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INSIDE
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PLANETS IN CHAOS

Breakdown in Newton's clockwork universe

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Chaotic heavens

Can mysterious wobbles in Jupiter and Saturn's orbits spell doom for life on Earth? **Marcus Chown** winds back the solar system 65 million years to find out

IT WAS Isaac Newton who finally showed why the heavenly bodies move in predictable ways. He proved that the planets move in response to the sun's gravitational pull, endlessly repeating their orbits like celestial clockwork. If you know the position and velocity of a planet today, you can work out its motion far into the future.

Or so we thought until recently. "Our research shows that for tens of millions of years, the planets orbit the sun with the regularity of clockwork," says geophysicist Michael Ghil. "Then, quite unexpectedly, everything goes crazy." According to Ghil, who works at the École Normale Supérieure in Paris and the University of California at Los Angeles, this planetary madness is all down to chaos. In chaotic systems, tiny changes in conditions can lead to huge differences in outcome. Though you can predict what the changes will do in theory, the system is so sensitive that you'll never get it right.

If the only consequence was a little unpredictability, that would perhaps be a shame, but not too troubling – just a slight departure from Newton's clockwork ideal. But it's much worse than that. According to Ghil's latest work, carried out with Ferenc Varadi and Bruce Runnegar at UCLA, the solar system's chaotic nature can also unleash an asteroid storm, flinging massive rocks out of their usual orbits and showering the solar system's inner planets with debris. It may even have been what killed the dinosaurs.

We have known for a while now that the planets aren't as stable as we like to think. If the Earth and sun were alone in space, Earth would trace out an elliptical or circular orbit. In the case of this "two-body" system, the path can be predicted exactly. But the solar system is more complicated. In addition to the steady gravitational pull of the sun, each planet feels smaller, varying tugs from the other eight planets and all the various moons. Mathematicians have proved that it is impossible to solve Newton's equations exactly even when there are as few as three bodies present, let alone dozens. Instead, scientists have to make approximations about a planet's position and the forces it experiences, and these errors can grow over time and send orbital calculations wildly off beam.

In 1988 Gerry Sussman at MIT, working with Jack Wisdom at the University of California, Santa Barbara, worked out that Pluto's orbit is chaotic. In other words, if you try to predict the shape of Pluto's elliptical orbit around the sun in the long term, your calculation will be extremely sensitive to the parameters you put in at the start. A year later, Wisdom and Jacques Laskar of the Bureau des Longitudes in Paris proved that the Earth's orbit is also chaotic. They showed that an error as small as 15 metres in measuring the position of the Earth today would make it impossible to predict where the planet will be in its orbit in 100 million years' time.

But Ghil and his colleagues have also discovered a more disturbing way that chaos can creep in. They were wondering what influence Jupiter and Saturn might have, and suspected that when the two biggest planets in the solar system line up in front of the sun, in the same way that the Earth, moon and sun align during a total solar eclipse, their gravitational pull could cause dramatic effects. Under the right conditions, they thought, these gas giants might be able to nudge a nearby celestial body into a more elongated orbit.

"For tens of millions of years, the planets orbited the sun with the regularity of clockwork. Then, quite unexpectedly, everything went crazy"

Like solar eclipses, this alignment between Jupiter, Saturn and the sun is rare. In the time it takes Saturn to complete two orbits around the sun, Jupiter has whizzed round almost five times. This means that the planets are only on the same side of the sun as each other every 20 years.

