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Bifurcations and Patterns in Nonlinear Dissipative Systems

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1. EXECUTIVE SUMMARY

This project consists of experimental investigations of heat transport, pattern formation, and bifurcation phenomena in non-linear non-equilibrium fluid-mechanical systems. These issues are studies in Rayleigh-Bénard convection, using both pure and multicomponent fluids. They are of fundamental scientific interest, but also play an important role in engineering, materials science, ecology, meteorology, geophysics, and astrophysics. For instance, various forms of convection are important in such diverse phenomena as crystal growth from a melt with or without impurities, energy production in solar ponds, flow in the earth's mantle and outer core, geo-thermal stratifications, and various oceanographic and atmospheric phenomena. Our work utilizes computer-enhanced shadowgraph imaging of flow patterns, sophisticated digital image analysis, and high-resolution heat transport measurements.

We investigated binary-mixture convection. For positive separation ratios Ψ we studied square patterns. For negative Ψ , we investigated the formation of localized pulses in two dimensions.

We studied convection in a gas (CO_2) under pressure (about 30 bar) with a Prandtl number $\sigma \simeq 1$ in a very large aspect ratio sample (radius/height up to 150). For parameter values where time-independent parallel straight rolls were theoretically predicted to be stable, we found a state of spiral-defect chaos (SDC). These experimental results have stimulated a great deal of theoretical work, using both analytical and numerical methods and various model equations for convection.

We extended our experiments on SDC to small σ by using mixtures of gases. If one component of the mixture has a large and the other a small molecular mass, σ as small as 0.14 can be reached. The first appearance of SDC shifts closer to the onset of convection as σ decreases. This gives information about the origin of SDC, but has not yet been explained quantitatively.

We investigated convection in a nematic liquid crystal in a horizontal magnetic field H . We found excellent agreement with recent theoretical predictions for the bifurcation line $R_c(H)$, and for the convection-roll orientations as a function of H . We also used this system to study convection when two phases (the nematic and isotropic phase) are present in the cell. Convection in the presence of a first-order phase change is relevant to convection in the earth's mantle; ours are the first quantitative experiments relevant to this important problem.

2. WORK COMPLETED DURING THE DURATION OF THIS GRANT, JULY 1 1987 TO SEPTEMBER 14 2003

A. Experimental Methods

1. Ultra-high resolution shadography

We refined the shadowgraph technique of flow visualization to the point where it has ultra-high resolution. We did this by using appropriate optics which yields an effective image distance of about 30 *m*. The technically difficult aspect of this problem was to avoid excessive image distortion and time/temperature dependent shifts of images relative to the reference image. We are now able to make quantitative measurements of pattern amplitudes even when the flow contribution to the heat transport is well below 0.01%. This refinement of the classical visualization technique enabled us to carry out the studies of pattern formation in binary-mixture convection described below.

2. Apparatus for Convection in Gases

A major technological development consisted of the design and construction of apparatus for the study of convection in gases. By now apparatus like it has been used at Los Alamos, the University of Toronto, and at Cornell University. A detailed description of it has been provided in a detailed Invited Paper in the Review of Scientific Instruments. Gas convection has opened up several qualitatively new vistas in the study of pattern formation in nonlinear systems. In our own laboratory, it led to the discovery of spiral-defect chaos, was used for experiments on RBC with rotation, and enabled the study of low-Prandtl-number convection in gas mixtures.

B. Convection in Binary Mixtures

1. Convection in Binary Mixtures with $\Psi > 0$: Square Patterns

We carried out an investigation of convection in water-ethanol binary mixtures with separation ratios Ψ close to zero. Measurements of the Hopf frequency for $\Psi < 0$ were used to determine the relationship between Ψ and the mass concentration c with high precision.

These results are consistent with but more precise than earlier measurements by conventional techniques. For $\Psi > 0$, the pattern close to onset consisted of squares. Our data give the threshold of convection $r_c \equiv R_c/R_{c0}$ (R_c is the critical Rayleigh number of the mixture and R_{c0} that of the pure fluid) from measurements of the refractive-index power of the pattern as revealed by a very sensitive quantitative shadowgraph method. Prior to our work there had been no method with sufficient resolution to detect the very feeble flows below the Rayleigh onset of mixtures with $\Psi > 0$. Over the range $\psi \lesssim 0.011$, corresponding to $r_c \gtrsim 0.2$, the results are in good agreement with linear stability analysis. The measured refractive-index power varies by four orders of magnitude as a function of r , and for $r \gtrsim 0.55$ is in reasonable agreement with predictions based on the ten-mode Lorenz-like Galerkin truncation of Müller and Lücke. For smaller r , the model predicts a cancellation between contributions to the refractive index from concentration and temperature variations which does not seem to occur in the physical system. Determinations of the wavenumbers of the patterns near onset are consistent with the theoretically predicted small critical wavenumbers at positive Ψ . As r approaches one, we find that q approaches the critical wavenumber $q_{c0} \simeq 3.1$ of the pure fluid. This work was published in the *Physical Review*.

