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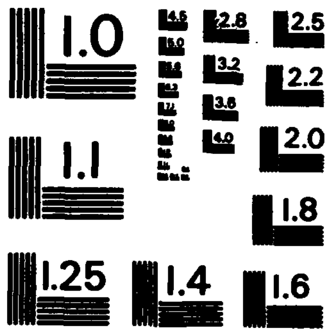

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FINAL REPORT TO THE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

The emphasis in this program was on the

The emphasis in the AFOSR supported turbulence program, was on bringing together, in connection with the overall effort on dynamical systems, researchers from physics, mathematics and engineering, working in the various ~~fields~~ aspects of ~~attracted by~~ turbulence: fluid dynamics, plasma physics, liquid helium theory, crystal growth, etc., and using the various available approaches: numerical methods, dynamical systems, statistical mechanics, etc. Several prominent visitors: Kadanoff, Foias, Klainerman, Guckenheimer, as well as several younger scientists, came for visits during the Spring, and a conference/workshop was held in January/February 1984. This report summarizes the results of a workshop and contains 8 abstracts on related topics.

Three postdoctoral fellows, I.L. Chern, P. Constantin and L.S. Young were supported by the AFOSR grant. There was exceptionally good interaction between the senior scientists, these postdocs, and workers at U.C. Berkeley, Lawrence Berkeley Laboratory and Stanford. In addition to papers completed during the period of the program, groundwork was laid for many further publications, advancing the state of knowledge. Chern completed research on a conservative front tracking method for hyperbolic conservation (joint with P. Colella at LBL). Constantin studied the development of singularities in the solutions of Navier-Stokes equations. L.S. Young, in joint work with Ledrappier, studied metric entropy of diffeomorphisms and established formulas relating entropy, dimension, and Lyapunov exponents.

The January conference/workshop was well attended and drew a lot of praise. The general view is that everyone was surprised by at least one talk. The topics covered included: disorder in crystal growth, meterology, vortices in liquid helium, wake turbulence, the geophysical dynamo, attractors, Lyapunov exponents and dimension, the Navier-Stokes and Euler equations. The program seems to have had a major influence on the participants. Two examples of work that grew out of the program can already be pointed out. A discussion of the numerical work done at Berkeley on blow-up of the solutions of Euler's equation has led Constantin, Klainerman and Majda to a model system whose blow-up can be proved, an important first step towards unravelling the still mysterious long-time behavior of the Euler equation in fluid mechanics. The talk of C. Schwarz on liquid helium showed to several people in the audience that the problem of turbulence in liquid helium is within the ken of available numerical methods, and several papers and theses on the subject are in preparation at Berkeley alone.

The format of the conference/workshop has since been imitated by several other groups, including the International Union on Theoretical and Applied Mechanics, which held its version in Tokyo in September 1984.

Attached is information about the workshop.

Conference on

TURBULENCE

January 30 - February 3, 1984

at the

MATHEMATICAL SCIENCES RESEARCH INSTITUTE
BERKELEY, CALIFORNIA

The Mathematical Sciences Research Institute is holding a one week conference devoted to the topic of Turbulence, January 30-February 3, 1984. The organizing committee in charge of the conference consists of John Guckenheimer, Roger Temam, Alexandre Chorin, and Andrew Majda. The conference will be a multifaceted examination of turbulence and fluids. Recent progress in experimental techniques, theoretical developments, and advances in computational methods will be discussed. Emphasis will be placed on issues that extend beyond transition regimes and address the nature of fully developed turbulence. Invited speakers include the following:

Steven Childress
Paul Dimotakis
Ciprian Foias
Uriel Frisch
Louis Howard
Akiva Jaglom
Leo Kadanoff
Robert Kraichnan
James Langer
Albert Liebchaber
Hans Lieppman
Richard Lindzen
Edward Lorenz
Steven Orszag
Yves Pomeau
Mario Pulvirenti
David Rand
Anatol Roshko
David Ruelle
Klaus Schwarz
Edward Spiegel
Harry Swinney
Roger Temam

The mathematical sciences community is warmly invited to attend. Additional, more detailed information will be sent to people indicating a desire to attend. There will be a limited amount of money available to provide partial expenses for people wishing to attend and participate. Preference will be given to new and recent Ph.D.'s in awarding these partial expenses. Address applications for support and other inquiries concerning the workshop to *Calvin C. Moore, Deputy Director, Mathematical Sciences Research Institute, 2223 Fulton St., Room 603, Berkeley, California 94720.* Funding for the workshop is provided by the National Science Foundation and the Air Force Office of Scientific Research.