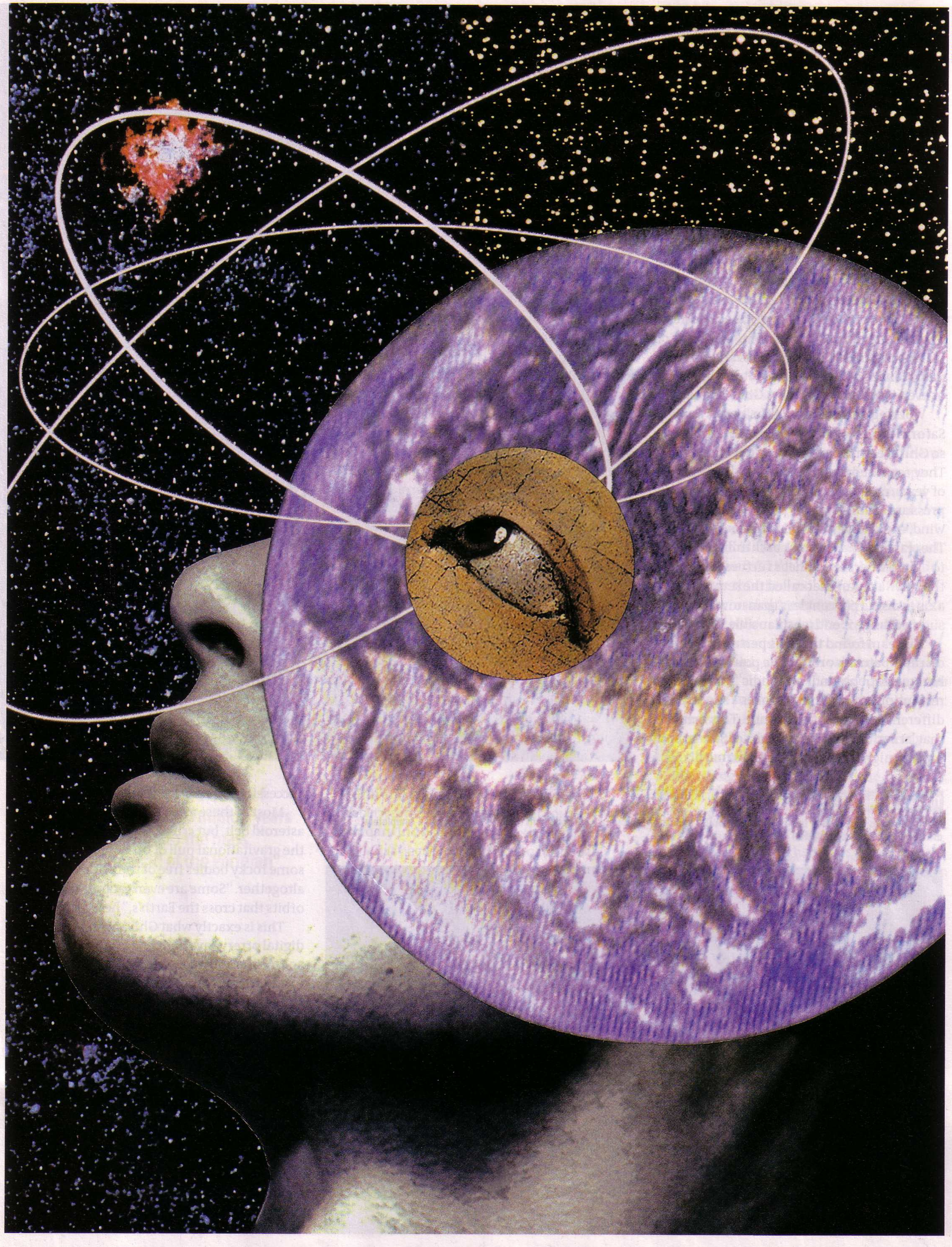
But that's not the end of the story. The orbit Saturn makes around the sun lies in a slightly different plane to Jupiter's orbit. In other words, the planets' pathways are inclined to each other. So every 20 years when Jupiter overtakes Saturn, the planets do not line up exactly: Saturn usually lies above or below Jupiter. This means that the combined gravitational pull of the two gas giants is much weaker than it would be if the planets were in perfect alignment.

