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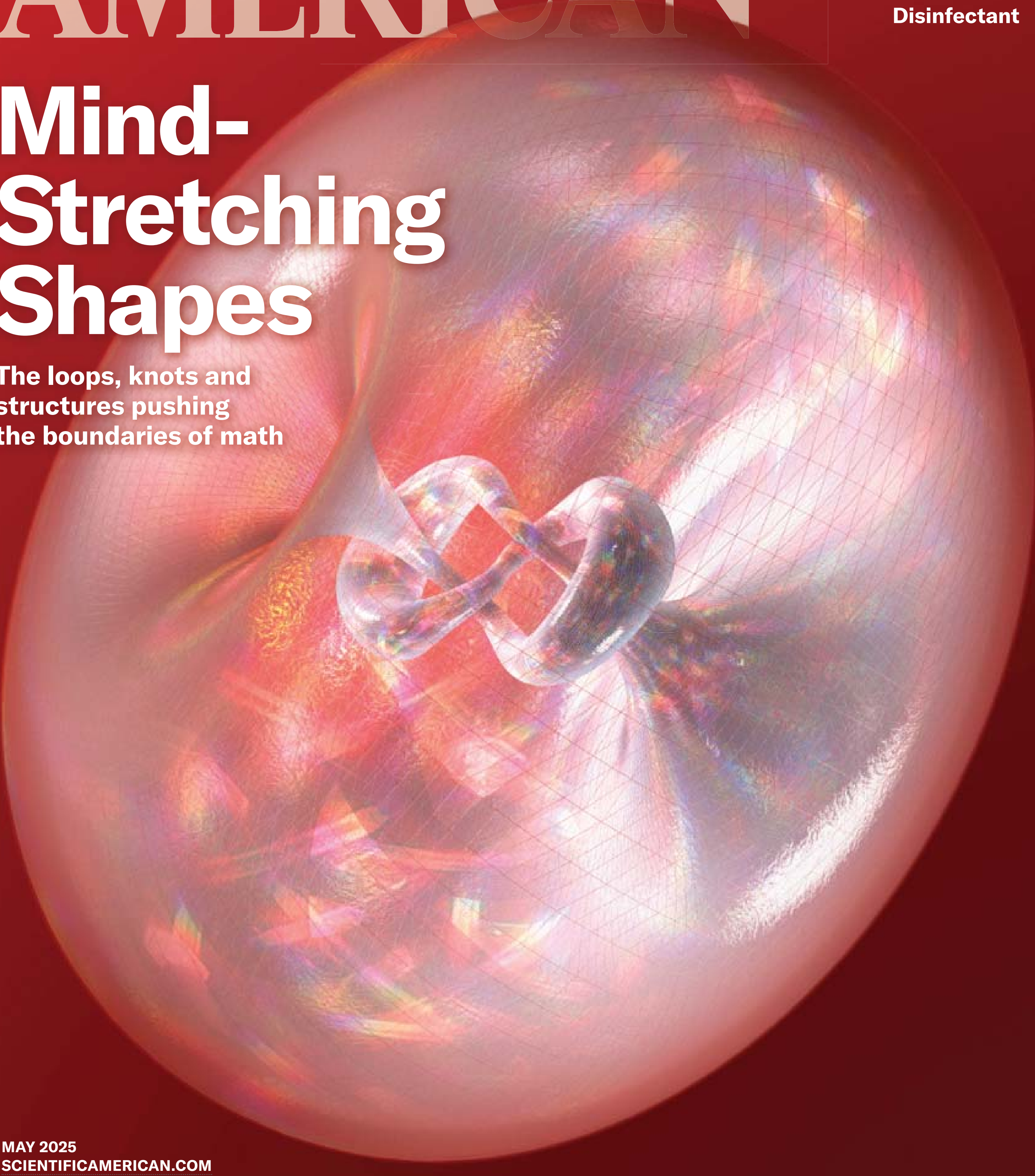

