

Our Solar System

In the new story of the solar system, the future is a bit dicey, and **it all began in chaos**.

**By Robert Irion**

**Art by Dana Berry**

**The dust speck had been plucked from the tail of a comet more than 200 million miles away. Now, under an electron microscope in a basement lab at the** University of Washington, its image grew larger, until it filled the computer screen like an alien landscape. Zooming in on a dark patch that looked like a jagged cliff, Dave Joswiak upped the magnification to 900,000. The patch resolved into tiny, jet-black grains. “Some of these guys are only a couple of nanometers in size—that’s amazingly small,” Joswiak said. His tone was reverent. “We think this is the primordial, unaltered material that everything formed from in the solar system.”

The dust speck has a name: Inti, for the Inca god of the sun. It probably spent nearly all of the past 4.5 billion years in a deep freeze beyond Neptune, inside the comet Wild 2 (pronounced VILT-two). Decades ago Wild 2 somehow got nudged into an orbit that drew it in past Jupiter, where it began to disintegrate in the sun’s heat. In January 2004 a NASA spacecraft called Stardust zipped past Wild 2 and snared thousands of dust specks with a trap made of aerogel—a puffy, glassy material that looks like frozen smoke. Two years later a capsule carrying this delicate cargo parachuted into the Utah desert. The Stardust team teased the specks from the gel, stuck them in their electron microscopes, and stared back at the birth of our solar system. They were stunned by what they saw.

Scientists have long known that the planets, comets, and other bodies orbiting the sun were born, some 4.5 billion years ago, from a spinning disk of dust and gas called the solar nebula. They’ve long assumed that things formed more or less where they orbit now. In the frigid realm beyond Neptune, the material available for making comets would have been a mix of ice and fluffy, carbon-rich dust. But Inti’s dark grains contained exotic minerals—hardy bits of rock and metal such as tungsten and titanium nitride that could only have been forged near the newborn sun, at temperatures of more than 3000 degrees Fahrenheit. Some violent process must have hurled them into the outer solar system.

“We were dumbfounded,” says Donald Brownlee, head of the Stardust team and Joswiak’s boss. “It was astounding to find these highest-temperature materials in the solar system’s coldest bodies. The solar system was literally turning itself inside out.”

**When most of us** were growing up, the solar system seemed reliable and well behaved. “There were nine planets orbiting in well-determined orbits like clockwork, forever,” says Renu Malhotra of the University of Arizona. “Forever in the past, and forever in the future.” Planetarium displays and the lovely mechanical devices called orreries embodied this idea, which went back to Isaac Newton. In the late 17th century Newton showed that a planet’s orbit could be calculated from its gravitational interaction with the sun. Soon clockmakers were building increasingly elaborate orreries, with brass planets that circled the sun on unchanging pathways.

Newton himself knew that reality was messier. The planets, he recognized, must also interact with one another. Their gravitational tuggings are far weaker than those of the sun, but over time they affect the paths of neighbors. As a result, as Brownlee puts it, “there’s no such thing as a circular orbit.” In principle the relentless pull of gravity can amplify these small deviations until orbits migrate, cross, or otherwise go haywire. Newton concluded that God must step in from time to time to fix the clockwork. But he couldn’t say when. Even he who invented calculus was defeated by the “n-body problem”: He had no formula for calculating into the distant future the orbits of multiple bodies that were all pulling on one another.

In practice no one saw evidence that planetary orbits had ever changed. So the clockwork solar system stuck with us—enduringly stable, it seemed, even without fixes from the Creator.

But a far more dramatic view has arisen in the past decade or so. While the findings from Stardust indicate the solar system was turned inside out during infancy, many scientists now think it also went through a raucous adolescence: Hundreds of millions of years after they formed, the biggest planets swept into new orbits, casting large rocks and comets every which way. In this view the scarred surface of the moon is lingering testimony to a period of epic mayhem.

“Who would have thought the giant planets might move, that the entire layout of the solar system could change?” says Alan Stern of the Southwest Research Institute in Boulder, Colorado. Some signs were there, Stern says. But it took new telescope surveys to reveal them, along with “digital orreries”—clever algorithms that apply brute computing power to calculating the past and future orbits of the planets.

The first clue came from Pluto. The oddball of the solar system, it dips far above and below the pancake-like plane in which the eight planets travel; it swoops on an elongated orbit that takes it from 30 to 50 times Earth’s distance from the sun. But the most curious thing about Pluto is its bond with Neptune. It’s called a resonance: For every three times that Neptune orbits the sun, Pluto orbits twice, and in such a way that the bodies never approach each other.

In 1993 Renu Malhotra figured out how that exact synchrony could have evolved. She proposed that when the solar system was young and full of asteroids and comets, Neptune was closer to the sun. If one of those bodies approached Neptune, the planet’s powerful gravity might either fling the object closer to the sun or out of the solar system entirely, in a cosmic version of crack the whip. Because action begets reaction, Neptune’s orbit would shift a tiny bit too. A human, even a Newton, could never calculate the effect of trillions of such interactions—but Malhotra’s computer model showed that on average they would compel Neptune to migrate away from the sun. In her scenario, that led it to “capture” Pluto, which was already farther out, and sweep it into gravitational lockstep.

