facilitation results from a block of the calcium-dependent potassium channel that underlies the slow after-hyperpolarization that follows excitation due to the influx of sodium or calcium. The effect of this is to potentiate greatly the response of pyramidal cells to depolarization.

Now if this effect of noradrenaline were involved in plasticity it would be consistent with a hypothesis put forward by Singer[10] following from Hebb's work. Singer's central thesis is that synaptic modification occurs only when dendritic depolarization of the postsynaptic target cells passes a critical level and that this level requires the conjunction of a 'gating input' with the visual input. Clearly the proposed facilitatory action of noradrenaline would greatly potentiate the postsynaptic response to a visual input. But so also, for example, would that of acetylcholine, which seems to influence both the voltage- and calcium-dependent potassium channels in pyramidal cells[16,17]. We know that the visual cortex receives a cholinergic input, so in the light of present evidence, it seems essential to check the involvement of cholinergic processes in plasticity. Until this has been done, both for acetylcholine and for other substances with similar actions, any unique role of noradrenaline in relation to visual cortical plasticity must stand open to question. □

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Multicomponent convection

Turbulence in Earth, Sun and sea

from Herbert E. Huppert

EVERYONE is familiar with one-component convection, such as thermal convection, which occurs when pure water is heated in a kettle. But when, as in the oceans, there are two components — heat and salt — with hot salty water overlying colder fresher water, strong convective flows can be driven by the vertical salinity gradient even though dense fluid everywhere underlies less dense fluid and naive arguments would predict stability. Less than twenty years ago such multicomponent convection was considered merely an 'oceanographical curiosity'. Today it is realized that in many disciplines, complex convective patterns can arise in fluids with two or more components of different molecular diffusivities. In a chemical experiment the two components may be different inorganic solutes or high-molecular-weight polymers. Inside a star there may be four components — angular momentum, heat, the magnetic field and the hydrogen/helium composition — all diffusing at different rates. The broad implications of multicomponent convection were illustrated at a recent conference* where astrophysicists, chemists, fluid dynamicists, geologists, geophysicists, metallurgists and solar pond engineers met to discuss ideas and results relevant to their fields.

S. Turner (Australian National University) described experiments illustrating two main points. First, that double-diffusive transport can be much larger than either the heat or mass transport in a single-component fluid, and second, the need to consider two-dimensional effects due to property gradients in the horizontal as well as the vertical. Application of the results to problems as diverse as the storage of liquid natural gas, the evolution of stars and the melting of icebergs was described. When effects due to the cooling and crystallizing of liquids are also incorporated, the subject is of considerable fundamental fluid mechanical interest, as well as opening up a new area of geology — the fluid dynamical evolution of magma chambers beneath volcanoes. The similarities between the new results on the melting of a vertical ice wall and the solidification on the side of a magma chamber were described, with the concluding question: could igneous geologists be expected to read papers on melting icebergs?

The underlying linear and nonlinear theories were reviewed by H. Huppert and M. Proctor (University of Cambridge). They contrasted the situation when linear motion sets in as a monotonic mode — as can occur, for example, when hot salty water overlies colder fresher water — with that for which an oscillation is initiated — as occurs when the colder fresher layer is on top. In the former case the resulting nonlinear motions are not very different from the linear ones, while in the latter case strong nonlinear effects can occur quite close to the linearly marginal state. For example, the formation of a nonlinear wave packet in a horizontally unbounded domain, which breaks up and develops chaotic motion, was demonstrated in a computer simulation at parameter values close to the linear oscillatory bifurcation point (C. Bretherton, Massachusetts Institute of Technology). Further from this bifurcation point, numerical integrations of the partial differential equations for nonlinear double-diffusive convection in two-dimensional rolls between horizontal boundaries have solutions which reproduce the period-doubling behaviour and transition to chaos found for many ordinary differential and difference equations. An example of a chaotic solution is shown in Fig. 1.

