Seeing Chaos in a Simple System

The complicated motion of two barium ions held in an electromagnetic trap has been shown to be an example of chaotic behavior, thus providing a simple system to test theories of chaos

CHAOTIC BEHAVIOR has been found in a number of physical systems in recent years, ranging from predator-prey populations to turbulent fluid flow. Indeed, now that scientists are aware of chaos, it seems nearly ubiquitous. Most of the chaotic physical systems that researchers have examined, however, have been macroscopic, such as the driven pendulum, electronic oscillators, turbulent fluid flow, and the celestial three-body problem.

Now researchers at IBM's Almaden and T. J. Watson research centers report they have found a microscopic system—two atomic particles—that is easily observed in the laboratory and whose chaotic behavior is readily calculated. This system, which consists of two ions held in an electromagnetic trap, may provide a valuable proving ground for theories of chaos.

The newly developed science of chaos has been called revolutionary because it challenges many classical beliefs about how physical and mathematical systems behave. In the past, scientists and mathematicians had generally assumed there was a basic difference between simple and complex behavior. If, for example, the Earth's weather shows complex patterns, that must imply the atmospheric system is very complicated. Chaos theory, however, has shown there is a fine line between simple and complex. Simple systems can evolve very complicated behavior—behavior so complicated that it appears random—while complicated systems can exhibit simple patterns.

A standard example from fluid mechanics is the development of turbulence in fluid flow. As water flows around a rock, for instance, it will circle the obstacle quite smoothly if the water is slow. On the other hand, if the water is moving rapidly, eddies and turbulence will develop on the back side of the rock. The water flow seemingly becomes random since if one watched, say, a leaf float past the rock into the turbulence, it would be impossible to predict the exact path the leaf would take. Yet the water flow is not actually random—it still obeys the same fluid equations it did when the water was moving smoothly. This seemingly random behavior in a deterministic system—in a system whose components obey explicit equations of motion—is called chaos.

Fluid flow, like most physical systems that develop chaotic behavior, is less than ideal for experimentation. Since a fluid contains a nearly uncountable number of particles, it is impossible to model completely. Instead, one would prefer to test the theories of chaos in a very simple physical system.

This is what the IBM team has provided, with work reported in the 18 July issue of *Physical Review Letters* (*1*). As a bonus, the paper explains a phenomenon that was first observed 30 years ago—predating the field of chaos—but for which no one had ever provided a physical explanation.

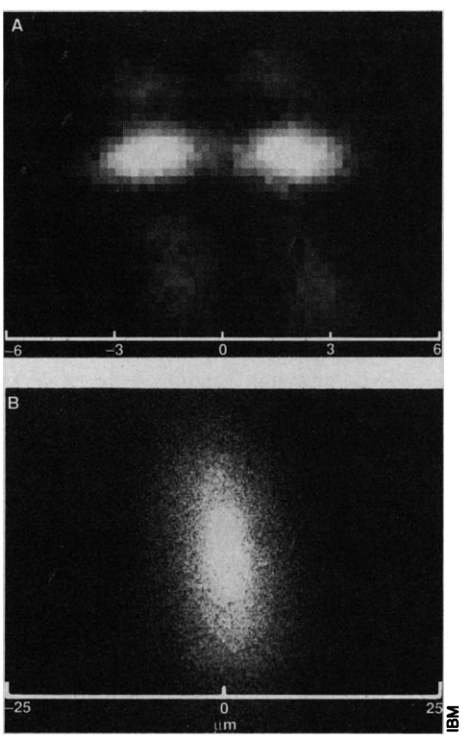
The IBM work examines the behavior of two barium ions (Ba^+) held in a tiny trap that uses an electric quadrupole potential to confine the ions. If the two ions are cooled by the radiation pressure of a laser beam so that their motions become very slow, they settle into stable positions relative to each other—they "crystallize." Then, if the electric potential of the trap is increased past a certain point, the ions suddenly begin to move all around the trap, losing this stability and showing seemingly random movement. Decreasing the potential will bring the ions back to their stable state.

These phase transitions were first reported in 1959, in trapped charged aluminum particles. Recently, other researchers (*2, 3*) have reported seeing collections of from 2 to 50 trapped ions move back and forth between such "crystallized" and "gaseous" states, but until the IBM paper no one had explained exactly what these transitions were.

"We have an explanation for what is going on," said Richard Brewer of the IBM team. "It is an order-chaos transition." Simple deterministic equations of motion describe both the ordered and the chaotic states, as well as the transition from one to the other, he said. Nevertheless, when the ions are in the chaotic state, knowing their positions at one moment does not allow predicting their future positions because the solutions are extraordinarily sensitive to initial conditions. It is this property that gives the motion its random character.

The IBM paper offers calculational proof of the claim that chaos is the cause of the ions' behavior. Working from the equations of motion for the system of two trapped ions, the scientists obtained computer solutions for the movements of the particles as the electric potential of the trap was increased. For smaller values of the potential, the calculations showed that the two particles should oscillate gently near their equilibrium points—they stay approximately in the same positions. As the potential increases, it pushes the ions closer together, increasing the nonlinear Coulomb interaction between them. Finally, when the potential reaches a critical value, the computer solution showed that the motion becomes chaotic with erratic movements.