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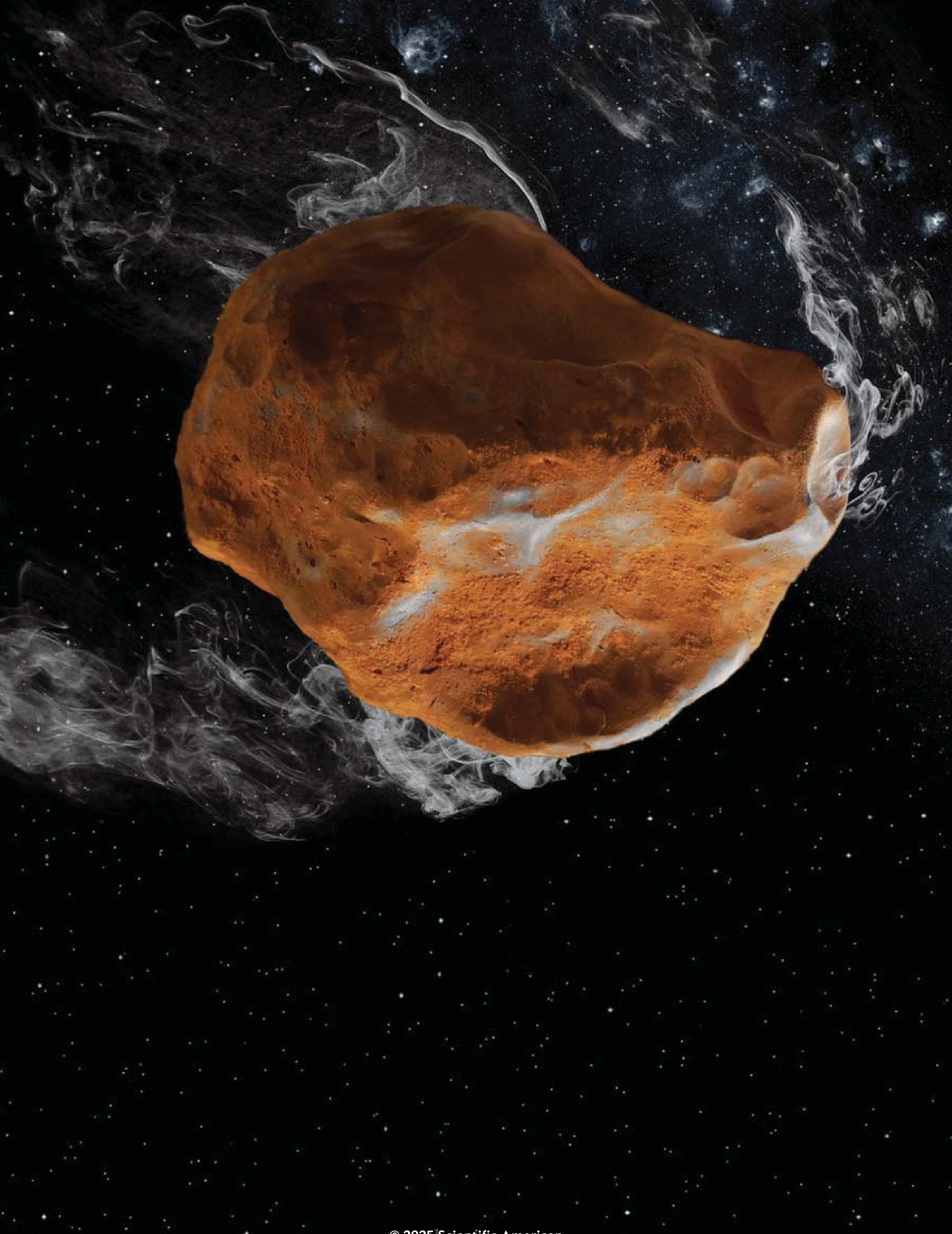
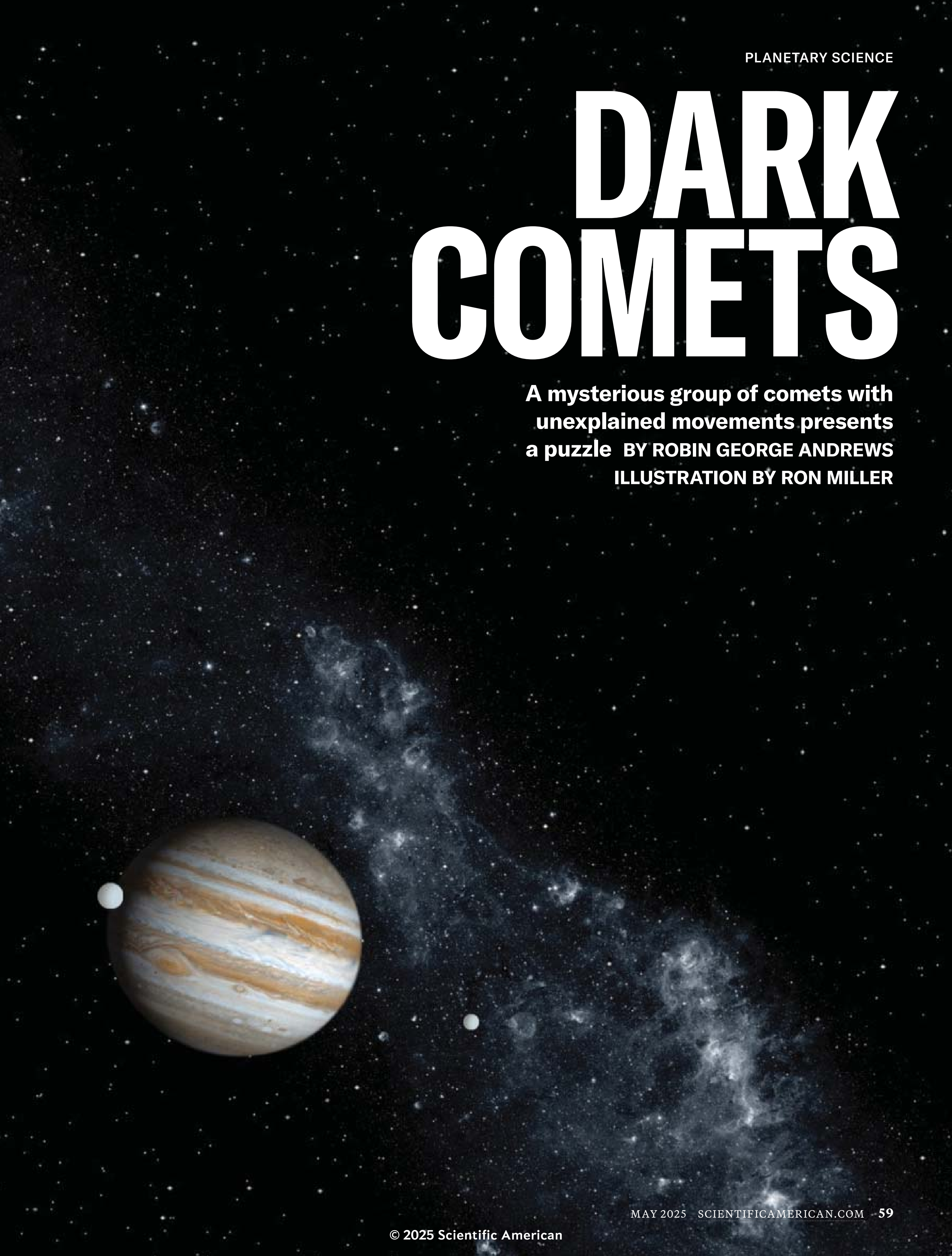