Her colleagues were doubtful, but Malhotra was proved right within a decade. In the Kuiper belt, a dark region extending far beyond Neptune, telescopes unveiled bunches of Plutinos—icy dwarf worlds that have the same two-to-three resonance with Neptune. That could only have happened, says Malhotra, if Neptune had advanced toward the Kuiper belt like a gravitational snowplow, piling up dwarf planets into new orbits. “Once the Plutinos were discovered, it was a slam dunk,” she says. “Planet migration practically became a textbook idea.”

The notion of migrating planets came along at a time when planetary scientists were puzzled by several other features of the solar system. By the early 2000s they had long since realized that the birth pangs of the solar system had been violent. The planets had not condensed gently from the solar nebula; instead they had grown to full size by absorbing planetesimals—rocky asteroids, icy comets, and larger objects—that smashed into them at high speed. According to one theory, the moon coalesced from the spray of molten rock that was blasted into orbit when a body the size of Mars collided with Earth. All this probably happened in the first 100 million years.

The puzzle was that the extreme violence didn’t end then. Many hundreds of millions of years later, the moon suffered a series of major impacts that left it permanently scarred with huge craters. This so-called Late Heavy Bombardment would have pounded Earth even more viciously. Scientists had no good explanation for what sparked it, since by the time it happened, the planets had swept their orbits mostly clean of debris.

Telescopes were unveiling a similar enigma in the Kuiper belt. Besides Plutinos, it was littered with bodies on wildly different orbits. Some of the bodies were grouped in a flat disk, some in a puffy doughnut-shaped cloud; others were on orbits even more crazily eccentric (the technical term for elongated) than Pluto’s. “It looked like a train wreck,” says Harold Levison, Stern’s colleague at the Southwest Research Institute. The smooth outward migration of Neptune that Malhotra had used to explain the Plutinos would not have strewn debris so widely.

Meanwhile, astronomers had started to discover planets around other stars—and to radically expand their notions of what’s possible in a planetary system. Hundreds of extrasolar planets have now been detected. Some are in tightly bunched orbits, much closer together than the planets in our solar system. Some are Jupiter- or Neptune-size worlds that race on insanely hot orbits close to their suns. Others loop deep into space on weird trajectories—on average the orbits of extrasolar planets are more eccentric than those in our solar system. Some planets even float freely in interstellar space.

None of this is what you would expect from planets that were born in a spinning disk around a star and stayed quietly in their birthplace. That process should produce well-spaced, near-circular orbits, like the ones in the brass orreries. Clearly many planets had migrated, but smooth migrations didn’t seem to account for extreme orbits and late bombardments, at least not to Levison. He began to suspect that our solar system’s history had been anything but smooth—that it had somehow endured a “global gravitational instability,” as he now calls it. In 2004 he gathered with three colleagues on sabbatical in Nice, France, to try to work out how.

**Levison, who goes by** “Hal,” is a burly man with thin, graying hair pulled back into a ponytail and an untamed Santa-style beard. He’s both serious and impish; his Boulder office contains lush old illustrations of planetary orbits, an Albert Einstein action figure, and a model of Gort, the robot from *The Day the Earth Stood Still.* He’s fond of giving provocative talks and will sometimes wear a catcher’s mask to ward off brickbats from the audience. “What I’m going to say is really absolutely crazy,” he said at the start of a recent seminar. “If we publish this, my career might be over.” He could have made the same remark back in 2004 about what is now called the Nice model—the hypothesis that he and his colleagues, including Alessandro Morbidelli of the Côte d’Azur Observatory in Nice, developed on the basis of dozens of computer simulations.

In essence Levison’s team proposed that our solar system’s four giant planets—Jupiter, Saturn, Uranus, and Neptune—had started out much more closely packed together, on nearly circular orbits, with the latter three closer to the sun than they are now. Early on they were embedded in the disk-shaped solar nebula, which was still full of icy and rocky debris. As the planets absorbed those planetesimals or flung them away after close encounters, they cleared gaps in the disk.

Because the planets were also tugging on one another, the whole system was fragile—“almost infinitely chaotic,” Levison says. Instead of each planet being linked only to the sun by a brass arm, it’s as if they were all linked by gravitational springs as well. The most powerful one linked the two biggest bodies, Jupiter and Saturn. A yank on that spring would jolt the whole system.

And that, the team believes, is what happened when the solar system was about 500 million to 700 million years old. As the planets interacted with planetesimals, their own orbits shifted. Jupiter moved slightly inward; Saturn moved slightly outward, as did Uranus and Neptune. Everything happened slowly—until at a certain point Saturn was completing exactly one orbit for every two of Jupiter’s.