Usually, the shadowgraph method has been used only to determine patterns, and no evaluation of the intensity has been attempted. Our work presents the first quantitative evaluation of the refractive-index field from the measurements. It turns out that our shadowgraph method has now been refined to the point where variations as small as one part in 10^9 can be resolved. This should have technological applications, for instance for the inspection of nearly-perfect surfaces and mirrors.

2. Convection in Binary Mixtures with $\Psi < 0$: Pulses

We found that 2d pulses form spontaneously in this system. We studied the pulses of BMC in an annular and a rectangular geometry, and demonstrated that they had a unique width which was independent of geometry. This work firmly established that the existence of these localized states was unrelated to sidewalls, etc. Our work was published in *Physical Review Letters*. It was also included in a review article.

We investigated the existence and stability of pulses in binary-mixture convection when the sample is spatially extended in two dimensions and found that 2d pulses form spontaneously in this system. They are long-lived (lifetimes of a day or more), but so far we have not been able to find a parameter range where these localized states are truly stable. The work was published in *Physical Review Letters*. It was also discussed in a recent review on non-potential systems.

More recently we made the remarkable discovery that the behavior of the system is quite different at two different ethanol concentrations for which the separation ratio Ψ is the same. We attribute the difference to the difference in the derivative $\partial\Psi/\partial c$ of Ψ , which is positive at large (25.0 wt. %) and negative at small (1.1 wt %) c (for both, $\Psi = -0.08$). For large c , convection goes through a series of transients, including localized pulses, to a cell filling steady state. At small c , there is a range of temperature differences for which there are repeated transients involving fluctuations and pulses of travelling waves, as well as a "wall

state” of azimuthally travelling waves which leaves the cell interior empty. These repeated transients continue indefinitely (a week), without ever leading to a filled cell. We consider this an example of spatio-temporal chaos which may be related to the one-dimensional ”dispersive chaos” observed in an annulus by Kolodner. Aside from the intrinsic interest in the chaotic state, we expect the difference in behavior at the two concentrations with the same Ψ to shed light on the nature of the instability. This work was published in the Physical Review.

C. Convection in the Presence of a Horizontal Flow

We made good progress in the study of Rayleigh-Bénard convection in a long, narrow, horizontal cell with an imposed flow parallel to the long side. In his system, rolls with their axes parallel to the short sidewall (transverse rolls) bifurcate from the conduction state for throughflow Reynolds numbers R less than 0.5. For larger R , longitudinal rolls first form. We explored experimentally the convectively unstable region for this system as a function of R . Sufficiently close to the convective instability this region normally contains no structures because any disturbances are swept away faster than they can grow. We developed methods for generating pulses of convection rolls with extremely small amplitudes at the inlet which grow as they travel downstream in the system and used these to measure growth rates. An interesting aspect of this system is that somewhat further above the convective, but well below the absolute, instability there exist spontaneously occurring noise-sustained structures. This is so because in our system even a very small perturbation has the opportunity to grow to a macroscopic level since the system is very long and thus a large time elapses before the perturbation is swept out of the system. We determined quantitatively the noise level necessary to explain this phenomenon so that a comparison with the influence of thermal noise on this system can be made.

D. Convection in Gases

1. Hexagons and Spirals

We extended our study of convection in a gas (CO_2) under pressure (about 20 bar). There are now two apparatus with a pressure stability of 5ppm, and a temperature stability of better than $10^{-3}K$. During the last year we improved the quality of the convection cells substantially. By making the sample cell extremely thin (0.3 mm), we achieve a very large aspect ratio (radius/height of about 150) without encountering excessive lateral diffusion times that would make it impossible to achieve a stationary state in the system. However, a thin sample requires exceptional uniformity of the spacing between top and bottom plates so as to keep the relative variation of the gap small. Our plates are optically flat (to better than $\lambda/4$). The bottom plate is positioned by three piezo-electric posts so that it is parallel to the top plate within about 0.1 μm .

By using thin samples and appropriate pressures, we achieved strong departures from the Oberbeck-Boussinesq approximation. Under those conditions, the bifurcation from conduction to convection becomes hysteretic, and the pattern that forms consists of hexagons rather than rolls. Whereas some of these effects have been seen qualitatively before, we now have quantitative measurements of the size of the hysteresis between hexagons and conduction. This hysteresis was not resolved in previous work. It is measurable in our experiments because of the high resolution and stability. Our results for the hysteresis are in reasonable agreement with theoretical predictions. Our sample has a large aspect ratio (radius/height), and we find that a defect-free lattice consisting of about 10^4 hexagonal cells forms above the bifurcation. As the temperature difference is further increased beyond the hexagon range, the system forms a giant spiral that fills the entire cell. Spiral patterns are known to occur also in chemical and biological pattern-forming systems. Our system has the great advantage that the spirals are perfect, stable indefinitely, and contain many turns. Our experimental work has stimulated considerable theoretical activity, and has directly provoked numerical calculations, using a modified Swift-Hohenberg equation, by Xi and Gunton. Our results have been published in *Physical Review Letters* and elsewhere.

