probably existed two billion years ago[12] but, because it's no longer around, we cannot sequence its genome to find out. However, molecular fossils of its lifestyle might be preserved in nuclear chromosomes, including our own, allowing us to piece together the bacterial part of our heritage.

Is anaerobic energy metabolism in eukaryotes a telling relict of our history, or an oddity with little significance? Eukaryotes now regarded as primitive tend to be anaerobes, so these are important questions. The road to answers leads straight to the genomes of eukaryotes from the anoxic world. For scientists studying oxygen-shunning eukaryotes with unconventional mitochondria, with hydrogen-producing mitochondria or with no mitochondria at all, these are exciting times. □

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Nonlinear physics

Universality of turbulence

Victor S. L'vov

Elsewhere in this issue (*Nature* **396,** 552–554; 1998) Bramwell *et al.* describe the discovery of a new type of universality in turbulence. It connects this strongly non-equilibrium phenomenon of classical fluid mechanics with critical phenomena in the thermodynamic equilibrium of solids (magnetically ordered crystals).

Intuitively, hydrodynamic turbulence is understood as the chaotic motion of fluids — be it of interstellar dust in spiral galaxies, of gaseous planetary atmospheres or of water flowing from a tap (Fig. 1). The length-scales vary from galactic distances of 10^{16}–10^{18} km, through planetary distances of 1,000–10,000 km down to the human scales of 1 mm–10 m (in the atmosphere and rivers, as well as in the kitchen sink).

Euler's basic mathematical description of fluid dynamics (1741) was corrected to account for viscous friction by Navier (1827) and Stokes (1945). The Navier–Stokes equation for the velocity $\mathbf{u}(\mathbf{r},t)$ of fluid at point $\mathbf{r}$ and time t is simply Newton's second law for the fluid particle:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \nu\nabla^2\mathbf{u} \qquad (1)$$

This equates a particle acceleration (the left-hand side) with the forcing due to the gradient of the pressure $p(\mathbf{r},t)$ and to the viscous friction (the term proportional to the kinematic viscosity of a fluid ν).

In principle, one has to solve this equation to fully understand all turbulent phenomena, but it is a mathematical nightmare. If one ignores the nasty nonlinear term, $(\mathbf{u}\cdot\nabla)\mathbf{u}$, the mean velocity of typical rivers turns out to be about 10^6 km hr^{-1}, and a maximum car velocity is found to be 2,000 km hr^{-1}, both of which are clearly nonsense. The reason is that the nonlinear term is usually much larger than the linear one. Their ratio is the Reynolds number Re and, for large Re, equation (1) is impossible to solve. Moreover, no one in their right mind wants the full solution of the turbulent velocity field at all points in space-time. It is the statistical properties of the flow, such as probability distribution functions of velocity or the rate of energy consumption, that are important. So, what can we do to understand turbulence?

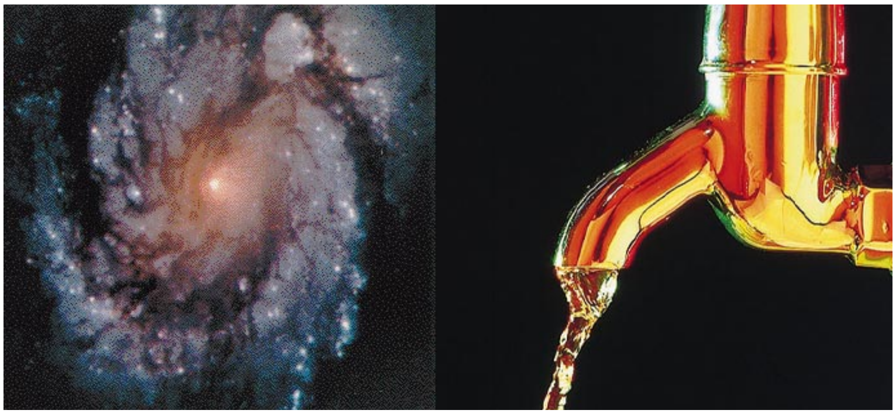
NASA, HUBBLE SPACE TELESCOPE
ADAM HART-DAVIS/SCIENCE PHOTO LIBRARY

Figure 1 **From interstellar space to the kitchen sink. The extreme scales of turbulence range from the motion of interstellar dust in the M100 spiral galaxy to water flowing from a tap.**

