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Fluid Dynamics

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and controls. It tested to full potential all the cryogenic systems and pressure piping, the power-supply system, and the quench-protection system. The successful carrying out of the test was the final step in the development of an overall system that would be reliable enough for operation when beam commissioning started about one year later.

Beam tests with 150-GeV injection began on June 17, 1983. Acceleration to 512 GeV was obtained on July 3, 1983, after about 210 h of available system uptime and about 20 operating days from the start of full-ring operation.

On August 15, 1983, protons were accelerated to 700 GeV. By April 1984 the energy had been raised to 800 GeV. Throughout the following three months, 800-GeV protons were used in fixed-target physics experiments. The major technical goals of a superconducting accelerator have been achieved. It is hoped that a beam energy approaching 1000 GeV will be achieved by the end of 1984.[1]

Helen Edwards, Fermilab

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[1] Phys. Today **37**, 17 (March 1984).

FLUID DYNAMICS

Fluid dynamics is the study of the flow, compression, deformation, expansion, and viscosity of fluids (gases and liquids). Understanding the flow of fluids is important in the design of airplanes, ships, and engines, in predicting weather patterns, and in the search for new energy sources. Specific areas of research in the physics of fluids include the study of statistical mechanics, kinetic theory, the structure and general physics of gases, liquids, and other fluids, as well as certain basic aspects of fluid behavior as it pertains to such disciplines as geophysics, astrophysics, and biophysics. Examples include such topics as magnetofluid dynamics, ionized fluid and plasma physics, shock wave phenomena, hypersonic physics, rarefied gases and upper-atmosphere phenomena, physical aeronomy, transport phenomena, hydrodynamics, boundary-layer and turbulence phenomena, liquid-state physics, and superfluidity.

Convection Patterns

Many different hydrodynamic instabilities lead to spatial patterns in which the flow velocity of a fluid is an approximately periodic function of position. These patterns occur both naturally (for example, in "cloud streets" and in the fine structure of the bands of Jupiter) and in the laboratory. Fluid patterns have much in common with other types of patterns, such as snowflakes.

Problems of hydrodynamic pattern formation are difficult to treat because they are nonlinear. That is, the response of a fluid to a driving force may not be proportional to the force. Therefore, much effort has been directed toward studying one of the simplest systems, convection in a fluid layer confined between rigid boundaries and heated slightly from below. When a critical value of the Rayleigh number—a parameter proportional to the temperature difference across the layer—is exceeded, a pattern of horizontal "rolls" develops in which the fluid circulates alternately clockwise and counterclockwise as the layer is traversed horizontally. A great deal is known from past theoretical and experimental work about the approximate sizes of the rolls (roughly the thickness of the fluid layer) and the conditions under which they are stable. If the roll diameter is too large or too small, or if the Rayleigh number is too large, the rolls themselves become unstable and fragment into smaller flow pieces.

However, there are many unresolved questions. What is the overall structure of the roll pattern and how is it related to the shape of the container? How does the roll size vary with the Rayleigh number? How do patterns evolve? How do defects or singularities in the patterns behave? Finally, what is the connection between patterns and the onset of time-dependent or turbulent flow? Many scientists are attempting to answer these questions both theoretically and experimentally.

During the past year or so, methods of digitally processing images of flow patterns have facilitated a new generation of experiments. For example, experiments by Ahlers and Cannell at the University of California at Santa Barbara have shown that patterns with cylindrical symmetry are stable in a cylindrical cell, but less symmetrical patterns are also stable.[1] The initial conditions play a major role in determining the actual pattern that is realized in this highly nonlinear system. In addition, a significant disagreement was noted between experiment and theory for the roll size as a function of Rayleigh number.

In another investigation, the evolution process from complicated initial states to simpler final patterns was studied by Heutmaker, Fraenkel, and Gollub at Haverford College.[2] This process took a surprisingly long time, about 30 hours for the pattern shown in Fig. 9. The time it takes to reach a steady state is apparently determined by the slow motion of

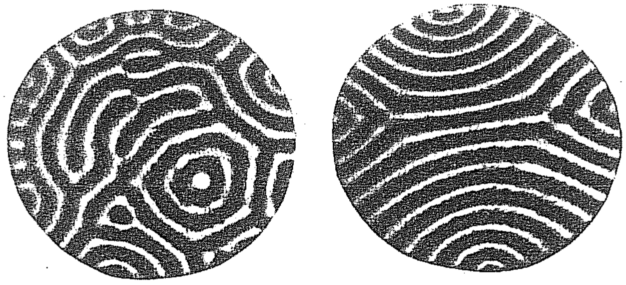

FIG. 9. Images of convection patterns formed by slightly refracted laser light in a cell of radius 43 mm and depth 3 mm. The Rayleigh number is 1.6 times the critical value for the onset of convection. Evolution from the first to the second pattern required about 30 hours. Digital analysis of these images is used to test models of pattern evolution.

defects in the pattern, in much the same way that defect motion in solids can cause slowly evolving transport properties. The final state of the pattern evolution is not unique.

