this point. "Simple models work well when the data are limited," says Smith, a specialist on sedentism in North America. "As the information base gets larger you get a detailed, information-rich, historical sequence through time. This is showing that the general causal models often don't fit particular sequences in the archeological record."

The search for single causal factors has seemed very reasonable, not least because sedentism and agriculture emerged, on a prehistoric scale at least, virtually simultaneously throughout the world: about 10,000 years ago in the Old World, and a few thousand years later in the New World. "When systems converge in a parallel manner we should expect to be able to come up with a general explanation," says Mark Nathan Cohen of the State University College, Plattsburgh, New York. Cohen has been the principal proponent of the population pressure hypothesis in recent years.

Unfortunately, the prehistoric record is often too incomplete to allow a separation of the cause/effect relationship between population numbers and intensification of food production. However, Cohen has been collating physical anthropological data that appear to show increasingly poor nutritional status coincident with the beginnings of agriculture, indicating, he says, food stress as an engine of the change.

Many other researchers fail to find any support for Cohen's case. For instance Kent Flannery of the University of Michigan states: "I don't see any evidence anywhere in the New World that suggests population pressure was responsible for the beginnings of agriculture. Population was not high enough to force anyone to do anything."

Climatic change has formed the focus of a rival single-cause hypothesis, and is clearly attractive in that the advent of sedentism tracks closely the end of the Pleistocene glaciation and the onset of the Holocene interglacial. Moore sees climatic change in the Levant being crucial in setting propitious environmental conditions for the establishment of Abu Hureyra. "It may be an unpopular idea, but it's true," he says. "I'd stake my reputation on that."

Although it is true that climate change was dramatic at the end of the Pleistocene, 10,000 years ago, it must also be true that conditions favorable to sedentism must have existed somewhere in the Old World in the last 75,000 years of the Pleistocene. And if anatomically modern humans have been around for at least this length of time, as recent anatomical and genetic data indicate, why did sedentism not develop earlier? Is it possible that low population levels through this period is the only answer? ■

ROGER LEWIN

Pluto's Orbital Motion Looks Chaotic

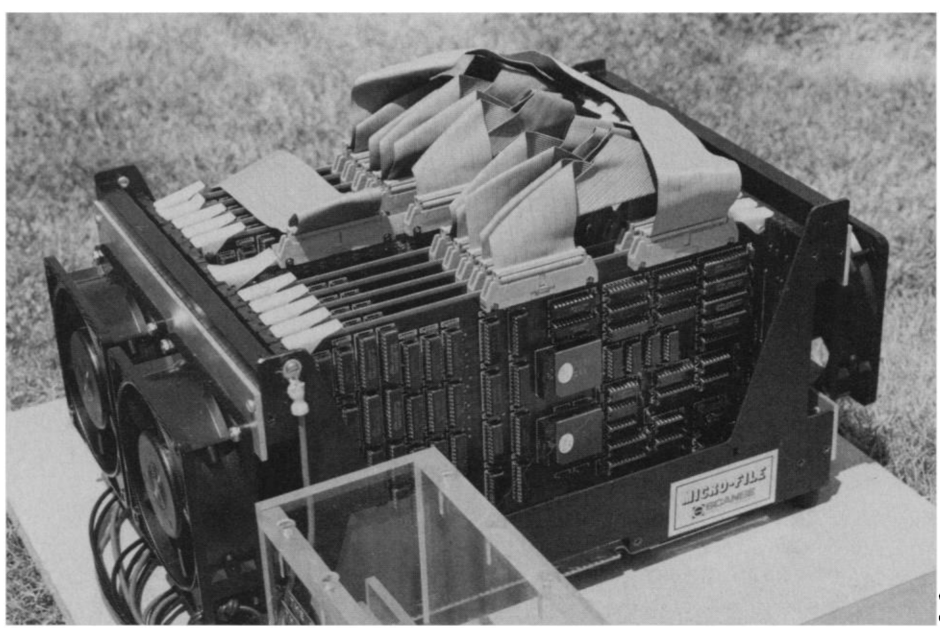
The oddest planet seems to have a new distinction: its motion around the sun is irregular to the point of unpredictability

PLUTO seems to have locked up its status as the oddball planet of the solar system. A near billion-year computer simulation of the motions of the planets provides strong evidence that over millions of years Pluto's motion about the sun cannot be predicted. Even the clocklike workings of the planets would thus seem to have their little glitches. The discovery adds another peculiarity to a planet that is probably a leftover from the early days of the solar system, a lucky, lone survivor of the swarm of small bodies that were either thrown from the solar system or pulled into one of the planets.