2. Spiral-Defect Chaos

At even higher temperature differences (say 1.5 to 2 times critical) we discovered that the regular large-scale spiral structures in our system break up into many interacting smaller spirals. The state that evolves is one of spatio-temporal chaos now known as spiral-defect chaos. We characterized this state by calculating the frequency-dependent structure function $S(k, \omega)$. To our surprise, the spiral-chaos state persists also under Boussinesq conditions, and seems to be the natural state of convection for Prandtl numbers of order one in a region where conventional stability analysis had predicted stable rolls. The correlation length of the pattern decreased rapidly with increasing control parameter so that the size of a correlated area became much smaller than the area of the cell. This suggests that the chaotic behavior is intrinsic to large aspect ratio geometries. Since the original experimental discovery, a large number of theoretical and experimental investigations [including have evolved, and SDC is of great interest to this day. The problem became so popular that an entire workshop at Los Alamos was devoted to it.

E. Fluctuations below the onset of convection in a pressurized gas

We made direct flow visualizations of fluctuations below the bifurcation from conduction to convection in a gas under pressure by taking advantage of the extremely thin sample ($d = 0.4 \text{ mm}$) that can be used in his system, and by working at a higher pressure to make the bifurcation accessible in his sample (the fluctuations are expected to be relatively stronger in a thinner sample). The fluctuations are *extremely* weak, and so far have never been observed in Rayleigh-Bénard convection (recently, they were studied in electro-convection in a nematic liquid crystal. We made quantitative experimental measurements of the intensity of noise-induced fluctuations below the critical temperature difference ΔT_c for Rayleigh-

Bénard convection. The structure factor of the fluctuating convection rolls was consistent with the expected rotational invariance of the system. In agreement with predictions based on stochastic hydrodynamic equations, the fluctuation intensity was found to be proportional to $1/\sqrt{-\epsilon}$ where $\epsilon \equiv \Delta T/\Delta T_c - 1$. The noise power necessary to explain the measurements agrees with the prediction for thermal noise. We consider this result to be an important confirmation of the fluctuating hydrodynamics proposed by Landau and Lifshitz. This work was published in Physical Review Letters.

F. Convection in Gas Mixtures

For liquid mixtures, the Lewis number $\mathcal{L}$ (the ratio between the time scales for mass and heat diffusion) is of order 10^{-2} . We carried out a program of investigating convection in mixtures of *gases*. These mixtures have Lewis numbers which are of order one. This is a parameter range that was completely unexplored by experiment. We made detailed measurements of RBC. In order to interpret the results quantitatively, we determined the necessary thermodynamic and transport properties for six mixtures (He-CO₂, He-SF₆, He-Xe, Ne-Ar, Ar-CO₂, and H₂-Xe) by a combination of data from the literature, molecular-theory calculations, and new thermal-conductivity measurements. All six mixtures have positive separation ratios Ψ . An important feature of the gas mixtures is that their Prandtl number σ (the ratio of the kinematic viscosity to the thermal diffusivity) can be lower than those of the two pure components. The minimum Prandtl number reached by using binary-gas mixtures is about 0.16. The critical temperature difference ΔT_c for the onset of convection is determined from measurements of the Nusselt number $\mathcal{N}$ (the effective thermal conductivity) and from the contrast of shadowgraph images as a function of ΔT . The results agree well with the prediction of linear stability analysis. In contrast to convection in binary-liquid mixtures with $\Psi > 0$, $\mathcal{N}$ for the gas mixtures increases significantly with $\epsilon \equiv \Delta T/\Delta T_c - 1$ as soon as the convection starts at the Soret onset and is qualitatively similar to the Nusselt number of pure fluids. However, the critical Rayleigh number R_c is lower than the value $R_{c0} = 1708$ of pure fluids. The pattern at onset in the gas mixtures initially consists of parallel straight rolls, in contrast to binary-liquid mixtures where the pattern consists of squares. Based on the gas-mixture properties, we find that the Dufour effect (the reciprocal process of the Soret effect) is relatively weak. The slope $d\mathcal{N}/d\epsilon$ of $\mathcal{N}$ at onset is found to be consistent with that predicted by an eight-mode Galerkin truncation. These results were published in a detailed paper in Physical Review E.

The *nonlinear* properties of these systems have been studied extensively by us. The flow patterns, and in particular the onset of spiral-defect chaos, have been determined with the shadowgraph method. A brief report on this work has appeared in Physical Review Letters. The onset of spiral-defect chaos (SDC) moves to smaller values of $\epsilon \equiv R/R_c - 1$ (R is the Rayleigh number and R_c its critical value) as σ decreases. The measurements suggest that large-scale mean flows, which are expected to be stronger at smaller σ , play an important role in the spontaneous generation of SDC. SDC can occur and fully develop in the regime dominated by the Soret effect.