DARK COMETS

A mysterious group of comets with unexplained movements presents a puzzle

BY ROBIN GEORGE ANDREWS
ILLUSTRATION BY RON MILLER



DAVIDE FARNOCCHIA HUNTS DOWN and tracks asteroids, and several years ago he saw something he couldn't explain. Farnocchia works at NASA's Center for Near-Earth Object Studies in California. Using software programs he helped to build, he follows all the known asteroids and comets zipping about close to the planet. He's a cartographer working in four dimensions. "Our job is to predict how things move in space," he says. "So if there's something novel or unexpected, that's where the advance in the field lies for us."

In 2016 Farnocchia saw something truly unusual: an asteroid, known as 2003 RM, that was wandering about seemingly with a mind of its own. Its orbit around the sun had shifted in a way gravitational effects couldn't account for. He even took into consideration the small nudge that sunlight imparts to space rocks, and the asteroid's orbit still didn't match expectations.

"Something else is going on," Farnocchia thought at the time. But what? Something was giving that asteroid a push, but there was no evidence of any rocketlike thrust. He was as puzzled as he was thrilled. "When things don't behave the way you expect, that means there is something exciting down the road."

Farnocchia and his colleagues spent some time ruminating on this autonomously moving asteroid, wary of making too big a deal of it. But in 2017, before they had a chance to come to any firm conclusions, they were interrupted by a messenger from another star. That October, for the very first time, an interstellar object was caught diving into and then scarpering away from our solar system. As it left, it accelerated dramatically—and, as with 2003 RM, nobody caught any sign of propulsion powering that acceleration.

This interstellar interloper, named 'Oumuamua, was the subject of a scientific and media frenzy at the time—it was even suggested (without compelling evidence) that the object was an alien spacecraft. But this pandemonium overshadowed its peculiar similarity to 2003 RM and 13 other celestial oddballs that scientists have since found careening through our solar system.

"These objects really look like asteroids in the images," Farnocchia says. "But their motion is more similar to that of comets." They act as if jets formed by ice turning into vapor are pushing them around. But to date, no evidence of any such jets has been found.

"This cannot be just random," says Darryl Seligman, a planetary scientist at Michigan State University. "There's got to be something going on with these accelerations." Because the source of their propulsion cannot be seen, Seligman has given these 14 solar system oddities a rather catchy name: dark comets.

