than in free space—their effective mass could be ten or more times higher, he said—and such heavy-seeming electrons might pull two deuterium nuclei much closer than they could otherwise come. Bringing the deuterium atoms nearer could allow them to fuse at a rate consistent with what Jones has measured, he said.

The harder question is why Pons and Fleischmann can get so much heat. Normally, when two deuterium atoms fuse to form a helium-4 atom, the energy of the helium-4 causes it to split apart immediately. It breaks into either a helium-3 atom and a neutron, or a proton and an atom of tritium—the isotope of hydrogen with one proton and two neutrons. Judging from the amount of neutrons and tritium detected in the University of Utah experiments, the fusion cells should be producing only one-billionth of the heat that they are, so something other than normal deuterium-deuterium fusion must be taking place.

Chevis Walling, a chemist at the University of Utah, hypothesized that almost none of the helium-4 inside the palladium electrode is splitting into fragments. Instead, he suggests, the helium-4 is somehow transferring its energy to the lattice of palladium atoms, which heats up the electrode but produces very few neutrons or tritium atoms. The acid test, of course, will be to measure how much helium-4 is inside the palladium electrode after the "fusion" takes place. "There's no evidence for it at this point," Walling said, but the Utah group is gearing up to look for helium-4 now.

Walling's mechanism would be a nearly perfect way to do fusion. Each fusion reaction between two deuterium atoms would create seven times as much energy as the reactions in which the helium-4 split apart, so that less fusion would create more energy. Further, there would be no waste. One of the major problems with fusion is that although it does not produce as much radioactive waste as fission, it does produce plenty of neutrons. Finding a way to produce fusion power without neutrons would be a dream come true.

For now, however, whether that dream comes true seems almost beside the point for the scientists involved. As Walling puts it, "We're having fun with this."

Utah is also having fun—it plans to spend $5 million on a fusion center to capitalize on the discovery. Bud Scruggs, chief of staff to Governor Norm Bangerter, said the plans would not be dampened even if the fusion manuscript, which has been submitted to *Nature*, failed the peer review process. "We are not going to let some English magazine decide how state money is handled," he said.

■ Robert Pool

NASA

Does Chaos Permeate the Solar System?

As faster computers allow celestial mechanicians longer looks at the behavior of the planets, chaos is turning up everywhere

Chaos first seeped into the solar system when Jack Wisdom, then a graduate student at the California Institute of Technology, began looking at how meteorites are being slung from the asteroid belt toward Earth. No one at the time could understand what would drive enough meteorites from their orbits. Using a new shortcut that eased the burden of calculating the gravitational interaction between bits of asteroid and Jupiter, Wisdom found that a periodic gravitational nudge from Jupiter could sometimes, without warning, send asteroidal rock careening off toward Earth.

It seemed that a soon-to-be meteorite was so sensitive to its initial conditions—its orbital motions in relation to Jupiter's—that its future behavior could not be predicted no matter how precisely those initial conditions were known. Its behavior became chaotic.

Wisdom, now at the Massachusetts Institute of Technology, went on to point out other chaotic behaviors in the solar system, such as the chaotic tumbling of the small Saturnian satellite Hyperion, but he also joined the 200-year-long effort to test the long-term stability of the planets themselves. The advent in recent years of faster computers is pushing analyses of solar system stability to longer and longer time spans until chaos is now appearing in the behavior of the planets, not just in the odd bits of the solar system.

Recently, J. Laskar of the Bureau des Longitudes in Paris reported that his numerical simulation of the orbital motions of the solar system reveals chaos throughout, especially among the inner planets, including Earth. This does not necessarily mean that Earth could at any second fly off into the Sun or interstellar space. The survival of a fairly regular system of planetary orbits for 4.5 billion years would argue against that. But if confirmed, Laskar's results would mean that, no matter how exactly present planetary motions are known, motions over geologic time cannot be predicted accurately. Such sensitivity to initial conditions may have played a role in shaping the solar system of today.

Laskar's is one of several approaches to detecting chaos that depend on the new power of computers. Wisdom teamed up with computer-builder Gerald Sussman of MIT in taking the long, hard route of calculating each and every motion of the four massive outer planets and Pluto with only the most minor of approximations, such as ignoring general relativity. Calculating new arrangements of the outer solar system every 32.7 days over 845 million years took them 5 months on a uniquely designed computer called the Digital Orrery that is dedicated to the calculation of solar system motions. They showed that the orbital behavior of Pluto, the most minor of the major planets, is chaotic and unpredictable beyond 20 million years into the future (*Science*, 20 May 1988, p. 986).

Laskar had nothing like the Orrery, and

its present power would not have sufficed for what he had in mind. Choosing to calculate the motions of the inner planets that whiz around their orbits in as little as 86 days, he took the faster but more approximate approach of neglecting motions on a time scale of less than 10 years or so. In effect, he smeared the mass of each planet around its orbital path and treated only the long-term behavior of this orbital "wire." Using this averaging approximation, he could take a 500-year rather than a 32-day time step in his 200-million-year calculation on a conventional supercomputer. The Orrery would have taken a couple of years to make the same calculation in its own way.