Chaos in the solar system has been becoming more obvious of late, at least among its minor bodies. None of the Newtonian laws of physics is being violated, it is just that the future motions of some bodies are so sensitive to their present conditions that their behavior cannot be predicted. An infinitesimal difference in their positions or motions now can lead to wildly different behavior in the future. Largely through the work of Jack Wisdom of Massachusetts Institute of Technology, it has become apparent that Jupiter's gravitational influence can send rock in the asteroid belt into chaotic, highly elliptical orbits that deliver meteorites to Earth. Saturn's tiny satellite Hyperion tumbles chaotically instead of locking one face toward Saturn. And the slight inclination of the orbit of Miranda, the innermost major satellite of Uranus, may also reflect chaotic behavior.

Of all the planets, Pluto has seemed the most likely to behave chaotically. In addition to its having a cockeyed orbit, which is tilted 16° to Earth's orbital plane and so elongated that Pluto is now temporarily inside the orbit of its neighbor Neptune, it is enmeshed in more periodic gravitational interactions with its neighbor, called resonances, than any other planet. The more resonances, the more likely chaotic behavior.

The best way to see if the solar system is stable and predictable is to have a computer simulate the motion of the four massive outer planets and Pluto long enough to see



G. Sussman, MIT

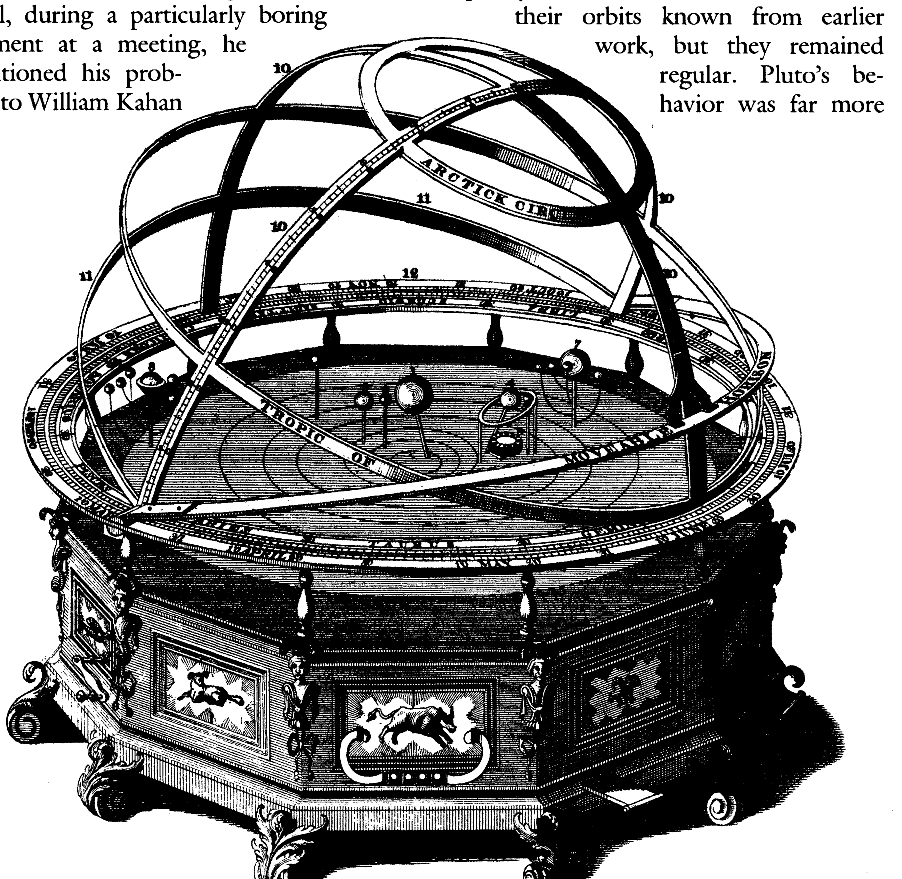
The new and the old orreries. *The mechanical calculation of the positions of the planets began in the 17th century with the original form of the orrery (right), named after the Earl of Orrery for whom it was first made. The Digital Orrery (above), a one of a kind parallel computer, is less stylish but much faster. Designed solely for simulating the motions of the solar system, it runs at one-third the speed of a Cray 1 supercomputer.*

