately 0.07–0.2 mK just

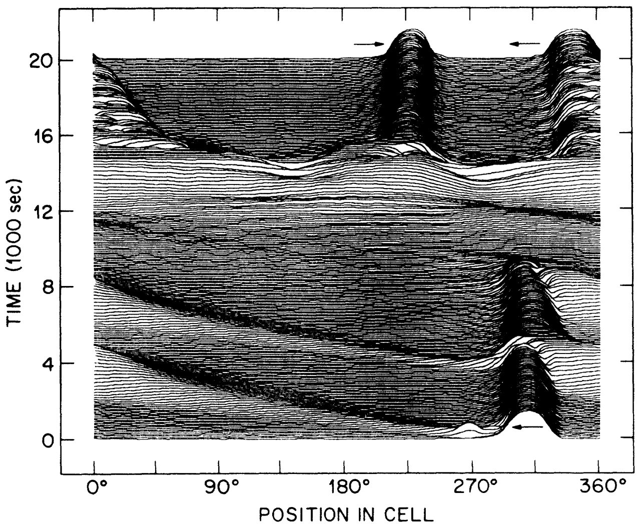

FIG. 3. Hidden-line plot of the interaction of a larger-amplitude wave packet with a pulse of left-going TW, somewhat below the cell-filling transition at ϵ_f. A small fraction of the wave packet was transmitted by the pulse and grew to such high amplitude during the next traversal of the system that it destroyed it on the next collision. This led to a transition to a state consisting of two pulses of oppositely propagating waves.

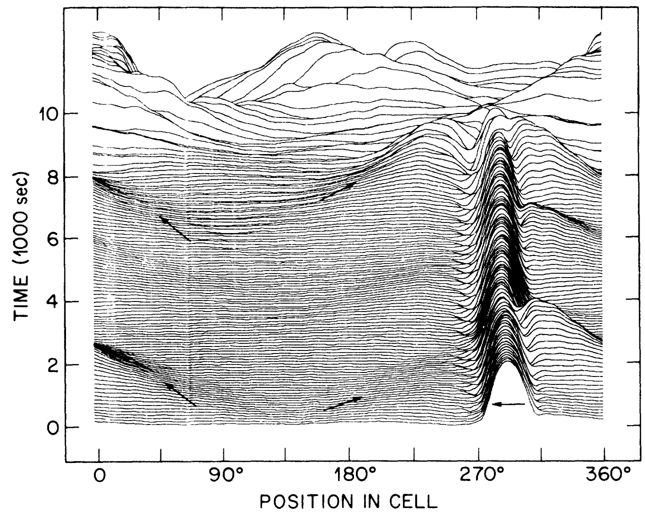

FIG. 4. Destruction of a pulse of left-going TW by spontaneous fluctuations. In the first 8000 sec of this run, left- and right-going disturbances (several are indicated by arrows) are seen to propagate through the left part of the plot. Convective amplification of these TW is sufficient to cause the destruction of the pulse and a transition to a new state. Above the threshold ϵ_f, this new state consists of slow TW which fill the cell.

below onset.[12] Thus, the system must be set above onset by an amount sufficient to produce a gain $\gamma = 40-400$ in order for fluctuations to trigger the cell-filling transition. This occurs at $\epsilon_f = s\tau_0\Gamma^{-1}\ln\gamma \sim 0.009-0.014$, comparable with the observed threshold. We concur with observation made in Ref. 1 that the absolute TW instability, occurring at $\epsilon_a \sim 0.06$, plays no role.

In summary, we are able to locally trigger the linear TW instability and thus to launch propagating wave packets which interact with stationary pulses. When a pulse is present in the system, its absorption of small-amplitude linear waves suppresses the TW instability. This partially answers the question of the stability of the pulses above the original onset of convection. Large-amplitude wave packets can destroy the pulse. Sufficiently above onset, spontaneous TW fluctuations can gain enough amplitude to destroy the pulse by themselves. This mechanism is responsible for the transition to a full-cell state.

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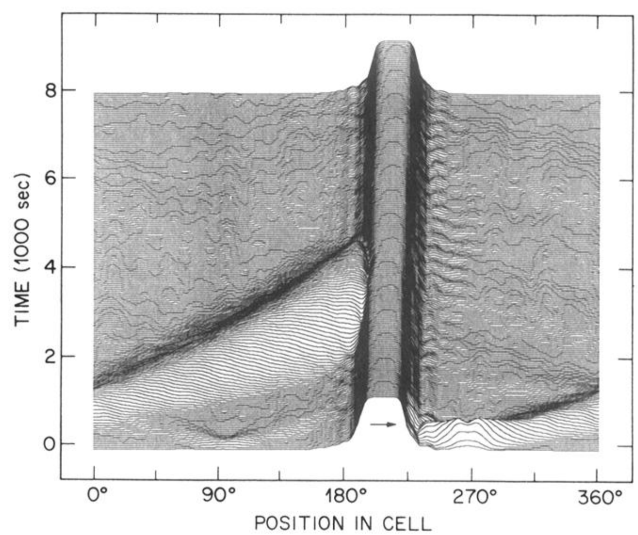

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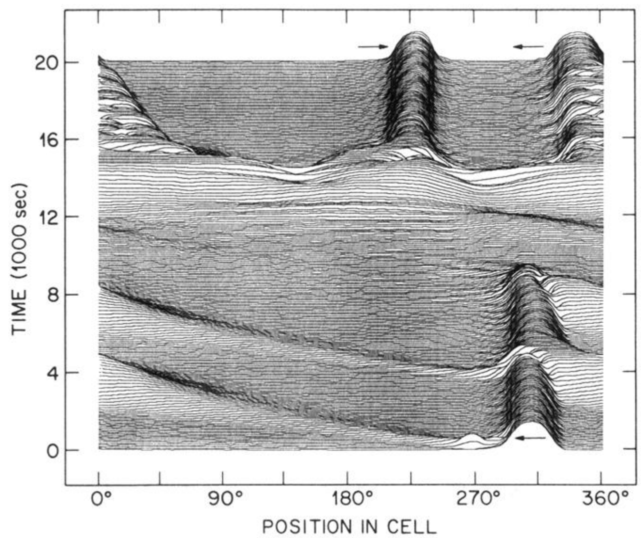

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