It is quite difficult to study these phenomena by numerical integration of the hydrodynamic equations, even on the largest computers available. For this reason theoretical efforts have centered on simplified model equations that are believed to contain the essential physics while being tractable numerically and to some extent analytically, in part because they are two dimensional and do not treat the less important vertical variations of the flow. They account for many of the phenomena seen experimentally and demonstrate directly the importance of the sidewalls of the fluid container and initial conditions in determining both the final patterns and the time scale of the evolution process.[3]

In this field, and in studies of nonlinear phenomena in general, one can see that the distinction between theory and experiment has decreased by the growing importance of numerical methods.

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2. M. S. Heutmaker, P. Fraenkel, and J. P. Gollub (to be published); J. P. Gollub and M. S. Heutmaker, Bull. Am. Phys. Soc. **29**, 437 (1984); *Proceedings of the International Symposium on Turbulence and Chaotic Phenomena in Fluids*, edited by T. Tatsumi (North-Holland, Amsterdam, 1984).
3. For example, see H. S. Greenside and W. M. Coughran, Jr., Phys. Rev. A **30**, 398 (1984) and references therein.

Strange Attractors in Weak Turbulence

In 1971 Ruelle and Takens[1] proposed that fluid turbulence could be described in an abstract phase space by low dimensional geometrical objects which they called "strange attractors." Recent experiments[2–4] have provided the first convincing evidence for the existence of these strange attractors in weakly turbulent flows.

An entire dynamical system at an instant of time can be represented in an abstract multidimensional phase space by a single point, whose coordinates can represent various physical quantities, such as the velocity of a fluid or the concentration of a chemical in a solution. The trajectory of this point then describes the time evolution of the system (see the cover and caption of *Physics News in 1983*). For a system that comes to rest after transients have decayed, the trajectories of the phase space point for different starting points all terminate at the same point, called a fixed point attractor. For a system that is periodic—such as a child pumping on a swing—the phase space trajectories (after transients have decayed) fall on a closed loop called a limit cycle attractor.

For systems described by fixed point or limit cycle attractors, trajectories that are initially close remain close for all times; hence, systems that are initially nearly identical will remain nearly identical for all times. Or, to put it another way, future behavior can be predicted because an uncertainty in the specification of the initial state will not grow (on the average) as time passes. In contrast, there are situations in which phase space trajectories separate exponentially fast, in which case any uncertainty in the specification of the initial state grows rapidly until that uncertainty is as large as the

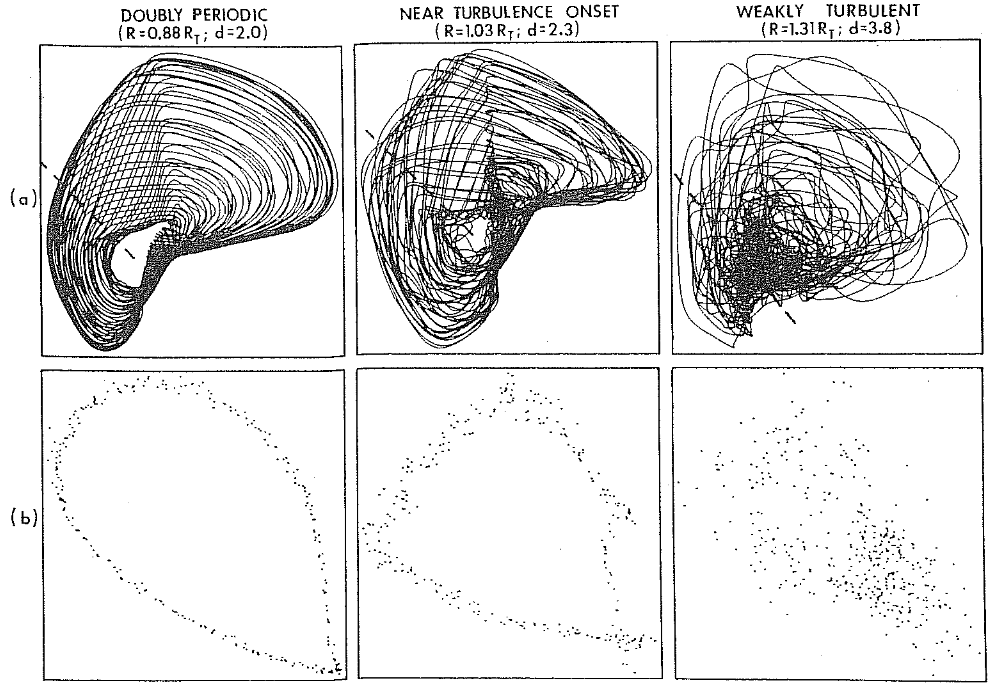

FIG. 10. (a) Two-dimensional projections of phase space attractors constructed from laser Doppler measurements of the velocity of a fluid contained between concentric cylinders. The behavior becomes chaotic (weakly turbulent) when the Reynolds number R exceeds a critical value, R_T. The attractor at $0.88R_T$ is a torus with dimension $d=2.0$, while strange attractors characterize the flow for $R>R_T$. (b) The structure of the attractors is indicated by these plots of the intersections of the trajectories of a three-dimensional attractor with planes normal to the paper passing through the dashed lines in (a).