Further applications were described in connection with solar ponds, which can be as large as 10 acres × 4m deep and which trap heat from the Sun in a uniformly hot very salty 3-m storage region beneath a region with strong gradients in temperature and salinity. A successful solar pond is one in which there is 'double-diffusive non-convection'. This is because any convection in the gradient region tends to break it up into a series of layers, the hallmark of multicomponent convection. This greatly increases the heat loss from the storage region to the atmosphere, hence decreasing the efficiency of the pond (F. Zangrando, Solar Energy Research Institute, Golden, Colorado). These observations have led to attempts to calculate the temperature and salinity gradients necessary to inhibit convection (L. Bertram, Sandia National Laboratories, Albuquerque, and I. Walton, Imperial College, UK).

Double-diffusive convection has sometimes been regarded as a nuisance to chemists measuring diffusion coefficients. Alternatively, however, the special effects can be exploited to make valuable measurements, such as has been done for the Soret coefficient of NaCl (D. Caldwell, Oregon State University). Furthermore, eliminating double-diffusive effects from experiments might make the measurements irrelevant to the more usual cases in which convection will be initiated. The importance of the cross-diffusion terms in ternary or higher-order systems was clearly illustrated by the formation of ordered finger-like structures in a wide variety of polymer systems in which the concentration of neither polymer increased with height (B. Preston, Monash University, Australia, and J. Wells, Uppsala University, Sweden). A theory has recently been given to account for this effect (McDougall & Turner *Nature* **299**, 812; 1982), but it is not yet clear whether the theory accurately describes the experimental results.

Observations of magnetic fields at the surface of the Sun indicate that flux is confined to isolated tubes with diameters varying from tens of thousands of kilometres in sunspots to a hundred kilometres for fields between granules. Such fields are examples of structures produced by strongly nonlinear multicomponent convection and

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*A conference on 'Double-diffusive convection' was held in Santa Barbara, under the auspices of the United States Engineering Foundation on 13–18 March 1983.

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have been extensively modelled (N. Weiss, University of Cambridge). Deep in the Sun and in other stars, strong motions may be driven either by unstably stratified magnetic fields or by radial variations in the rotation rate. So far, theories to account for such flows have necessarily been simple, and mainly linear and axisymmetric. Lack of observations also constrains theoretical calculations of the convection in the liquid core of the Earth, which is believed to be the cause of the Earth's magnetic field and its aperiodic reversals. One wonders about the influence of intense motions isolated in either space or time. Are there any important analogues in the interiors of the Sun or stars or at the boundaries of the Earth's liquid core of either the metre-wide vents at the bottom of the ocean from which water around 350°C emanates with a velocity of metres per second or the strong temperature gradients observed in the oceans, such as across fronts?

Oceanographic observations which provided the motivation for much of the early development of double-diffusive convection also attest to its influence. It still remains to determine quantitatively just how important double-diffusive effects are to oceanographic mixing and to develop a clear signature to distinguish double-diffusive effects from those of internal-wave mixing, turbulence and the like.

Parts of igneous geology have been given a new lease of life by the recent rash of fluid dynamical papers devoted to exploring multicomponent convection in evolving magma chambers. An obvious place to apply and test the new concepts is the Skaergaard intrusion, a very large layered complex in east Greenland. The idea that the Skaegaard layering is due to the settling of crystals after they form has a long history but is incompatible with the measured densities of crystals and the melts from which they originate. The layers look like double-diffusive layers, but the correct quantitative signature of such layers in a crystallizing system is still being actively sought.

The often unwanted dendritic growth of a crystallizing interface is well known to metallurgists. Some dendrites are due to an instability of the originally planar interface as it grows upwards into an increasing temperature field and a decreasing concentration field set up as relatively heavy components in the melt are rejected by the solid phase. A series of experiments with solidifying succinonitrile (N. Singh, Rensselear Polytechnic Institute, New York) showed that the formation of dendrites can retard the volume growth by as much as a factor of seven when compared with the theory for a planar interface. A theory for the rate of advance of a parabolic dendrite tip is in better agreement with the experiments, until the main dendrite faces become unstable to secondary branching and produce smaller dendrites emanating at right angles to the original one. It would therefore appear that further theory is still required.