TURBULENCE CONFERENCE
JANUARY 30 - FEBRUARY 3, 1984

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Margaret Cheng	Stanford University
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J.H. Curry	University of Colorado
David G. Ebin	SUNY, Stony Brook; visiting UCLA
Aaron Fogelson	University of California, Berkeley
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Amy Wendt	University of California, Berkeley
Kurt Wiesenfeld	University of California, Berkeley (Physics)
Lai-Sang Young	MSRI

CHAOTIC COHERENT STRUCTURES

By E. A. Spiegel

ABSTRACT

This abstract is derived from a talk that attempted to bring together a number of features of turbulent flows. Only one of these features is mentioned here: the modelling of the so-called coherent features. If one has bands of unstable modes for flows in channels of finite transverse extent but of infinite extent in the other two directions, one may derive evolution equations using standard asymptotic methods. In the simplest examples, such equations are nonlinear p.d.e.s involving time and one spatial coordinate. While such equations generally contain the effects of instability, dispersion and dissipation, the relative importance of these effects is controlled by parameters in the problem. Examples can be found arising from the fluid equations in which there is a parameter choice that makes the dissipation and instability disappear. In the simplest cases, soliton solutions are found at such parameter values. Near to such values, soliton-like structures persist, though they suffer mild instability and dissipation. The dynamics of such models was discussed on the basis of asymptotic treatments and numerical simulation. Prospects for further extensions were outlined.

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Physics of convection, Notes on Lectures 1981 Summer Study Program in Geophysical Fluid Dynamics, The Woods Holes Oceanographic Institution, F. K. Mellor, ed., p. 276.

"Intermittency Through Modulational Instability," (with C. S. Bretherton), Phys. Lett. A, 96, 152, 1983.

A CONCISE PRESENTATION OF THE EULER EQUATIONS OF HYDRODYNAMICS

By David Ebin

ABSTRACT

We give a concise proof of the well-posedness of the initial value problem for the Euler equations of hydrodynamics in a bounded domain. We also show that if the domain is two-dimensional, then smooth solutions exist for all time. Furthermore, we show that for any dimension the solution is a smooth (not just continuous) function of the initial data.

Our method entails rewriting the Euler equations as a first order ordinary differential equation on a certain non-linear function space -- namely the space of all diffeomorphisms (invertible smooth self-maps) of the domain. This new equation can be solved by the usual picard iteration.

DYNAMICS OF DENDRITIC PATTERN FORMATION

By J. S. Langer

ABSTRACT

Modern experimental and computational methods are bringing us to the verge of a new understanding of how complex forms emerge in nature. Dendritic solidification patterns are relatively simple examples of morphogenesis which, in addition to being of great interest themselves, are rich sources of tractable models. General features that are emerging from ongoing model-based investigations include the intrinsically nonequilibrium nature of pattern formation, the sharp selection mechanisms that are characteristic of certain kinds of nonlinear processes, and the delicacy of the separation between growth of regular patterns and chaotic behavior.

This lecture will present a review of recent developments in the theory of dendritic solidification including a summary of experimental evidence in favor of a marginal-stability criterion for velocity selection and a description of several one-dimensional models of pattern propagation in which this criterion turns out to be valid. Finally, a new, mathematically tractable, "boundary-layer" model of solidification will be discussed.

$$dx/dt = A_x \sum_{n=1}^{N} y_n z_n,\ dy_n/dt = A_y x z_n,\ dz_n/dt = A_z x y_n,\ A_x + A_y + A_z = 0,$$

which conserves the energy $E = x^2 + \Sigma(y_n^{\ 2} + z_n^{\ 2})$. If this system is modeled by the three-mode system

$$dx/dt = A_x^{'} yz,\ dy/dt = A_y^{'} xz,\ dz/dt = A_z^{'} xy,$$

there is no choice of the A' coefficients which can reproduce the equipartition behavior of the original system in equilibrium. The model system conserves $E' = x^2 + y^2 + z^2$ and gives $\langle x^2 \rangle = \langle E' \rangle/3$ in equilibrium while for the original system $\langle x^2 \rangle = \langle E \rangle/(1+2N)$. In the present scheme, the modeling is instead