If Jupiter made precisely five orbits for every two that Saturn makes, the planets would never line up with each other perfectly. But because the ratio is not exactly 5:2, the point where they pass slowly moves round the sun. As the planets get closer to perfect alignment, the extra tug they exert on other planets, moons and asteroids becomes stronger. The gravitational pull is strongest when Jupiter eventually overtakes Saturn at precisely the point where the orbits cross each other. "The effect on other bodies in the solar system rises to a crescendo every 1000 or so years," says Ghil.

Until now, most planetary scientists have ignored this occasional extra pull from Jupiter and Saturn in their models of the solar system because it happens so infrequently. Over long periods of time, they reasoned, this additional tug would be of little consequence.

"We weren't sure this was right," says Ghil. And so his group set out to study its effects in detail. To do that, they had to follow in the footsteps of 18th-century astronomers and construct an orrery, a machine that displays how the planets move relative to one another. But this would be no mechanical orrery. While early astronomers used cogs and wheels, modern planetary scientists use digital orreries, computer models dedicated to simulating complex planetary motions.

Although they still use approximations ▶



in their computations, Ghil, Varadi and Runnegar have constructed the most accurate digital orrery ever built. It crunches the numbers on finer time intervals than any other, thereby revealing much greater detail. With this, they can start with the positions of the planets and asteroids today and wind back the clock to see how the solar system looked tens of millions of years ago (*Icarus*, vol 139, p 286).

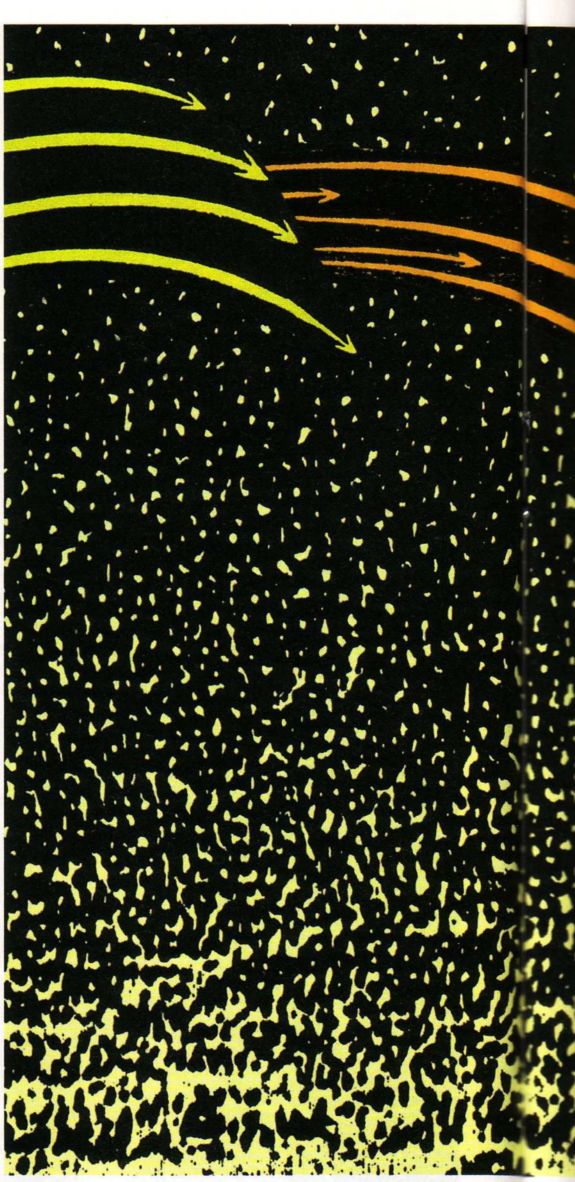
What the team found is remarkable. Jupiter and Saturn's orbits are poised on a knife-edge: most of the time their orbits are pretty much predictable, but the slightest disturbance can send them into chaos – meaning they become beset by unpredictable variations. Because such systems are so complex, it is impossible to pinpoint which aspect of a planet's orbit might go haywire. "The chaos might, for instance, manifest itself in wild variations in the length of Jupiter's orbit, its inclination or even its orientation," says Ghil.