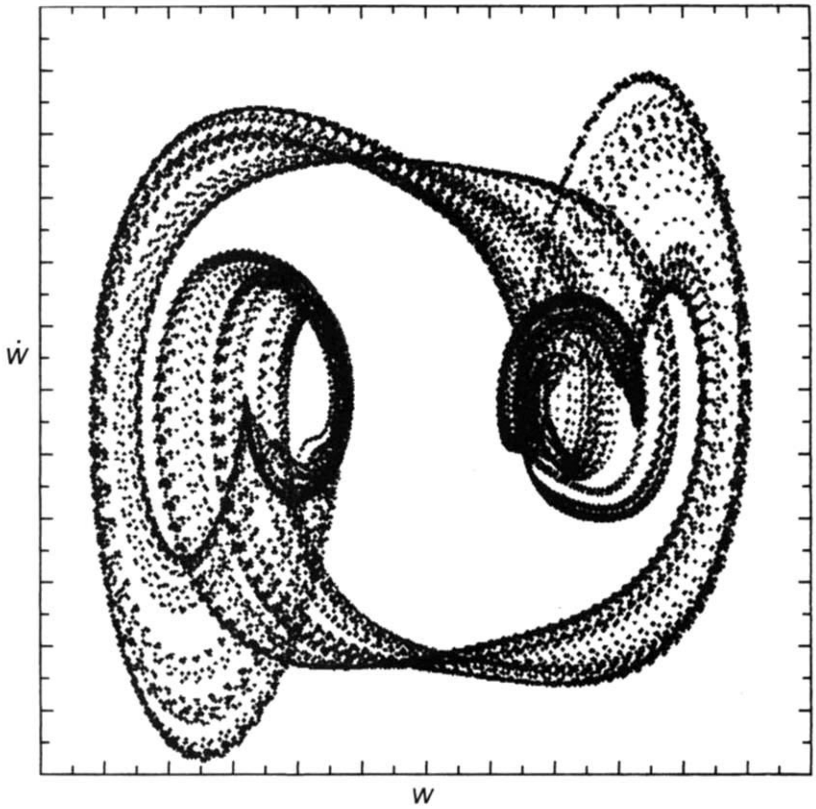

Fig. 1 Chaos in double-diffusive convection between horizontal boundaries. The phase plane of w, the vertical velocity at the edge of a convection cell mid-way between the boundaries, against $\dot{w}$, its time derivative. The solution at each time step in the numerical integration of the partial differential equations is represented by a dot in the phase plane.

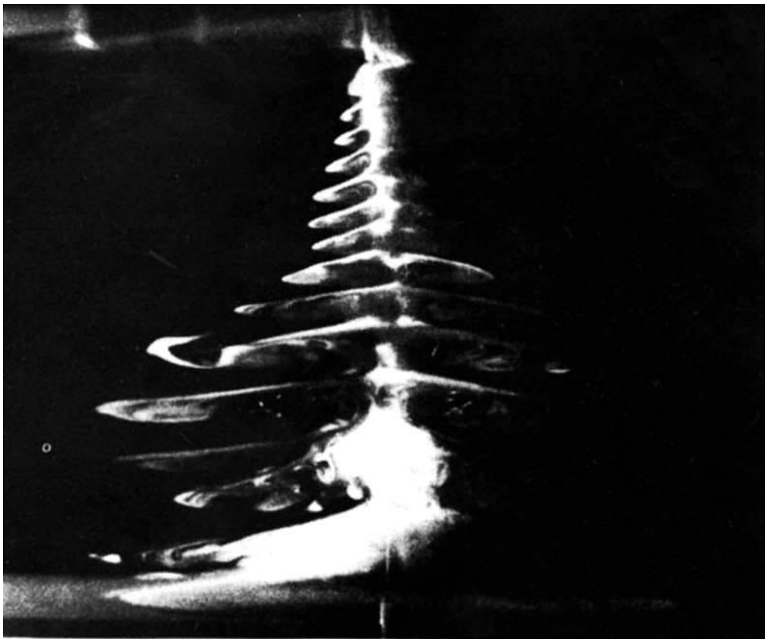

Fig. 2 Flow pattern produced by a point source of heat at the base of a stable salinity gradient. Dye at the level of the heat source has been lifted up and spread out in the 'Christmas-tree' pattern by the induced convection.

In the session on laboratory experiments, A. Tsinober (Tel-Aviv University, Israel) described the effects of heating a compositional gradient from a point source. A Christmas-tree pattern of evolving layers develops (Fig. 2), with large vertical and horizontal variability. It is easy to imagine this fundamental process, which was identified in the laboratory, occurring in many different natural circumstances. □

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