In 1922, looking at the evolution of turbulent atmospheric conditions, Lewis Fry Richardson suggested the 'cascade picture of turbulence'. In this, the largest eddies in a system are created by instabilities of the mean streamline flow, as in hurricanes. These decay giving rise to eddies of roughly half their size which decay in turn, creating even smaller third-generation eddies — and so on, until the smallest stable eddies lose their energy because of viscous friction that turns it into heat. In high-Re turbulence, eddies exist at various scales, from the largest ones at the scale of the system size down to the smallest ones at the viscous scale. This situation is called 'developed turbulence'.

In 1941 Andrei Kolmogorov estimated the energy $E(R)$ of eddies of scale R in a unit volume of developed turbulence to be $\rho(\bar{\epsilon}R)^{2/3}$. The assumption here is that the only relevant parameter (besides the obvious length scale R and density ρ) is a rate of energy consumption $\bar{\epsilon}$. Kolmogorov's crucial idea was the assumption of universality of small-scale motions (on scales $R \ll L$) in developed turbulence. Here, universality means an independence of the statistical properties of small eddies from the nature of the fluid (be it interstellar dust or water), independence from the mechanism stirring the flow and independence from the particular geometrical form of the container.

But what about the statistics of large-scale motions? Most of us used to believe these were non-universal and would depend on factors such as the geometry of the system. As Bramwell *et al.* now show, however, there is a class of turbulent flows for which at least some characteristics of large-scale turbulent statistics are universal.

The authors demonstrate the rate of power consumption $P(t)$ in turbulent flow in an enclosed air gap between two counter-rotating disks. For very large Re the probability distribution function Q_P is Re-independent when properly rescaled. Their Fig. 1a on page 553 shows plots of $\sigma_P Q_P$ versus $(P-\bar{P})/\sigma_P$ where $\bar{P}$ is the mean value of P and σ_P is the standard deviation of P (a characteristic width of the distribution Q_P). The normalized distributions $\sigma_P Q_P$ for different Re collapse onto the same curve even though they strongly deviate from Gaussian form for $P < \bar{P}$. Bramwell *et al.* argue that just two factors are important: that the integral Re is fixed at a constant value and that flow is confined in a closed volume (a cylindrical vessel).

This universality is just the beginning of the story presented by Bramwell *et al.* They also consider a two-dimensional magnetic system at a critical point near the second-order phase transition between magnetically ordered and disordered phases. In such systems the magnetic moment $m(\mathbf{r},t)$ strongly fluctuates, on a scale with the same probability distribution as velocity fluctuations in developed turbulence. The fluctuations of the total moment $M(t)$ may also be characterized by the probability distribution function Q_M and the authors observe that the functions Q_M and Q_P are amazingly close (see their Fig. 1c on page 553).

Magnetic systems near the second-order phase transition and developed turbulence are microscopically very different physical systems. Moreover, the first one enjoys thermodynamic equilibrium; the second, energy-flux equilibrium. Most surprisingly, however, Bramwell *et al.* show that there are similarities in statistical behaviour between these systems. These results may well serve as a starting point for further theoretical and experimental work to understand the underlying reasons behind such similarities, and their consequences. □

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Ocean geochemistry

Carbon dioxide uptake at sea

Alain Poisson

To what extent will the world's oceans be able to take up carbon dioxide and reduce its rate of increase in the atmosphere? Numerical modellers[1,2] have tried to give a provisional answer. But their estimates of the main parameters differ considerably — particularly in the Southern Ocean and the tropics, where the flux of anthropogenic CO_2 across the air–sea interface seems to be largest. On page 560 of this issue[3], however, Peng *et al.* claim that it is now possible to make a direct and reliable determination of anthropogenic CO_2 penetration into the ocean. Their approach is based on the temporal variation of measurements of the total dissolved inorganic carbon concentration in seawater.