entire attractor. Thus, the state of the system in the distant future could be predicted only if the initial state were specified with infinite precision, which is an impossibility. This inherently unpredictable behavior is called *chaos*; the corresponding attractors for this condition are called strange attractors.

A team of scientists at the University of Texas has recently found that the weakly turbulent flow of a fluid contained between concentric cylinders (with the inner cylinder rotating) is indeed described by strange attractors.[2] The flow behavior was investigated as a function of Reynolds number R—a dimensionless number proportional to the rotation rate of the inner cylinder. Below the onset of turbulence (i.e., when R is below a critical Reynolds number R_T) the trajectories emanating from nearby points in phase space were found to remain close as time passed, while above the onset of turbulence (for R larger than R_T) nearby points clearly exhibited the exponentially fast separation that is the defining property of strange attractors. (See Fig. 10.)

The dimension of a phase space attractor roughly corresponds to the number of active degrees of freedom of the dynamical system, that is, the number of variables necessary to specify the state of the system. Thus a fixed point attractor is zero dimensional and a limit cycle attractor is one dimensional. The dimension of a strange attractor must be greater than two for a continuum system, but it is in general not an integer. An object, such as a strange attractor, with a fractional dimensionality is called a fractal.[5] (See *Physics News in 1981*, p. 58.) The dimension of the observed strange attractors was found to increase from 2.0 at the onset of turbulence up to about 5 at the highest Reynolds number studied (about $1.8R_T$).

Since fluids are continuum systems it has long been assumed that a very large number of degrees of freedom are necessary to describe turbulence. Hence, theoretical approaches to the problem of turbulence have generally been statistical even though the equations of motion (Newton's laws for a continuum fluid) are deterministic. That is, the equations do not involve random driving forces. The revolutionary idea suggested by the work of Lorenz,[6] Ruelle and Takens,[1] and others is that turbulent flow, at least weakly turbulent flow, can be described by *low-dimensional* strange attractors. Then only a few variables, rather than a very large number, would be necessary to describe turbulence.

The experiment on flow between concentric cylinders (Fig. 2) and experiments on two other flow geometries[3,4] clearly demonstrate that the attractors just beyond the onset of turbulence are low dimensional. A fundamental question to be addressed now by future experiments is how rapidly does the number of degrees of freedom—or equivalently, the dimension—increase as the Reynolds number is increased beyond the weakly turbulent region into the region of fully turbulent flow?

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2. A. Brandstater, J. Swift, H. L. Swinney, A. Wolf, J. D. Farmer, E. Jen, and J. P. Crutchfield, Phys. Rev. Lett. **51**, 1442 (1983).
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6. E. N. Lorenz, J. Atmos. Sci. **20**, 130 (1983).

NUCLEAR PHYSICS

Nuclear physics is concerned with the properties of atomic nuclei in isolation and the interactions of nuclei with each other. At low energies, spectroscopy and the properties of nuclei under mild conditions of excitation have long been subjects of study, and yet new phenomenon continue to appear. One example, reported below, is the discovery of a natural radioactivity in which a carbon nucleus is ejected in the decay of a heavy nucleus. Previously, the only known natural radioactivities by nuclear particle emission were alpha decay and fission. Another example is the discovery of a new mode of motion for deformed nuclei in which the deformed bodies of neutrons and protons wobble about a common axis.

Lately nuclear physics has become more concerned with the exploration of nuclear systems at higher energies, approaching at times the domain of particle physics. With the present generation of heavy ion accelerators it is expected that collisions between nuclei can be made in which particle velocities exceed the sonic barrier of nuclear sound. In these collisions, the energy deposited can be greater than the binding energy of the nuclei, resulting in the emission of many light particles in the collision. In a recent experiment in this energy domain, it was found that pions could also be produced even though the energy of individual nucleons was much smaller than that required to produce a pion. This experiment, discussed below, showed that the cooperative motion of many nucleons can be important in some reactions.

At still higher energy, in the relativistic domain, the study of the nuclear medium at high compression and energy density is an important goal. This year for the first time, collision characteristics have been observed showing that the compression is limited by repulsive forces.

Several years ago experimental evidence for new kinds of particles generated in relativistic nucleus–nucleus collisions, named anomalons, was reported. Anomalons seemed to interact very strongly with other nuclei, traveling an unusually short distance between collisions. The standing of anoma-