Working out what could tip Jupiter and Saturn into chaotic orbits is a mammoth task, so Ghil's team focused on just one factor. They reasoned that, over hundreds of millions of years, non-gravitational effects such as the pressure of sunlight and particles in the solar wind, could have affected Saturn's orbit. The team wound the clock back millions of years to a time when the planet's furthest point from the sun – a parameter called the semi-major axis – was 0.1 per cent less than now. "We think such a change is entirely plausible," says Ghil.

His team found that this perturbation disrupts Saturn's orbit to the point where it becomes wobbly and "aperiodic" – each revolution around the sun takes a slightly different path from the last one. This means that, at certain times, the orbits of Saturn and Jupiter might be in virtually the same plane producing a much stronger gravitational pull than usual. This has the potential to unleash havoc in the solar system. In particular, it can trigger chaotic instability in the asteroid belt that lies between the orbits of Mars and Jupiter (see "Chaotic skies"). "I can certainly believe that changing Saturn's semi-major axis under certain conditions may lead to an instability in the planetary system," says Alessandro Morbidelli, a mathematician working on chaotic dynamics in the solar system at the Côte d'Azur Observatory in Nice, France.

It's all down to the way the planets can transfer their energy to nearby objects with particular orbits. In the same way as you can make a child's swing go higher if you push it at the right moment, Jupiter and Saturn can push asteroids from a regular orbit into a chaotic one. In the case of the child's swing, you transfer energy most efficiently if you shove the swing at a frequency known as the resonant frequency. Similarly, Jupiter and Saturn have more of an effect on asteroids whose orbital frequency around the sun forms an integer ratio with one of their orbital frequencies. For instance, an asteroid that goes round the sun three times for every two turns by Jupiter is said to be in a 3:2 resonance. And if an asteroid is in a resonant orbit, chaos in Jupiter's orbit can trigger a large and unpredictable change in the asteroid's path.

As yet, says Ghil, it is impossible to tell how long the chaotic effect on the asteroid belt persists, but they have calculated the likely outcome. "We find an incredible wealth of effects," he says. Some asteroids swing from their usual orbits into ones that are closer to the sun, while others fly out to larger, elongated orbits. "A whole population of asteroids can drift back and forth through a succession of resonant orbits," says Ghil.



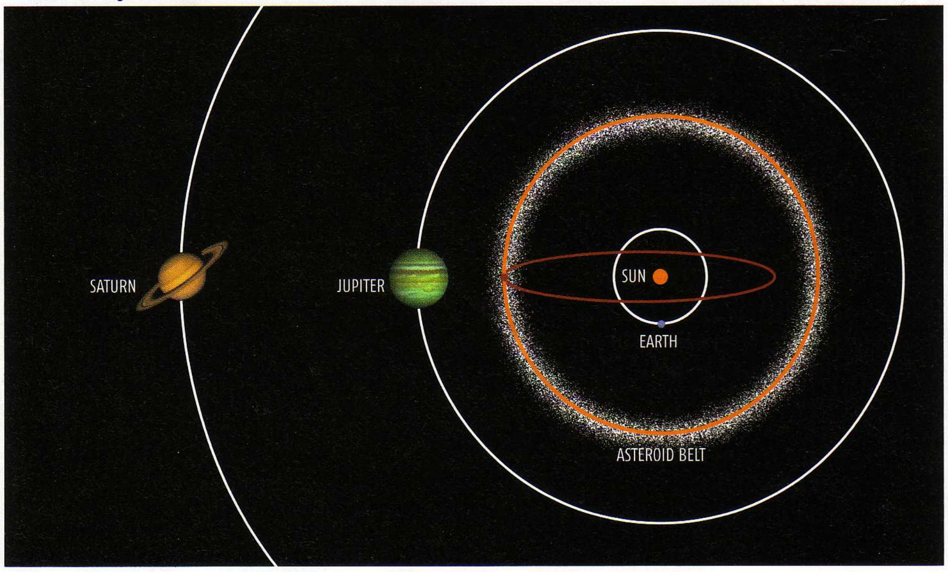
Most of these asteroids stay within the asteroid belt, but crucially, Ghil has found that the gravitational pull of other planets can yank some rocky bodies free of the asteroid belt altogether. "Some are even catapulted into orbits that cross the Earth's," he says.