Before the beginning of the industrial era (around 1850), the global CO_2 cycle was in steady state on a decadal timescale. Since then, the atmospheric concentration of CO_2 has risen increasingly rapidly; now, about one-half of the CO_2 emitted by the combustion of fossil carbon remains in the atmosphere, the rest being partly dissolved in the oceans and partly stored by the terrestrial biosphere. Researchers have long tried to measure the flux of anthropogenic CO_2 at the air–sea interface and through the oceans' water column, to determine the geographical distribution and rate of CO_2 penetration into deep waters. This is no easy task — data are scarce on the time scales required, and the annual increase of the signal is small relative to the local temporal variability in the oceans' dissolved inorganic carbon.

Twenty years ago, a direct method[4,5] was devised for estimating the total anthropogenic CO_2 inventory in the ocean. It was based on a simple concept. The total concentration of dissolved inorganic carbon in oceanic deepwater is the result of its original carbon content when it was at the surface, and the changes that the water has subsequently undergone. When a parcel of seawater sinks from the surface, its salinity and temperature alter because it becomes mixed with seawater from other origins, implying alteration also of its content of dissolved carbon. Moreover, phytoplankton and zooplankton in the surface layers create organic matter and carbonate skeletons that sink in the water column, are oxidized or dissolved, and produce more dissolved carbon in deep seawater. These changes are respectively estimated by the difference in oxygen content and alkalinity between surface and deep water, and are subtracted from the total inorganic carbon of deep water to obtain the original carbon content of that water when it was at the surface. It was claimed that comparing this original, 'preformed' carbon content with that of the present carbon content of surface water gives the anthropogenic CO_2 signal. But this is only true if the deep water was at the surface in preindustrial times; if it was at the surface after that, only the increase in the signal can be estimated.

This method was criticized for several reasons, mainly the way of estimating the composition of the preindustrial waters which mix together to form the deep waters, and that of correcting for the changes that occur as they sink. Nevertheless, the profiles of the anthropogenic signal obtained by this simple method are more or less similar to those of chlorofluorocarbons — CFCs, transient tracers whose penetration into the ocean is close to that of anthropogenic CO_2; this approach was later improved by using an exponential distribution of CFCs (ref. 6).

Only recently, however, has the issue of estimating a reliable CO_2 anthropogenic signal been taken up again, largely due to intensification of the collection of carbon data by the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). The main difficulties are elimination of the nonlinear effects of mixing, and determination of the preindustial carbon

Palaeontology

The face of Cinderella

The discovery of a complete skull of the hominid *Australopithecus*, associated with abundant limb bone material, is announced this week. The picture shows the exposed left side of the skull. The jaws, with a complete set of teeth in occlusion, can clearly be seen. As R. J. Clarke of the University of the Witwatersrand Medical School in Johannesburg reports (*South African Journal of Science* 94, 460–463; 1998), the skull is still embedded in the Member 2 breccia in the Silberberg Grotto of the Sterkfontein Caves near Krugersdorp, South Africa, and more finds are likely. The taxonomic status of the fossil has yet to be determined, although it is believed to

R. J. CLARKE

be more than three million years old.

In 1994, Clarke found four articulating foot bones of *Australopithecus* in rocks from the same site. Eight more foot and lower leg bones turned up last year, all from the same individual. This discovery prompted Clarke to send his colleagues Nkwane Molefe and Stephen Motsumi into the Silberberg Grotto — like Prince Charming, looking for the girl whose foot would fit a glass slipper — to search for *in situ* remains that would fit neatly onto fragments already found. Cinderella duly turned up, in the form of two lower legs arranged side by side, as if the individual had been buried face-down in the breccia. Further work produced parts of an upper arm and the skull as illustrated. Clarke speculates that the rest of the skeleton is still buried under breccia. **Henry Gee**