$$dx/dt = A_x yz + q,\ dy/dt = A_y xz,\ dz/dt = A_z xy,$$

where q is the constrained random forcing. Because of q, it is $\langle E \rangle = \langle x^2 \rangle + N\langle y^2 + z^2 \rangle$ which is conserved, and the original equipartition survives. The constraints which may be applied to q (with suitable independent initial statistics) include, at the lowest level, the conservation relation

$$\langle q(t)x(t) \rangle = (N-1)A_x \langle x(t)y(t)z(t) \rangle$$

and

$$\langle q(t)q(t') \rangle = (N-1)A_x^{\ 2} \langle y(t)z(t)y(t')z(t') \rangle,$$

which fixes the variance and time-correlation of q.

The decimation scheme does not appeal to small-perturbation theory. But in the limit of strong decimation, where the number of explicit modes is very small compared to the total number of modes, the scheme yields particular classes of renormalized perturbation-theory approximations, including the direct-interaction approximation. This limit can be set up even for small systems by dealing with collective coordinates for a large collection of such systems with similar statistics.

The present scheme is conceptually close to renormalization-group (RNG) philosophy, but it differs in several ways from typical RNG approaches. The decimation is here done all at once. The moment relations which fix the random forcing representing the eliminated modes come just from symmetries. The dynamics do not come in as such until the final

ON THE VORTICITY GENERATED BY THE BOUNDARY IN THE NAVIER-STOKES FLOW

By M. Pulvirenti

ABSTRACT

One of the most interesting features in the time evolution of a viscous incompressible fluid is its behavior near the boundary, especially for very high Reynolds numbers. What is characteristic in this behavior is a production of vorticity at the boundary, due to the fall-down of the velocity, to satisfy the perfect adherence boundary conditions [1]. Therefore, it seems natural to try to estimate the rate of production of vorticity at the boundary and to give a method to construct the Navier-Stokes flow, taking into explicit account this feature. This program can be performed in the half-plane case [2].

The main idea is to look at the Navier-Stokes evolution for the vorticity as perturbed by a singular term, to be determined by means of the solution itself and the boundary conditions. Doing so, one obtains an equation for such a sheet-source production, that can be solved in a suitable Banach space.

The same procedure can be applied (obviously for short times) to the half-space case.

This approach has been inspired by a numerical algorithm due to A. J. Chorin ([3], [4]), which may be thought as a discretization of the above method. For this, one can hope to use the ideas in [2] to prove the convergence of the Chorin product formula. (See [4] for the position of the problem). Results in this direction are in progress.

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[3] A. J. Chorin. J. of Fluid Mechanics 57, 785 (1973).

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LOW-DIMENSIONAL STRANGE ATTRACTORS IN COUETTE-TAYLOR FLOW*

By Harry L. Swinney

ABSTRACT

We have studied the onset and development of chaotic behavior in experiments on the Couette-Taylor system[1] and on the Belousov-Zhabotinskii reaction[2] in a well-stirred flow reactor. The data have been analyzed to obtain phase space portraits, Poincaré sections, maps of the interval, maps of the circle, the largest Lyapunov exponent λ, and the dimension d of the attractors. Although noise is inevitably present at the smallest temporal and spatial scales of the experiments, it is found that the limiting processes required to determine λ and d are well-defined for some laboratory data; thus the global structures of the attractors persist in the presence of small amounts of noise. Moreover, the limiting processes can provide a direct measure of the experimental noise level. The requirements on the quantity of data required to deduce d and λ increase rapidly with increasing d. For Couette-Taylor flow at Reynolds numbers twice that corresponding to the onset of chaos we have obtained d $\approx$ 5; thus, even though the flow appears visually to be quite turbulent, it is still described by a low dimensional strange attractor.[1]

---

*This research is supported by NSF Fluid Dynamics Program Grant MEA82-06889.

[1] A. Brandstäter, J. Swift, H. L. Swinney, A. Wolf, J. D. Farmer, E. Jen, and J. P. Crutchfield, Phys. Rev. Lett. **49**, 245 (1983).

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A VORTEX-TUBE MODEL OF INERTIAL-RANGE EDDIES

By Stephen Childress

ABSTRACT

A vortex-tube geometry representing the cascade of energy to small-scale eddies in fully developed turbulence is proposed. The model, which is a special case of the beta model of Frisch, Sulem, and Nelkin (1978) is based in part on kinematic considerations which conserve the principle invariants of an Euler flow. We assume, however, that viscosity permits crucial changes in the local topology of vorticity even when energy and total helicity are effectively conserved.