That one-to-two resonance wasn’t stable like the one between Neptune and Pluto; it was a brief, vigorous yank on the spring. As Jupiter and Saturn approached and pulled each other repeatedly at the same point in their orbits, those near-circular orbits were stretched into the ellipses we see today. That soon ended the precise resonance, but not before Saturn had moved close enough to Uranus and Neptune to accelerate them. Those two planets hurtled violently outward. In about half the Nice team’s simulations, they even swapped places.

As Uranus and Neptune plowed through zones of the solar system that were still full of icy planetesimals, they triggered a devastating cascade. Ice balls were catapulted in all directions. The giant planets captured a few as oddly orbiting moons. Many objects, perhaps including the comet Wild 2, were scattered into the Kuiper belt. An untold number—perhaps a trillion—were banished even farther to the Oort cloud, a vast cocoon of comets reaching halfway to the next star. A lot of comets were also hurled into the inner solar system, where they crashed into planets or fell apart in the heat of the sun.

Meanwhile the giant-planet migrations also disrupted the rocky asteroid belt between Jupiter and Mars. Scattering asteroids joined comets from farther out to create the Late Heavy Bombardment. A recent NASA mission called GRAIL documented how badly our moon suffered then and earlier in its history: Its entire crust was deeply fractured. Earth would have caught even more flak, but shifting tectonic plates have erased the craters. Any early life could only have survived deep underground.

The worst of the Late Heavy Bombardment was over, according to the Nice model, in less than 100 million years. But recent work by Bill Bottke of the Southwest Research Institute suggests that ongoing impacts may have disrupted life for up to two billion more years. When an asteroid slams into Earth, tiny droplets of molten rock are lofted high into the atmosphere, and they later rain out as solid, glassy beads called spherules. Deposits of spherules from the six-mile-wide asteroid that hit the Yucatán some 65 million years ago, wiping out the dinosaurs, have been discovered all over the world. So far at least a dozen comparable spherule beds have been found that date from a series of impacts between 1.8 billion and 3.7 billion years ago.

The computer simulations by Bottke’s team trace the source of those impacts to a now vanished inner rim of the asteroid belt, which shed asteroids for two billion years after Jupiter disturbed it. According to Bottke, as many as 70 may have struck Earth, each comparable to the one that extinguished the dinosaurs.

“Solar system evolution is dynamic,” Levison says. “It’s violent. Our solar system is probably on the mild side compared with what happens elsewhere. You probably need that mildness in order to have a habitable planet.”

**The Nice model** is a hypothesis, and not all scientists are convinced it’s true. Everyone now agrees that at least some planets migrated, but whether that set off a violent solar-system-wide paroxysm is up for debate. “It’s a fascinating concept,” says Donald Brownlee. “It must happen in places, around other stars. Whether or not it happened here, we don’t know for sure.” It’s clear that comet particles like Inti were blasted outward from near the sun, he says, but the planets may have shifted more gently.

The key to testing the Nice model is mapmaking. Charting the composition and orbits of distant objects should reveal whether and how the planets cast them there. Stern is leading a NASA mission called New Horizons that will send an unmanned probe past Pluto and its five known moons in July 2015. From there Stern hopes to redirect New Horizons to examine at least one other body in the Kuiper belt.

Powerful new telescopes planned for the next decade will expose far more objects in the Kuiper belt. They may also peek into the Oort cloud, which Stern calls the solar system’s attic. The debris cast there by Jupiter may include some lost planets. “I think the Oort cloud will blow our minds,” says Stern. “It will be littered with planets. I think we’ll find lots of Marses and Earths out there.”

What about the future of the planets we know? Forecasting the solar system is like forecasting the weather. There’s so much randomness in the system, says theorist Greg Laughlin of the University of California, Santa Cruz, that the forecast—as well as any historical reconstruction—has to be given in probabilities. Scientists are as certain as they can be that the four giant planets have finished wandering and will still be on the same orbits five billion years from now, when the aging sun is expected to balloon outward and engulf the inner planets. It’s a little bit less certain that the inner planets—Mercury, Venus, Earth, and Mars—will still be around to die that way.

“There is a one percent chance the inner solar system will go dramatically unstable during the next five billion years,” says Laughlin. The problem is a weird long-distance connection between Jupiter and Mercury. When Jupiter’s closest approach to the sun lines up with Mercury’s noticeably squashed orbit in just the right way, Jupiter exerts a slight but steady tug. Over billions of years this gives Mercury a 1-in-100 chance of crossing the orbit of Venus. There is a further 1-in-500 chance that if Mercury goes nuts, it will also perturb the orbit of Venus or Mars enough for one of them to hit Earth—or miss it by several thousand miles, which would be almost as bad. “The entire Earth would get stretched and melted like taffy,” says Laughlin, eagerly demonstrating with his hands.

That faint risk of apocalypse—a 1-in-50,000 chance that the Earth will succumb to orbital chaos before the sun incinerates it—is our legacy of the solar system’s youth, when it turned inside out. “If you give gravity enough time,” says Levison, “it will do stuff like this.”