Solving the riddle of these dark comets will do more than scratch an astronomical itch. If there is a family of stealthy comets in the solar system, then perhaps they delivered water to the inner solar system long ago. "We don't know where Earth's oceans came from," Seligman says. "That's one of the main reasons to study comets. How did we get here?" And if these objects are moving erratically, their flight paths need to be fully understood—just in case any of them eventually try to crash into our planet.

"Comets are already by themselves weird objects,"

Robin George Andrews is a volcanologist and science writer based in London. His most recent book is *How to Kill an Asteroid* (W. W. Norton, 2024).

says Federica Spoto, an asteroid dynamics researcher at the Center for Astrophysics | Harvard & Smithsonian. The recent surprise of dark comets implies there's even more about comets in general that we don't understand. "We didn't know they were there; we didn't know the solar system worked that way," Spoto says.

Unlike many cosmic detective stories, this one may quickly yield revelations. With two powerful telescopes poised to offer help, scientists hope to zoom in on these strange objects and perhaps detect cometlike outgassing for the first time. And, thanks to a stroke of sheer luck, a Japanese spacecraft whose primary mission has already been completed is on its way to visit a dark comet up close. "We will get the answers to what's going on," Seligman says.

JAXA

The Japanese Hayabusa2 probe visited the asteroid Ryugu in 2018. It's now on an extended mission to survey more asteroids, including a dark comet.

THE MOTIONS OF ASTEROIDS—rocky debris left over from the formation of the solar system—aren't dictated only by the gravitational pull of the sun and other planets. Sunlight also plays a role in steering them.

As the particles of sunlight, photons, hit a space rock, they exert a small push on it over time. It's a noticeable but minor effect. "The pressure of just sunlight bouncing off you is not that large; otherwise we'd all be blown over every time it was a sunny day," says Alan Fitzsimmons, an astrophysicist at Queen's University Belfast. Then there is the Yarkovsky effect. Photons get absorbed by the sunward side of a rotating asteroid, heating that surface up. When the warmed surface rolls to the shadow side, it cools down and reemits that radiation, which acts as a minithruster to push it.

In 2016 Farnocchia and some of his colleagues were looking for evidence of the Yarkovsky effect in a catalog of near-Earth asteroids. Their report notes that several of these asteroids seemed to have nongravitational accelerations that couldn't be explained even when the scientists invoked the shuffling effects of sunlight. They expected that most of these spurious detections would be accounted for by errors in the observations and that the orbits would look normal after correction.

But one of the asteroids steadfastly refused to play ball. "Something weird was going on with 2003 RM," Seligman says. It was acting as if it were an icy comet. Erratic comet movements are typically easy to explain. "There is ice on the surface of the comet, and when the comet gets close enough to the sun, that ice starts sublimating, and that gives comets a little push," Farnocchia says.

Cometary outgassing tends to be invisible; it can be viewed only with special telescopic filters. But the dust jettisoned off a comet as it hisses and splutters is highly visible. Even just a kilogram of dust, with each grain no wider than one thousandth of a millimeter, is easily detected: it spreads out into a very thin but expansive disk that enthusiastically scatters starlight. "You can see dust at any wavelength," Fitzsimmons says.

But 2003 RM looked like a speck of light. There was no gas-and-dust coma around it; there was no tail. From afar it simply looked like an asteroid.

That didn't mean it wasn't concealing a supply of vaporizing ice. "There's this growing recognition that asteroids and comets are end-members of a spectrum of bodies," says Steve Desch, an astrophysicist at Arizona State University. And in the past few decades hybrids have been discovered. Some asteroids are suffused with water and ice.

Comets like to hang out beyond Neptune, where various substances—water, ammonia, carbon dioxide and monoxide—can remain frozen. But somehow, despite being considerably closer to the warm glow of the sun, several objects with comas and dust tails have been found meandering through the asteroid belt between Mars and Jupiter, as if they got lost while on vacation. Astronomers call them main belt comets.

With all this in mind, it wouldn't be surprising if 2003 RM outwardly resembled an asteroid but occasionally displayed cometary activity. "The problem is nobody's ever reported any coma or dust from it," Fitzsimmons says. Seligman, Farnocchia and their colleagues later wrote a paper with a parablelike title: "The Asteroid That Wanted to Be a Comet." They were, for some time, befuddled.

And that's when 'Oumuamua crashed the party.