any irregularities. That means lots of computer time. Gerald Sussman of MIT and Wisdom used a computer called the Digital Orrery that was custom-made to simulate solar system motions by Sussman and colleagues at California Institute of Technology. An unimposing collection of electronics that would fit inside a Cuisinart, the Orrery consists of ten independent computers on small boards operating in parallel using circuitry designed specifically for the calculation of the gravitational interaction of a few bodies. The Orrery is unsuited to do any other job, but it can model the solar system 60 times faster than a VAX 11/780, a familiar mid-level computer on many campuses, and at one-third the speed of a Cray 1 supercomputer. And unlike any supercomputer available to academics, the Orrery could be dedicated to Sussman and Wisdom's 845-million-year integration for a solid 5 months of running time.

Besides the unique hardware, this record long integration depended on a brilliantly simple trick for minimizing the errors that seemed to inevitably accumulate in all such simulations. Sussman had noticed that the rate of accumulation of error in the total energy of the simulated system depended on the size of the step between one calculated arrangement of the solar system and the next, the size of the step having traditionally been 40 days. That insight led nowhere until, during a particularly boring moment at a meeting, he mentioned his problem to William Kahan of the University of California at Berkeley. Kahan suggested what, in hindsight, seems so obvious: because under larger step sizes the errors lead to energy growth and under smaller step sizes the energy decreases, they should look for a step size in the middle where the energy does not change.

By trial and error, Sussman and Wisdom found that a step size of 32.7 days reduced the rate of error accumulation by three orders of magnitude. With such a small error, one can extrapolate from shorter integrations to show that Pluto's orbital motion could be integrated forward for the run's entire 3.4 million revolutions about the sun, then run backward, and Pluto would be only 10 minutes of arc, about one-third the apparent width of the moon, from its starting position. Says Carl Murray of Queen Mary College in London, "The amazing thing is that they can integrate forward and backward with this magic step size and get back to where they were. It's staggering. It will revolutionize the whole concept of numerical simulation" of few-body systems such as the solar system.

When the 845-million-year integration was completed, plots of the behavior of planetary orbital parameters still did not look chaotic to the eye. The four outer planets—Jupiter, Saturn, Uranus, and Neptune—displayed the subtle variations in the ellipticity, inclination, and orientation of their orbits known from earlier work, but they remained regular. Pluto's behavior was far more complicated, exhibiting five resonance-induced variations with periods up to 150 million years and a suggestion of another with a 600-million-year period, but they all appeared to be regular.


The Bettmann Archive

The chaos showed up in two more sensitive indicators. When more than one "Pluto" was placed in the simulation at slightly different starting points, they diverged at an exponential rather than a linear rate. That is characteristic of chaotic behavior. And unlike the other outer planets, Pluto does not seem to have a limited number of orbital variations having discrete periods. Its periods appear to be continuous over a broad range, which is seen as another sign of chaos.

The subtlety of Pluto's chaos suggests to Wisdom that the planet now occupies a relatively small chaotic zone. He and Sussman have yet to map out the size of the complete zone, so predicting even the range of possible behavior is still impossible. If this small chaotic zone were connected to a larger one, Pluto could without warning head off into a new orbit, the way some objects in the asteroid belt can.

As to Pluto's past, astronomers still cannot say. The intersection of Pluto's orbit with Neptune's has prompted suggestions that Pluto, which is hardly half the size of our moon, had escaped from an orbit about Neptune. That is now thought unlikely. Pluto has a moon, Charon, more than half its size, an arrangement that is unlikely to survive expulsion from an orbit about another planet. "I think it more likely," says Wisdom, "that Pluto formed in place or at a low inclination and eccentricity and made its way to this place through the chaotic zone."

Almost certainly, Wisdom says, Pluto is a survivor from the early days of the solar system. Then the solar system was awash with small bodies. The planets that had already formed slung these planetesimals from the solar system, drove them into a distant cloud of what are now called comets, or pulled them into collisions with themselves, growing larger at their expense. Pluto alone it seems survived, thanks perhaps to the resonance with Neptune that keeps it well out of the plane of Neptune's orbit when they are closest. Becoming a planet takes some luck, it seems. In Pluto's case, remaining one against the forces of chaos may take some luck as well. ■

Richard A. Kerr

ADDITIONAL READING

J. Wisdom, "Urey Prize Lecture: Chaotic dynamics in the solar system," *Icarus* 72, 241 (1987).

P. Hut and G. J. Sussman, "Advanced computing for science," *Sci. Am.* 257, 145 (October 1987).