This is exactly what Ghil and his colleagues' digital orrery says happened 65 million years ago. As if some mischievous god had reached in and stirred things up, the solar system suddenly became a hornets' nest of activity. Chaos in the Jupiter-Saturn system caused a flurry of Earth-crossing asteroids, and among them may have been the one thought to have had the dinosaurs' name written on it. Something certainly crashed off the Yucatan coast in Mexico at the end of the Cretaceous period, just when the dinosaurs died out. "We can't say we've actually caught the culprit that fell into the Yucatan peninsula yet but we're on its trail," says Ghil. "The dinosaurs might have been the victims of an event hard-wired into the dynamics of the solar system."

TURMOIL IN THE HEAVENS

A burst of chaos triggered by the alignment of Jupiter and Saturn can send a rocky body in the asteroid belt into a completely different orbit and on a collision course with Earth

— Asteroid in regular orbit — Asteroid in chaotic orbit



"Ghil's team calculate that a burst of chaos occurred about 250 million years ago. It may be linked to the mass extinction at the end of the Permian"

Ghil and his colleagues first suggested a link between chaos and the Cretaceous-Tertiary boundary in 2001. Since then, their digital orrery has been working hard to refine the calculations, and they are now confident that the last burst of chaos in the skies did indeed occur at that significant point 65 million years ago (*Astrophysical Journal*, vol 592 p 620).

And last year, Ghil's team calculated that another burst of planetary chaos occurred about 250 million years ago, give or take 10 million years. They speculate that it may be linked to the catastrophic impact event that many believe was responsible for wiping out 95 per cent of species at the end of the Permian period, 251 million years ago. Ghil is not worried about the 10 million year uncertainty. He points out that simulating the solar system with his digital orrery becomes difficult beyond 70 million years. As you look further back in time, the accuracy of the calculations deteriorates due to uncertainties in the current position of the planets. The timing of this burst of chaos is at the very limit of the digital orrery's precision, so it may be possible to link it with the Permian-Triassic boundary.

Such suggestions are contentious, of course. Indeed, not all palaeontologists are convinced that the mass extinction at the end of the Permian was due to an asteroid impact. Many believe that a massive and prolonged volcanic eruption may have been the real culprit (*New Scientist*, 26 April 2003, p 38).

Finding evidence to corroborate the chaos theory will be difficult. Some of the asteroids stirred up at this time will have been flung into orbits crossing Mars and Venus, so other planets and moons should be scarred with 65 million-year-old impact craters. But strong winds and other weather effects erode ancient craters on planets, making them difficult to date. And although our moon has no atmosphere to weather its craters, past geological activity makes it extremely difficult to date impacts accurately.

But whatever the truth about the dinosaurs, we are still gaining a new understanding of Newton's "clockwork" heavens. Ghil's work is one of several watershed discoveries that is changing our view of the solar system, says Thomas Quinn at the University of Washington in Seattle. Though our solar system evolves quietly and sensibly for tens of millions of years, it also goes through periods of madness, and what has happened in the distant past will happen again. "Our simulations last year show that another burst of chaos is due in 30 million years time," says Ghil.

Should we be worried? Well, when the dinosaurs met their untimely end, seemingly insignificant animals ended up inheriting the Earth. Look around you today. Our successors may already be waiting in the wings. ●

You can view the digital orrery at http://order.ph.utexas.edu/clock/