G. Convection in a Nematic Liquid Crystal

Stimulated by theoretical work in the Institute of Professor Lorenz Kramer at the University of Bayreuth, we started a new program of experimental study of Rayleigh-Bénard convection in a horizontal layer of a nematic liquid crystal heated from below and in a horizontal magnetic field. The theoretical work at Bayreuth had suggested that there should be a richness of bifurcation phenomena in this system, including forward and backward bifurcations, tricritical bifurcations, and Lifshitz points. We were able to acquire at no cost a 12-inch Varian magnet to provide the field. With the expertise of the Quantum Institute at UCSB, Dr. Lars Berge, we were able to custom design pole pieces for this magnet which gave us a field homogeneity of 0.1 % over a volume of $5 \times 5 \times 5 \text{ cm}^3$. We built a special non-magnetic convection apparatus that fits into the magnet gap and measured the bifurcation line as a function of the magnetic field for a rectangular sample cell. The results agree reasonably, but not perfectly, with the prediction. We also made studies of one of the Lifshitz points in this system. Measurements of the angle of the oblique rolls as a function of the magnetic field agree well with general expectations about Lifshitz points, but differ in detail from the predictions for this system. Ours are the first quantitative experimental results for this type of bifurcation point that we know of. Because our experiments differ substantially from the detailed calculations for this particular system, we plan additional work in samples of different shapes and sizes. We expect to explore this problem further in collaboration with the theorists in Bayreuth in order to see to what extent the experimental results may be indicative of basic flaws in the equations of motion which have been used in the theory.

We extended our work on convection to a thin horizontal layer of a nematic liquid crystal with homeotropic alignment using a *vertical* magnetic field and heated from below. For relatively low field strengths the first instability is a subcritical Hopf bifurcation. Theory predicts the critical Rayleigh number, critical wavenumber, and Hopf frequency as a function of field strength. Using 4-n-pentyl-4'-cyanobiphenyl contained in a cylindrical cell of radial aspect ratio 10.6, we were able to observe travelling and standing waves during the transitory convective regime. At different field strengths we optically measured the Hopf frequency and critical wavenumber of such travelling/standing waves. At higher fields, we found a codimension-two point beyond which there is a subcritical stationary bifurcation. We are now working at even higher fields, studying a tricritical bifurcation where the stationary bifurcation changes from being subcritical to being supercritical. Generally there is good agreement with the results of linear stability analysis; but additional theoretical work is suggested by some of our results.

H. Two-Phase Convection

We obtained experimental results for convection in a horizontal layer of a fluid that is heated from below and that undergoes a first order phase change. The fluid is the nematic liquid crystal 5CB. We found that for some parameter ranges the denser layer may be stably stratified above the lighter one, as predicted by Busse and Schubert. Over various parameter ranges we observed hexagonal, inverted-hexagonal, and roll flow. Interesting

interactions between two-phase convection and Rayleigh-Bénard convection are observed near two codimension-two points. In a collaboration with Professor W. Pesch from Bayreuth, Germany we advanced the theory for this system significantly and found partial agreement with the experimental results. The results were published in *Physical Review Letters* and in *Physical Review E*.

I. Convection with Rotation about a Vertical Axis

In our collaboration with R. Ecke at Los Alamos, we made measurements for Rayleigh-Bénard convection of a fluid (CO₂) in a cylindrical cell with radius-to-height ratio 40 and rotated about a vertical axis. At dimensionless rotation rates $12 \leq \Omega \leq 20$ and for Prandtl numbers $\sigma \simeq 1$, Küppers-Lortz-unstable patterns offered a unique opportunity to study spatio-temporal chaos (domain chaos) immediately above a supercritical bifurcation where weakly-nonlinear theories in the form of Ginzburg-Landau (GL) or Swift-Hohenberg (SH) equations can be expected to be valid. We measured the frequency ω_a and the correlation length ξ of the pattern dynamics. They could be fit by power laws in ϵ only when exponent values much smaller than those predicted from amplitude equations were used. Alternately, the predicted exponents could be retained if the threshold was shifted to negative values of ϵ , thus yielding finite ω_a and ξ at onset. We regard this difference between experiment and theory as a major problem in the field of spatio-temporal chaos. Our results were published in *Physical Review Letters*.(12)

It had been speculated that the anomalous scaling of the correlation length for domain chaos might be caused by defects generated at the cell sidewall. We carried out a quantitative study of domain chaos at $\Omega = 16.4$ in the cell with the radial ramp so as to eliminate (or at least dramatically alter) the sidewall influence on the pattern. In this geometry, we reproduced the same anomalous scaling of the correlation length which was observed with the conventional rigid sidewall.

