body—that is, insulin—seems to have a profound effect on our brain, but we don't know what it's doing."

–Ingrid Wickelgren

Additional Reading

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PHYSICS

From a Turbulent Maelstrom, Order

Daniel Dubin and Dezhe Jin didn't set out to introduce a Zen koan—a paradoxical statement that stimulates the intuition—into physics. But the team at the University of California, San Diego (UCSD), is offering a notion that sounds very like a Zen paradox to explain a bizarre phenomenon seen 4 years ago in turbulent gases of electrons. The vortices that develop in these fluids arrange themselves in neat, long-lasting "crystals," looking like a phalanx of tornadoes marching in perfect formation. Dubin and Jin have now shown that this kind of order can be the natural consequence of an increase in disorder.

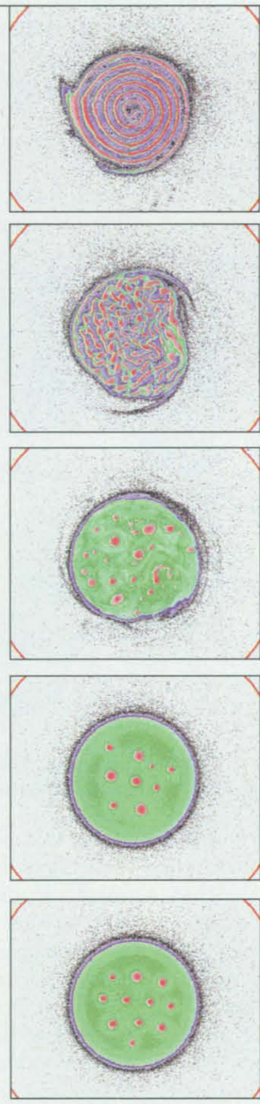
Theory as well as common sense had rebelled at the finding, because stable patterns should be anathema to the high entropy, or randomness, of turbulent flows. But in a flash of insight, the team realized that each large vortex in these electron fluids acts as a Mixmaster, stirring and randomizing the background flow. That entropy increase opens the way for the vortices to gel into predictable, orderly, crystalline patterns. "The moral," says Dubin with the cryptic laugh of a Zen master, "is that entropy is maximized except where it isn't."

Other physicists are suitably bemused. "It's very hard to get your head around," says Michael Brown, a physicist at Swarthmore College in Pennsylvania, of the theory. But the theory, which is accepted for publication at *Physical Review Letters*, accurately predicts not only the crystals but also the distribution of vorticity or "swirliness" seen in the random sloshing of the background. "It is very much in quantitative agreement with the experiment," says UCSD's Fred Driscoll, whose own group discovered the crystals (*Science*, 9 December 1994, p. 1638). The new understanding should help the teams search for the behavior in other laboratory systems and ultimately in nature.

In the original experiments, Driscoll and his colleagues, including Kevin Fine, Ann Cass, and others, caged about a billion electrons at a time in a vacuum chamber using strong magnetic fields. Electrons trapped in this way bounce back and forth so rapidly between charged plates capping the field lines that they smooth out any structures that might form in that direction. The experimenters focus on two-dimensional (2D) patterns that develop across the field lines, like the eddies in a spinning bucket of water or the swirls in a suspended soap film. The big difference between the electrons and other turbulent fluids is that Driscoll's magnetically caged plasma has almost no viscosity or friction with the walls, so it offers a purer picture of turbulence and any structures that may emerge from it.

Driscoll generates turbulent initial states by injecting pulses of electrons from filaments mounted on one of the end caps. He then "photographs" the plasma after various time delays by dumping it onto a phosphorescent screen at the other end, which glows brighter where the electrons are concentrated. These snapshots showed that one or several strong vortices grew as the smaller vortices present in the stormy initial state merged. The vortices, embedded in weaker background eddies, eventually stopped rattling around and "chilled" into crystalline patterns.

Dubin and Jin tried to understand the crystals by drawing on a venerable tradition dating back to work by David Montgomery, now at Dartmouth College in Hanover, New Hampshire, and others in the 1970s. The pair treated the 2D plasma vortices and eddies statistically. They analyzed the ways in which vorticity could be distributed in the fluid to find the most likely patterns, regardless of how they came about. It's essentially the same approach that says roughly equal numbers of heads and tails will come up when you toss 100 pennies, no matter how individual pennies spin and fall. Because the most likely patterns are also the most disordered ones, theorists call this the maximum-entropy approach.



DRISCOLL *ET AL.*

Orderly tornadoes. Vortices in a turbulent sea of electrons "crystallize" into a regular pattern.

If the large vortices break up over time, maximum-entropy theory would predict a vorticity distribution something like sand thrown randomly into a pile, with a single, broad peak. But the two theorists recognized, says Dubin, "that the vorticity in the strong vortices is trapped and cannot be mixed. Those vortices are so strong that nothing can get to them." These persistent, large vortices stir up the background, increasing its entropy and losing energy. And because the total entropy increases, the vortices can settle into an orderly pattern—a crystal.

Bizarre as the outcome may seem, it's not the first time physicists have recognized that entropy can create paradoxical patches of order (*Science*, 20 March, p. 1849). And the theory accurately predicts the details of the vortex crystals Driscoll's group observed. "The amazing thing to me, as an experimentalist, is that the theory actually works," says Driscoll.

It may also work in systems far from the frictionless gas of electrons. For example, the energy of vortices in a large and nearly 2D system like the film of atmosphere on Jupiter might overwhelm viscosity, allowing such strange effects to emerge. They could only do so, however, if crystalline patterns can take shape from vortices that can spin in both directions, unlike those in the electron gas, which are forced to spin in the same direction by the interaction of the electrons and the magnetic field lines.

So far Dubin and Jin's theory doesn't say whether that is possible. But both the theorists and the experimentalists are hoping to find out. Adding the electrons' positively charged, antimatter counterparts—positrons—to the laboratory systems would produce both left- and right-handed vortices. To paraphrase a famous koan, that should reveal whether the crystals amount to more than the sound of one hand clapping.

–James Glanz