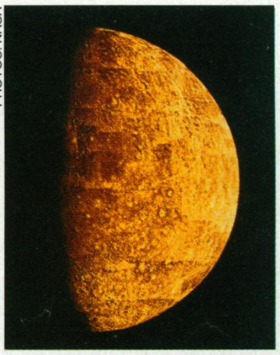
PLANETARY SCIENCE

From Mercury to Pluto, Chaos Pervades the Solar System

Newton didn't exactly have it wrong with his picture of a clockwork solar system. The National Space and Aeronautics Administration (NASA) can still launch a probe toward Jupiter and expect the planet to be there as predicted when the spacecraft arrives a few years later. But confidence that planetary positions could be predicted into the distant future has recently suffered drastic erosion. And now comes the clincher: In this issue of *Science* (p. 56), Massachusetts Institute of Technology (MIT) researchers Gerald Sussman, who builds computers, and Jack Wisdom, who calculates the motions of solar system bodies with those computers, report that 100-million-year simulations of the orbits of the planets show that all nine are chaotic. The slightest change in a planet's initial conditions of position or velocity makes its motions millions of years hence entirely unpredictable.

PHOTOS: NASA



A chaotic quartet. The orbital motions of the four inner planets—Mercury, Venus, Earth, and Mars—are chaotic, perhaps due to a gravitational interaction between Earth and Mars.

The result culminates a quest for planetary chaos that first hit pay dirt in 1988 when Sussman and Wisdom found that Pluto's orbit is chaotic. That discovery was broadened by Jacques Laskar of the Bureau des Longitudes in Paris, who calculated that the rest of the solar system is chaotic too (*Science*, 14 April 1989, p. 144). But because Laskar used a computational shortcut that had not been proven entirely trustworthy, there was room for doubt. No longer. Sussman and Wisdom have dispelled any uncertainty by calculating the motions of all nine planets without shortcuts. And that leaves researchers free to move on to the next questions: What makes the solar system chaotic? And given all the evidence for chaos, why haven't the planets plunged out of their stable orbits?

Just proving the existence of this pervasive chaos is "a spectacular achievement," says Scott Tremaine of the University of Toronto. The only way to do so was by calculating all the complex gravitational interactions of the solar system over millions of orbits. By varying the initial position of a planet by just millimeters and then looking for wildly different outcomes from integration to integration, the researchers could hunt for chaos.

That might sound simple, but it takes a staggering amount of computer power. General purpose computers are too slow to calculate planetary motions over long periods, so Sussman and Wisdom relied on a specially designed machine: the Supercomputer Toolkit, built by MIT and Hewlett Packard Company specifically for calculating planetary motions. Just one of its eight parallel processors can perform that task as fast as a Cray 1 supercomputer—and a mathematical technique developed by Wisdom makes the calculations 10 times faster still. Even so, a solid month of computer time was consumed by each 100-million-year run, which is only a fraction of the 5-billion-year lifetime of the solar system but long enough for chaos to emerge.

Finding chaos doesn't tell you what throws off the celestial clockworks, but Laskar believes that he has identified the major source of at least the inner solar system's chaos: a complex gravitational interaction between Earth and Mars. Such resonances pump up planetary chaos much the way you pump a swing, timing inputs of energy so that they reinforce one another. The same Earth-Mars resonance highlighted by Laskar also emerged in a 6-million-year integration of planetary motions run by Thomas Quinn of Oxford University, Tremaine, and Martin Duncan of Queen's University in Kingston, Ontario. But Wisdom and Sussman aren't sure the dance of Earth and Mars is to blame. "Even though we get the same numbers as Laskar, we are saying there are ways that his explanation could be wrong," says Wisdom.

Beyond identifying what spurs chaos, celestial mechanicians face the more subtle question of what holds it in check. Among the smaller bodies in the solar system, where chaos has also been identified, it wreaks havoc, flinging asteroids out of the asteroid belt and sending Saturn's moon Hyperion into a wild tumble (*Science*, 24 November 1989, p. 998). And yet the planets' chaos seems to be constrained, not catastrophic. In both computer calculations and the real world, planets may wander a bit, but they do not fly out of their orbits.

A clue may lie in a simpler example recently dissected by Andrea Milani and Anna Nobili of the University of Pisa, Italy. They showed that although the orbit of the asteroid Helga is chaotic because of a resonance with Jupiter, becoming unpredictable after only about 7000 years, the orbit remains stable for the full 7 million years of their calculation. Milani and Nobili think that Jupiter, the source of the chaos, is also the source of the constraint. Two other resonances between Jupiter and Helga seem to ensure that the chaos never brings them so close that Jupiter can fling Helga out of its orbit. "We believe this is not exceptional," says Milani, "this is just the best example." Indeed, Gerald Quinlan of the University of Toronto, studying simplified "mock solar systems" made up of the four Jovian planets arranged in varying orbits, has found that constrained chaos shows up far more often than the catastrophic variety.

Further insights into the solar system's odd mix of chaos and stability might come from what Tremaine calls "the Holy Grail": an integration of planetary motions for the solar system's entire 5-billion-year lifetime. Then again, he says, after Sussman and Wisdom's giant step, "there's a good chance there's nothing qualitatively new" to be found.

–Richard A. Kerr

Additional Reading

J. Laskar, T. Quinn, S. Tremaine, "Confirmation of Resonant Structure in the Solar System," *Icarus* **95**, 148 (1992).

A. Milani and A. M. Nobili, "An Example of Stable Chaos in the Solar System," *Nature* **357**, 569 (1992).