We started a major effort in image analysis that determines the local wave director field rather than depending on Fourier analysis. It enables us to obtain the angular correlation function of the domain-chaos wave director. The correlation length extracted from its decay is a good measure of the domain size. This work is still under way, but early results suggest that the domain size remains finite at the onset of convection. This behavior can not be captured by the conventional Ginzburg-Landau descriptions. of this state.

J. Rayleigh-Bénard convection with rotation at Small Prandtl numbers

Prandtl numbers in the range $0.16 < \sigma < 0.7$ can only be reached in mixtures of gases. These fluids offer rich opportunities for the study of a line of tricritical bifurcations, of supercritical Hopf bifurcations to standing waves, of a line of codimension-two points, and of a codimension-three point. We have concentrated on this region of the bifurcation diagram. We continued our work on a Prandtl number of 0.17 obtained with a H₂-Xe mixture, and studied in detail the unusual subcritical bifurcation without hysteresis but

with intermittency. This work has stimulated theoretical work by Kramer, Coulet, and Pesch in Bayreuth, Germany. A detailed paper has been published in Physical Review E.

K. Convection in Acetone

We carried out a study of convection using acetone which has a Prandtl number $\sigma \simeq 4$. We found that the spiral-defect-chaos (SDC) attractor which exists for $\sigma \simeq 1$ has become unstable at the larger σ . Gradually increasing the temperature difference ΔT from below to well above its critical value ΔT_c no longer leads to SDC. A sudden jump of ΔT from below to above ΔT_c causes convection to grow from thermal fluctuations and does yield SDC. However, the SDC is a transient; it coarsens and forms a single cell-filling spiral which then drifts toward the cell wall and disappears. The work has been published as a Rapid Communication in Physical Review E.

L. Rayleigh-Bénard convection in elliptic and stadium-shaped containers

Patterns formed in Rayleigh-Benard convection, and in chemical, biological, optical, and other nonlinear systems, may be near-perfect, for instance consisting of parallel rolls or stripes, of squares, or of hexagons. However, in naturally occurring patterns defects are also characteristic features. Defects can be grouped into a small number of universality classes. Examples of most of these have been observed over the years in our DOE-supported work using convection in a horizontal layer of fluid heated from below. They include focus singularities, convex and concave disclinations, domain walls, and spiral defects. Recently a new defect class was predicted on the basis of the mathematics of director fields by Ercolani et al. It occurs because of director frustration when an outermost roll is forced to have an elliptical shape, and corresponds to the formation of caustics for instance in optics. In recent experiments our undergraduate student Woravat Meevasana carried out the corresponding experiment in a convection cell where some of the heat was supplied to an elliptical sidewall, thereby forcing the outermost convection roll to be parallel to the wall. The central part of the resulting pattern contains the expected new singularity. We also studied the corresponding stadium system (two semicircles connected by straight lines) and, as expected theoretically, found two convex disclinations.

M. Karhunen-Loève decomposition of patterns

We generated very long time series of spatially chaotic patterns, using the spiral-defect chaos state which was discovered in our laboratory a decade ago with DOE support. Each time series spans as much as a month, and consists of one to two thousand images. The availability of this experimental information opens up new vistas in the field of time dependent pattern analysis.

In collaboration with Henry Greenside and Scott Zoldy, we analyzed the time series by the method of Karhunen-Loève decomposition. This is the first time that this decomposition has

been done on two-dimensional experimental patterns. We found the spatio-temporal chaos to be extensive, i.e. its attractor dimension was proportional to the area of the system.

N. Wavenumber selection and large-scale-flow effects due to a radial ramp of the spacing in Rayleigh-Bénard convection

The problem of wavenumber selection by a spatial ramp in the control parameter has been investigated extensively in one spatial dimension. There is no information we know of on the selection problem in systems which are spatially extended in two dimensions. We measured the wavenumbers q_s selected in a thin horizontal fluid layer heated from below. The cylindrical sample had an interior section of uniform spacing $d = d_0$ for radii $r < r_0$ ($\Gamma_0 \equiv r_0/d_0 = 43$) and a ramp $d(r)$ for $r > r_0$. For Rayleigh numbers $R_0 > R_c = 1708$ in the interior, straight or slightly curved rolls with an average $\langle q_s \rangle = \tilde{q}_c + \alpha \epsilon_0$ ($\epsilon_0 \equiv R_0/R_c - 1$) and $\tilde{q}_c < q_c = 3.117$ were selected, and q_s varied on two length scales approximately equal to Γ_0 and to four roll wavelengths. For $\epsilon < 0.03$ and $\epsilon > 0.18$ the pattern repeatedly formed defects which moved in specific directions by a combination of climb and glide. The direction of defect motion has stimulated significant theoretical activity. The group of Greenside and Cross, which is supported by the DOE, have carried out illuminating numerical calculations based on the Boussinesq equations which provide information about the relevance of mean-flow effects in this system.