Observations of the experimental system bore out the theoretical predictions. The team used an imaging photomultiplier to detect laser light scattered off the two ions, and displayed the resulting information about their positions on a computer screen. At first, the computer screen would show the stable positions of the ions as two smeared-out points of light. (The positions were smeared out because the ions oscillate slightly around the equilibrium positions and do not stay exactly in one spot.) Then, as the trap potential reached the critical value, the screen showed a big blob of light, indicating that the ions were moving all over



Order into chaos. *Computer images of two trapped barium ions in their "crystalline" (A) and "gaseous" (B) states.*

the place. "You see chaos appear right before your eyes," Brewer said.

The IBM team's predicted value of the trap potential at which the system would move from order to chaos matched almost exactly with the experimental value. The group has still not calculated the value at which the system lapses back from chaos to order, which is a slightly different number and is much harder to compute.

Much remains to be done, Brewer said. The group has made a number of predictions and "it would be nice to experimentally confirm some of them." Calculations show, for instance, that at certain trap potentials there are "windows" of order inside the chaos. In such cases, the ions have a relatively simple, stable motion the group would like to observe.

Past that, various theories exist about exactly how a system moves from order to chaos, and the IBM group plans to determine which one, if any, describes the system of trapped ions. "It appears that the two-ion system offers significant advantages in the future in elucidating the nature of chaos," Brewer said. ■ **ROBERT POOL**

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Study Raises Estimate of Vietnam War Stress

In sharp contrast to a massive study released just a few months ago, a new study, funded by the Veterans Administration (VA), has found that 470,000 Vietnam veterans still suffer from a major psychological disorder directly related to the war. The earlier study, conducted by the Centers for Disease Control (CDC), found only 66,000 to be affected with post-traumatic stress disorder, or PTSD.

The discrepancy between the two studies seems certain to fuel the debate on the psychological aftermath of the Vietnam war, a debate that has focused largely on PTSD. Congress is keenly interested in the prevalence of this disorder, as it bears directly on the adequacy of the VA's treatment and benefits programs.

From the outset, PTSD has been mired in controversy, both over what it is and how many veterans are affected. Although the disorder was officially recognized by the American Psychiatric Association only in 1980, it has surfaced after every war, when it has been known as shell shock or battle fatigue.

As now defined by the American Psychiatric Association, PTSD is a problem of varying intensity, from mild to life-threatening, that results from exposure to a traumatic event—"an event outside the range of usual human experience." It can take many forms, but the main symptoms include reexperiencing the event (in nightmares, flashbacks, or "intrusive recollections"); avoidance or withdrawal from the outside world; and increased arousal, such as hypervigilance or exaggerated startle reaction.

In 1984 Congress told the VA to find out exactly how many Vietnam veterans are affected, and thus what the need for services is. But CDC completed its study first, which was a broader look at physical and psychological health of Vietnam veterans. CDC found that only 2% of Vietnam veterans currently suffer from PTSD, although veterans were twice as likely to have serious problems like depression and anxiety (*Science*, 8 July, p. 159).

In part because of the publicity surrounding the CDC study, Senator Alan Cranston (D–CA), chairman of the Veterans Affairs Committee, called hearings on PTSD on 14 July. At those hearings, the VA presented its preliminary findings from its long-awaited National Vietnam Veterans Readjustment Study. The final study should be completed in November.

According to the new study, conducted for the VA by the Research Triangle Institute of North Carolina, 15% of veterans who served in Vietnam, Laos, or Cambodia still suffer from PTSD. That translates into 470,000 of the 3.14 million men who served in the war. For the 7,166 women who served, mostly as nurses, the prevalence is 9%. For minorities, the figures are far higher: the prevalence is 19% among blacks, and a whopping 27% among Hispanics.

The study, which was based on face-to-face interviews with 1600 Vietnam veterans, also found that PTSD cases are concentrated among those veterans who experienced heavy combat or were otherwise exposed to high "war zone stress," such as loss of buddies or witnessing or participating in atrocities. They were three to five times more likely to have PTSD than their counterparts exposed to less combat or stress.

Although these figures are preliminary, "we are very confident in the results," says Richard Kulka of the Research Triangle Institute. And, he adds, "we are very confident that 2% is not correct."

To the Research Triangle Institute team, the dramatic differences between the two studies can be traced to the instruments used to measure the prevalence of PTSD. CDC used a structured interview known as the Diagnostic Interview Schedule. The problem, says Kulka, is that while that interview works well for most psychological disorders, it had never been tested to see how well it picks up PTSD. As part of the VA-funded study, the Research Triangle Institute researchers tested that instrument, as well as three others, to see if they could distinguish persons diagnosed with PTSD from those who do not have it. Says Kulka: "The DIS did not do very well"; in fact, it significantly underestimated the number of cases. The VA-funded study used instead a modified version of the Diagnostic Interview Schedule and the Mississippi Scale for Combat-related PTSD.

CDC, on the other hand, maintains that the VA study used a looser definition of PTSD and thus identified less severe cases. To Frank Destefano of CDC, the key message is that "both studies show a substantial number of Vietnam veterans still suffer from PTSD 15 to 20 years after the war. The exact percentage is probably between 2% and 15%."

How the differences between the two studies will be sorted out is not clear. For now, they provide an upper and lower bound, and the underlying message for Congress, both research teams agree, is that many veterans still need treatment.

Cranston has introduced legislation, expected to pass the Senate soon, that requires the VA to give priority care to any veteran diagnosed as having combat-related PTSD, whether or not the benefits branch has made a formal determination that compensation is due—a determination that can take years. On 13 July the Senate also added on to the VA appropriation an extra $5 million for PTSD treatment. ■ **LESLIE ROBERTS**