Laskar found several indications of chaos. Over long time scales the inner planets displayed many periodic gravitational interactions called resonances. The more resonances, the more likely chaotic behavior. The pattern of orbital variations of the inner planets shifted from time to time as those of the outer planets remained steady. And two nearly identical test orbits diverged exponentially with time, demonstrating that precise predictions of solar system behavior are impossible beyond 10 million years into the future. "It's a nice result," says Wisdom, "and the solar system probably is chaotic, but it needs to be confirmed with a different method. Everyone knows averaging works, but no one can prove it."

There are other new signs of chaos in the solar system. Martin Duncan of Queen's University at Kingston, Ontario, and Thomas Quinn and Scott Tremaine of the University of Toronto have used a different shortcut—distinguishing between crucial near-planet and less influential distant interactions—to search for orbits between the planets that might still harbor as yet undetected debris from the formation of the solar system. They found that many orbits lying between Uranus and Neptune become chaotic, supporting Sussman and Wisdom's suggestion that Pluto may have entered its present odd orbit through chaotic shifts.

The principal investigators of project LONGSTOP (Long-term Gravitational Stability Test for the Outer Planets)—Anna Nobili and Andrea Milani of the University of Pisa and Mario Carpino of the Astronomical Observatory of Milan—have run a 100-million-year calculation of the motion of the outer planets on a standard computer. The run is a short one, but by careful analysis they believe they see evidence of chaos even in the massive outer planets. These planets do not seem to have a limited number of orbital variations having discrete periods, as simple interactions of resonances would induce. Instead, there is a continuous variation of periods characteristic of chaos.

"In every case of a long-term integration," notes Tremaine, "researchers have found pretty strong evidence of some sort of chaotic behavior." That suggests to him that chaos is pervasive. Speculating a little further, Tremaine notes that the general character of our solar system, in which there are nine systematically spaced major planets with little debris between them, might have been determined by chaotic processes. Perhaps only those bodies whose chaotic behavior has tight limits survive without being thrown into collision courses with other bodies. Once the recent results are confirmed, the next step will be to investigate the exact limits of present-day chaos and what confines it to those limits. Approximation methods run on conventional supercomputers will help, but the race will probably be won by the next generation of computer dedicated to simulating the solar system. ■ RICHARD A. KERR

ADDITIONAL READING

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PARC Brings Adam Smith to Computing

Part computer virus and part market theory, Spawn is both an efficiency tool and a laboratory for experimental economics

SOMEHOW, IT COMES AS NO SURPRISE to realize that Spawn is a housebroken computer virus. This is the Xerox Palo Alto Research Center (PARC), after all, the rambling hillside laboratory that has already brought forth such inspired flights of lunacy as the personal computer and the "Macintosh" graphics interface. "Spawn is a *useful* computer virus," laughs Bernardo Huberman, the Argentine-born physicist who leads the group* that is developing the system. Indeed, Spawn is able to fan out through a computer network and infect the machines in just such a way that they all do productive work together—without the help of a central planner.

Huberman, not a man to contain his enthusiasm, is deep into an explanation of Spawn as soon as a visitor reaches his seat.

"What we want to study is how to design programs that collaborate and cooperate on a given problem," he says. Look around the laboratory: big-screen, high-powered graphics workstations everywhere, all connected by a high-speed data network. It is a scene that is increasingly common both in the business world and in academia. And yet at any given time, says Huberman, you will always find a few people running problems that strain their computers to the limit, while everyone else is just typing away on low-intensity applications such as word processing, or even letting their machines sit idle. What's needed is a way for the high-intensity users to capture some of that wasted capacity.

And that, he says, is precisely what he and his colleagues have designed Spawn to do. Basically, it balances the load by setting up a kind of automated, on-line marketplace within the network. And in the process, not incidentally, it provides them with a new kind of laboratory for empirical research into economics and ecology.

For specificity, says Huberman, he and his colleagues have tested the system on just two problems: the formatting of large, complex documents, and Monte Carlo calculations, the latter being a statistical approximation technique widely used by physicists. But they could just have well worked on the factorization of large numbers, or cryptography, or indeed, any other problem that can easily be broken into pieces. Whatever the problem, he says, the key issue is to figure out how the computers are supposed to organize themselves to accomplish the task.

The most obvious solution would be to institute some kind of central planning mechanism, using one master computer to give detailed instructions to all the subsidiary computers. But, when collaborative computers systems are actually designed this way, they quickly bog down. The machines spend so much time in communication and coordination with the central computer that they have very little time left to do the work. The trick, says Huberman, is to get the

*Carl A. Waldspurger, Tad Hogg, Jeffrey O. Kephart, and Scott Stornetta.