CHAOS AND IRREVERSIBILITY IN SHEARED SUSPENSIONS AND IN STIRRED REACTING FLUIDS

Jerry P. Gollub

Physics Department
Haverford College
Haverford, Pennsylvania 19041, USA
jgollub@haverford.edu

The irreversibility of the macroscopic world is usually ascribed to the second law of thermodynamics, but chaotic dynamics also produces irreversible phenomena. This talk presents several striking examples: (a) an unexpected threshold for irreversibility in sheared suspensions [1], and (b) irreversible chemical reactions produced by chaotic mixing [2].

Shearing a fluid in a Couette cell at low *Re* is normally perfectly reversible, except for the usually negligible Brownian motion. All fluid elements return to their starting position after a full cycle. However, if the fluid contains solid particles that are too large to diffuse significantly, but are matched in density to the fluid to avoid settling, then time-reversibility fails if the imposed strain exceeds a certain concentration-dependent threshold value. This observation is surprising, because the creeping flow equations are time-reversible. The particles fail to return to their starting positions after one or more full shearing cycles, instead suffering pseudorandom displacements that closely follow the statistics of a random walk when sampled periodically.

In [1] the observations of Pine and Gollub were explained by numerical computations undertaken by our collaborators Brady and Leshansky. It is known that particles in sheared suspensions interact chaotically with each other [3]. Following up on this fact, Brady and Leshansky showed that the Lyapunov exponent describing the strength of these chaotic interactions grows very fast when the fluid is sheared beyond a certain characteristic strain before reversal; the thresholds found in both the experiments and computations are in agreement. However, the physical reason for the particular threshold strain is still unclear, as is its functional dependence on the concentration of solid particles.

In a second example, I show how the irreversibility of a time-periodic two-dimensional flow develops progressively as *Re* is increased. This is a particular example of the well-known phenomenon of chaotic mixing, which can cause a chemical reaction between initially separated reactants, such as an acid-base pair. The novel element of this experiment is that the stretching properties of the flow are characterized locally using a method developed by Voth et al. [4]. This is basically the spatially resolved finite-time Lyapunov exponent. Arratia and Gollub [2] show that the spatial average of this quantity can be used to predict the extent of the chemical reaction as a function of time, a useful practical application of nonlinear dynamics. The physical reason this works is that the stretching of fluid elements extends and sharpens the interfaces between reactants.

References

[1] D.J. Pine, J.P. Gollub, J.F. Brady, and A.M. Leshansky, “Chaos and threshold for irreversibility in sheared suspensions”, Nature **428**, 997-1000, 2005.
[2] P.E. Arratia and J.P. Gollub, Phys. Rev. Lett. 2006, in press.
[3] D. Drazer, J. Koplik, B. Khusid, and A. Acrivos, “Deterministic and stochastic behavior of non-Brownian spheres in sheared suspensions.” J. Fluid Mech. **460**, 307-335, 2002.
[4] G. A. Voth, G. Haller, and J.P. Gollub, "Experimental measurements of stretching fields in fluid mixing," Phys. Rev. Lett. **88**, 254501 (2002).

Keywords: suspensions, chaos, mixing