O. Squares at onset in the presence of rotation.

We studied Rayleigh-Bénard convection with rotation about a vertical axis at dimensionless rotation rates $0 \leq \Omega \leq 250$ and $\epsilon \equiv \Delta T/\Delta T_c - 1 < 0.2$. Critical Rayleigh numbers and wavenumbers agree with predictions of linear stability analysis. However, for $\Omega > 70$ and small ϵ the patterns are cellular with local four-fold coordination. Stable as well as intermittent defect-free square lattices exist over certain parameter ranges. Over other ranges defects dynamically disrupt the lattice but cellular flow and local four-fold coordination is maintained. These observations came as a surprise because theoretical stability analysis predicted that the first pattern above onset to be seen should be domain chaos. Our observations have since been supported by observations of squares in numerical integrations of the Boussinesq equations, but the conflict with stability analysis is yet to be explained.

P. Traveling concentric-roll patterns in Rayleigh-Bénard convection with modulated rotation

We studied the effect of modulated rotation about a vertical axis on Rayleigh-Bénard convection. The dimensionless rotation rate Ω was varied as $\Omega_m = \Omega [1 + \delta \cos(\phi \Omega t)]$. We used a cylindrical cell of aspect ratio (radius/height) $\Gamma = 11.8$ and varied Ω , δ , ϕ , and $\epsilon \equiv R/R_c(\Omega) - 1$ (R is the Rayleigh number). The fluid was water with a Prandtl number of 4.5. Sufficiently far above onset even a small $\delta > 0.02$ stabilized a concentric-roll (target) pattern

and thus suppressed the Küppers-Lortz instability. Multi-armed spirals were observed close to onset. The rolls of the target patterns traveled radially inward independent of the sense of rotation. Our observations stimulated a theoretical analysis by Riecke et al. (also supported by DOE) which explained the occurrence of concentric rolls but so far has not yet discovered the origin of their traveling nature.

Q. Recent Developments in Rayleigh-Bénard Convection

The PI co-authored a major review of pattern formation in Rayleigh-Bénard convection with Eberhard Bodenschatz of Cornell University (a former postdoc of ours), and with Werner Pesch (a theorist in Bayreuth, Germany). This review was published in *Annual Reviews of Fluid Mechanics*, and is 68 pages in length. It summarizes results for Rayleigh-Bénard convection which have been obtained over the past decade or so, mostly in our laboratories with DOE support and in those of Professor Bodenschatz at Cornell University. It concentrates on convection in compressed gases and gas mixtures with Prandtl numbers near one and smaller. In addition to the classical problem of a horizontal stationary fluid layer heated from below, it also covers briefly convection in such a layer with rotation about a vertical axis, with inclination, and with modulation of the vertical acceleration.

3. PUBLICATIONS SUPPORTED BY THIS GRANT

1. *Experimental test of the Perturbation Expansion for the Taylor Instability at Various Wavenumbers* R.M. Heinrichs, D.S. Cannell, Guenter Ahlers and Michael Jefferson, *Phys. Fluids* **31**, 250 (1988).
2. *Initial States of Pattern Formation in Rayleigh-Bénard Convection*, C.W. Meyer, G. Ahlers, and D.S. Cannell, *Phys. Rev. Lett.* **59**, 1577 (1987).
3. *Deterministic and Stochastic Effects near the Convective Onset*, Guenter Ahlers, Christopher W. Meyer and David S. Cannell, *J. Stat. Phys.* **54**, 1121 (1989).
4. *Pattern Competition in Temporally Modulated Rayleigh-Bénard Convection*, Christopher W. Meyer, David S. Cannell, Guenter Ahlers, J.B. Swift and P.C. Hohenberg, *Phys. Rev. Lett.* **61**, 947 (1988).
5. *Onset of Convection*, David S. Cannell, Christopher W. Meyer, and Guenter Ahlers, in *1988 ASI Random Fluctuations and Pattern Growth: Experiments and Theory* (Kluwer Publishers, The Netherlands, 1988).
6. *Experiments on Bifurcations and One-Dimensional Patterns in Nonlinear Systems Far From Equilibrium*, G. Ahlers, in *Lectures in the Sciences of Complexity*, SFI Studies in the Sciences of Complexity, Vol. I, edited by D. Stein (Addison-Wesley Longman, Reading, MA, 1989), pp. 175.
7. *Localized Travelling-Wave States in Binary-Fluid Convection*, Joseph J. Niemela, Guenter Ahlers, and David S. Cannell, *Phys. Rev. Lett.* **64**, 1365 (1990).
8. *A Simple Model for the Bénard Instability with Horizontal Flow Near Threshold*, H.R. Brand, R.J. Deissler and G. Ahlers, *Phys. Rev. A*, **43**, 4262 (1991).
9. *The Stochastic Landau Equation with Time Dependent Drift*, J.B. Swift, P.C. Hohenberg and G. Ahlers, *Phys. Rev. A*, **43**, 6572 (1991).
10. *Experiments with Pattern-Forming Systems*, G. Ahlers, *Physica D* **51**, 421 (1991).
11. *Thermally Induced Hydrodynamic Fluctuations Below the Onset of Electroconvection*, I. Rehberg, S. Rasenat, M. de la Torre-Juarez, W. Schöpf, F. Hörner, G. Ahlers and H.R. Brand, *Phys. Rev. Lett.* **67**, 596 (1991).
12. *Stochastic Influences on Pattern Formation in Rayleigh-Bénard Convection I. Ramping Experiments*, C.W. Meyer, G. Ahlers and D.S. Cannell, *Phys. Rev. A* **44**, , 2514 (1991).
13. *Effect of Noise on Bifurcations and Patterns in Dissipative Systems*, G. Ahlers, in *The Global Geometry of Turbulence*, edited by J. Jimenez Sendin, (Plenum, London, 1991).
14. *Transitions between Patterns in Thermal Convection*, E. Bodenschatz, J.R. de Bruyn, G. Ahlers, and D.S. Cannell, *Phys. Rev. Lett.* **67**, 3078 (1991).