In the proposed "gamma" models, active vortex tubes split into smaller active tubes carrying smaller circulation and an inactive structure. The Hausdorff dimension D of the set of active tubes at the termination of the cascade may then be related to an inertial-range spectrum, as in any beta model.

We describe two examples of gamma models, based upon ring and helical vortex tubes. The helical geometry is suggested as a candidate for the structure of a singularity of the inviscid limit of a Navier-Stokes flow, when modeled by vortex tubes.

The parameters describing a gamma model are not unique, but the simplest helical model has $D = 13/5$, a value in agreement with that given by Hentschel and Procaccia (1982), by analogy with established results for certain branched polymers.

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SUPERFLUID TURBULENCE - A PROBLEM IN CLASSICAL HYDRODYNAMICS

By K. W. Schwarz

ABSTRACT

Because of their light mass and very weak mutual attraction, helium atoms do not freeze into a solid as the temperature is reduced, but remain in liquid form all the way down to absolute zero. Since quantum mechanical effects predominate at very low temperatures, the flow properties of this superfluid are very different from those of an ordinary liquid. For example, a flow set up in superfluid helium experiences no dissipation and will persist forever.

The only way in which the superfluid velocity field can differ from pure potential flow is through the appearance of quantized vortex lines, which thread the superfluid and make the flow field more complicated. It has long been known, for example, that if the superfluid is made to exceed a certain critical velocity, it spontaneously changes to a state where it becomes permeated by a dense random tangle of such quantized vortex lines. This transition is analogous to the transition of a classical fluid to the turbulent state, and the phenomenon is referred to as superfluid turbulence.

Quantized vortex lines behave exactly like classical vortex filaments subject to a small frictional force. Because of the great difficulty of treating a random tangle of such filaments, however, it has not been possible to extend this description to obtain an understanding of superfluid turbulence or critical velocities. We have taken an entirely new approach to this problem by implementing the classical rules in a numerical simulation. An important new physical concept which is introduced is the idea that as the vortex filaments cross, they will reconnect to each other and thus change the topology of the tangle. This reconnection process continually generates new quantized vortex singularities, and in this way maintains the vortex tangle in a steady state. A quantitatively accurate, deterministic description of superfluid turbulence is thus obtained. It appears that the topology-changing reconnections provide the underlying mechanism which generates the random "turbulent" behavior.

TURBULENCE AND METEOROLOGY

By R. S. Lindzen

EXTENDED ABSTRACT

The problems of meteorology (predicting and understanding weather and climate) are of evident importance and research in this area has been relatively easy to justify to the public. Not unreasonably, it has become commonplace for research in other areas to be justified by its relevance to meteorology. Turbulence and solar physics are two such areas that come immediately to mind. Not surprisingly, however, the relevance is not always obvious. This lecture will probe into the role that turbulence studies can play in meteorology. The treatment will be superficial--but not so glib as the casual statement that turbulence is the fundamental unsolved problem in fluid mechanics and hence automatically relevant to everything. While there is a measure of truth to this statement, it is equally clear that not everything about turbulence is equally relevant to any particular problem.

Two potential roles are discussed. First is the use of turbulence calculations as a paradigm for the treatment of nonlinearity in numerical simulations of the atmosphere. Advocates of this role tend to view atmospheric eddies as turbulent eddies writ large. Moreover, there is an inclination to assume that nonlinear processes are not strongly dependent on the physical origin of the eddies. Under such conditions, turbulence computations stripped of the cumbersome physics of general circulation models might offer important insights into appropriate numerical methodologies and even into hydrodynamic processes. It is difficult to completely refute such hopes, but there are at least a few indications that suggest problems. First, simple mechanistic descriptions of two instabilities are presented: convection and shear instability. The former involves clear force imbalance and is commonly involved in generating boundary layer turbulence as well as patches of turbulence in the free atmosphere. Such turbulence is generally unresolvable in weather models. The latter involves kinematic distortion of wave fields at steering levels and the maintenance of this interaction by wave fluxes. Examples of shear instabilities are baroclinic and barotropic instability which generate transient weather systems. It seems unlikely that the nonlinear evolution of such disturbances should, in fact, be independent of

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