15. *Hexagonal and Roll Flow Patterns in Temporally Modulated Rayleigh-Bénard Convection*, Christopher Meyer, David S. Cannell, and Guenter Ahlers, *Phys. Rev. A* **45**, 8583 (1992).
16. *Experiments on Three Systems with Non-Variational Aspects*, Eberhard Bodenschatz, David S. Cannell, Robert Ecke, Yu-Chou Hu, Kristina Lerman, and Guenter Ahlers, *Physica D* **61**, 77 (1992).
17. *Convection in gases at Elevated Pressures*, E. Bodenschatz, S. Morris, J. de Bruyn, D.S. Cannell, and G. Ahlers, in *Proceedings of the KIT International Workshop on the Physics of Pattern Formation in Complex Dissipative Systems*, edited by S. Kai (World Scientific, Singapore, 1992).
18. *Transient Localized States in 2d Binary Mixture Convection*, K. Lerman, E. Bodenschatz, D.S. Cannell, and G. Ahlers, *Phys. Rev. Lett.* **70**, 3572 (1993).
19. *Convection in the Presence of a Phase Change*, G. Ahlers, L.I. Berge, and D.S. Cannell, *Phys. Rev. Lett.* **70**, 2399 (1993).
20. *Thermal Convection in the presence of a First-Order Phase Change*, G. Ahlers, L.I. Berge, and D.S. Cannell, *Phys. Rev. Lett.* **70**, 2399 (1993).
21. *Thermal Convection in a Planar Nematic Liquid Crystal with a Stabilizing Magnetic Field*, L.I. Berge, G. Ahlers, and D.S. Cannell, *Phys. Rev. E* **48**, R3236 (1993).
22. *Spiral Defect Chaos in Large Aspect Ratio Rayleigh-Bénard Convection*, S.W. Morris, E. Bodenschatz, D.S. Cannell, and G. Ahlers, *Phys. Rev. Lett.* **71**, 2026 (1993).
23. *Spatial and Temporal Averages in Chaotic Patterns*, L. Ning, Y. Hu, R.E. Ecke, and G. Ahlers, *Phys. Rev. Lett.* **71**, 2216 (1993).
24. *Convection Near Threshold for Prandtl Numbers Near One*, Y. Hu, R. Ecke, and G. Ahlers, *Phys. Rev. E* **48**, 4399 (1993).
25. *Behavior of Focus Patterns in Low Prandtl Number Convection*, Y.C. Hu, R. Ecke, and G. Ahlers, *Phys. Rev. Lett.* **72**, 2191 (1994).
26. *Transition to Spiral-Defect Chaos in Low Prandtl Number Convection*, Y.-C. Hu, R.E. Ecke, and G. Ahlers, *Phys. Rev. Lett.* **74**, 391 (1995).
27. *Over Two Decades of Pattern Formation, a Personal Perspective*, G. Ahlers, in *25 Years of Nonequilibrium Statistical Mechanics*, edited by M. Rubí (Springer, 1995)
28. *Convection for Prandtl Numbers Near One: Dynamics of Textured Patterns*, Y.-C. Hu, R. Ecke, and G. Ahlers, *Phys. Rev. E* **51**, 3263 (1995).
29. *Thermally Induced Fluctuations below the Onset of Rayleigh-Bénard Convection*, M. Wu, G. Ahlers, and D.S. Cannell, *Phys. Rev. Lett.* **75**, 1743 (1995).
30. *Time and Length Scales in Rotating Rayleigh-Bénard Convection*, Y.-C. Hu, R. Ecke, and G. Ahlers, *Phys. Rev. Lett.* **74**, 5040 (1995).

31. *Experiments on Thermally Driven Convection*, G. Ahlers, in *Pattern Formation in Liquid Crystals*, edited by L. Kramer and A. Buka (Springer, 1996).
32. *Excitation of Spirals and Chiral Symmetry Breaking in Rayleigh-Bénard Convection*, R. Ecke, Y.-C. Hu, R. Mainieri, and G. Ahlers, *Science* **269**, 1704 (1995).
33. *Rayleigh-Bénard Convection in Binary Mixtures with Separation Ratios near Zero*, M.A. Dominguez-Lerma, G. Ahlers, and D.S. Cannell, *Phys. Rev. E* **52**, 6159 (1995).
34. *Different convection dynamics in mixtures with the same separation ratio*, K. Lerman, G. Ahlers, and D.S. Cannell, *Phys. Rev. E* **53**, R2041 (1996).
35. *Apparatus for the Study of Rayleigh-Bénard Convection in Gases under Pressure*, J.R. deBruyn, E. Bodenschatz, S. Morris, S. Trainoff, Y.-C. Hu, D.S. Cannell, and G. Ahlers, *Rev. Sci. Instrum.* **67**, 2043 (1996).
36. *The Spatio-Temporal Structure of Spiral Defect Chaos*, S. Morris, E. Bodenschatz, G. Ahlers, and D.S. Cannell, *Physica D* **97**, 164 (1996).
37. *Spiral-defect chaos in Rayleigh-Bénard convection with small Prandtl numbers*, J. Liu and G. Ahlers, *Phys. Rev. Lett.* **77**, 3126 (1996).
38. *Convection under Rotation for Prandtl Numbers Near One: Part I. Linear Stability, Wavenumber Selection, and Pattern Dynamics*, Y. Hu, R.E. Ecke, and G. Ahlers, *Phys. Rev. E* **55**, 6928 (1997).
39. *Competition between Spiral-Defect Chaos and Rolls in Rayleigh-Bénard Convection*, K.M.S. Bajaj, D.S. Cannell, and G. Ahlers, *Phys. Rev. E* **55**, R4869 (1997).
40. *Rayleigh-Bénard Convection in Binary Gas Mixtures: Thermophysical properties and the Onset of Convection*, J. Liu and G. Ahlers, *Phys. Rev. E* **55**, 6950 (1997).
41. *Experiments on Spatio-Temporal Chaos*, G. Ahlers, *Physica A* **249**, 18 (1998).
42. *Strukturbildung in der Natur und im Labor*, Otto von Guericke Vortrag, 14. Oktober 1997, G. Ahlers, in *Journal der Universität Magdeburg*.
43. *Square Patterns in Rayleigh-Bénard Convection with Rotation About a Vertical Axis*, K.M.S. Bajaj, J. Liu, B. Naberhuis, and G. Ahlers, *Phys. Rev. Lett.* **81**, 806 (1998).
44. *Convection Under Rotation for Prandtl Numbers Near One: Küppers-Lortz Instability*, Y. Hu, W. Pesch, G. Ahlers, and R.E. Ecke, *Phys. Rev. E* **58**, 5821(1998).
45. *Pattern Formation in Rayleigh-Bénard Convection at Small Prandtl Numbers and with Rotation About a Vertical Axis*, G. Ahlers, in *Proceedings of the Sixteenth Symposium on Energy Engineering Sciences*, Argonne IL May 13-15, 1998.
46. *Extensive Scaling and Nonuniformity of the Karhunen-Loève Decomposition for the Spiral-Defect Chaos State*, S.M. Zoldi, J. Liu, K.M.S. Bajaj, H.S. Greenside, and G. Ahlers, *Phys. Rev. E* **58**, R6903 (1998).

47. *Rayleigh-Bénard Convection with Rotation at small Prandtl Numbers*, G. Ahlers and K.M.S. Bajaj, in *Proceedings of the IMA workshop on Pattern Formation in Continuous and Coupled Systems*, edited by M. Golubitsky, D. Luss, and S. Strogatz (Springer, 1999).
48. *Wavenumber Selection and Large-Scale-Flow Effects due to a Radial Ramp of the Spacing in Rayleigh-Bénard Convection*, K.M.S. Bajaj, N. Mukolobwicz, N. Currier, and G. Ahlers, *Phys. Rev. Lett.* **83**, 5282 (1999).
49. Recent Developments in Rayleigh-Bénard Convection, E. Bodenschatz, W. Pesch, and G. Ahlers, *Annu. Rev. Fluid Mech.* **32**, 709 (2000).
50. *Traveling concentric-roll patterns in Rayleigh-Bénard convection with modulated rotation*, K.L. Thompson, K.M.S. Bajaj, and G. Ahlers, *Phys. Rev. E* **65**, 046218 (2002).
51. *Rayleigh-Bénard convection with rotation at small Prandtl numbers*, K.M.S. Bajaj, G. Ahlers, and W. Pesch, *Phys. Rev. E* **65**, 056309 (2002).
52. *Hochpräzision im Kochtopf*, G. Ahlers, S. Grossmann und D. Lohse, *Physik Journal* **2-2**, 31 (2002).
53. *Rayleigh-Bénard convection in elliptic and stadium-shaped containers*, W. Meevasana and G. Ahlers, *Phys. Rev. E* **66**, 046308 (2002).