ON SEPTEMBER 9, 2017, a voyager from a distant realm was making its closest flyby of a yellowish, fairly milquetoast star within the orbit of a small, cratered, rocky world. This sojourner went unnoticed by the nearly eight billion inhabitants of the nearby blue-green planet named Earth—at least until October 19, just a few days after it passed a mere 24 million kilometers above their heads.

Almost immediately after a telescope in Hawaii spotted the object, astronomers around the world scrambled to track it—and quickly found themselves awed. This rock was on an extremely arched trajectory that indicated it came not from within the solar system but from far outside it. Follow-up observations revealed that it was shaped like either a pancake or a cigar and that it was fairly shiny. But it was the fact that it sped up as it left the solar system—faster than could be explained by the gravitational-slingshot shove it received as it swung around the sun—that truly stunned the astronomical community.

Because the object was spotted while it was already making its escape, astronomers had only a limited time to gather observations. A shiny object that was engaging in nongravitational acceleration was, they thought, probably a comet. But this acceleration was far stronger than anyone would have expected from a typical comet—and, despite hasty efforts to find it, they saw no evidence of any cometary outgassing or expelled dust.

"It reminded everyone so much of *Rendezvous with Rama,*" Desch says, referring to a 1973 science-fiction novel by Arthur C. Clarke in which an enigmatic cylindrical spacecraft passes through the solar system. The 2017 object was sometimes casually referred to as Rama before it was officially given a Hawaiian name: *'Oumuamua,* meaning "a messenger from afar arriving first."

Certainly it was fun to think about the object, with its odd shape and invisible propulsion, as an alien spaceship, but most scientists didn't take the idea seriously. Infamously, Harvard University astrophysicist Avi Loeb argued that it could be an extraterrestrial reconnaissance probe powered by solar radiation pressure. Yet no convincing evidence exists to support that claim, one that astronomers—including Desch—have comprehensively torpedoed. "In the past, people would not call on spaceships. They would call on dragons or fairies," says Olivier Hainaut, an astronomer at the European Southern Observatory. "What is more likely: a slightly weird comet that behaves a little like those we know or a spacecraft?"

To be fair, the source of 'Oumuamua's nongravitational acceleration during its exodus remains unknown. The object has left our galactic neighborhood forever, and the few observations of it offer only clues, not certainty. Some have suggested that it was a piece of a planet like Pluto and that effervescing nitrogen ice gave it its rocket-like boost. Others wondered whether it was a sublimating hydrogen iceberg instead.

In 2023 Seligman and his colleagues speculated in a paper that 'Oumuamua might be a water-ice comet after all. Maybe when it gets zapped with cosmic rays, water particles break down into hydrogen and oxygen, which get trapped in pockets of shapeshifting ice. When bathed in sunlight, the ice releases that hydrogen gas, propelling the otherwise typical icy comet at breakneck speeds.

There is a small chance that 'Oumuamua wasn't behaving like a comet at all. Pressure from solar radiation could be pushing it away from the sun, but that would work only if the object has a very specific shape: "a ginormous snowflake-type thing," Seligman says—kind of like an ultralow-density icy sail. But, he says, it is probably a weird comet.

"'Oumuamua was interesting because it was the first interstellar object to be discovered," says Farnocchia, who also studied it closely. But, crucially, for those also pondering 2003 RM's shifty movements, it rang a bell. Both objects moved in a comet-like way, probably through some kind of ice vaporization that couldn't be detected. Although 'Oumuamua's unusual shape and variety of exotic ice possibilities made it more of a cousin to 2003 RM than a sibling, its presence did suggest that 2003 RM was probably not alone in our solar system.

Farnocchia and his team quickly scanned the solar system for signs of any other stealthy, cometlike objects. In 2023 Seligman, Farnocchia, Hainaut, and others announced a new discovery—well, six, actually. They had identified half a dozen additional 2003 RM–like objects, each with inexplicable nongravitational accelerations, each lacking any evidence of cometary activity, even when the most eagle-eyed telescopes in the world were pointed at them.

The hunt was on to find even more of them, and it didn't take long: by 2024 the team had found seven more, bringing the total to 14. And that's when things got really weird.

AS BEFORE, THE EFFECTS of sunlight on these new objects couldn't explain their anomalous accelerations. And, just as the scientists had expected, they could find no sign of any dust being jettisoned by any of these 14 rocks. Other astronomers not involved with the study can find no fault in the team's analyses. "They're really good at this," Fitzsimmons says. "There are no mistakes in this work."

Dust blasted off the surface of comets is, remember, very easy to see. That fact implies that when these objects are cooked by the sun, and their ices vaporize, they "are only emitting puffs, like a little squirt of air," says Meg Schwamb, a planetary astronomer at Queen's University Belfast. But it was frustrating that no one could see any of that dust.

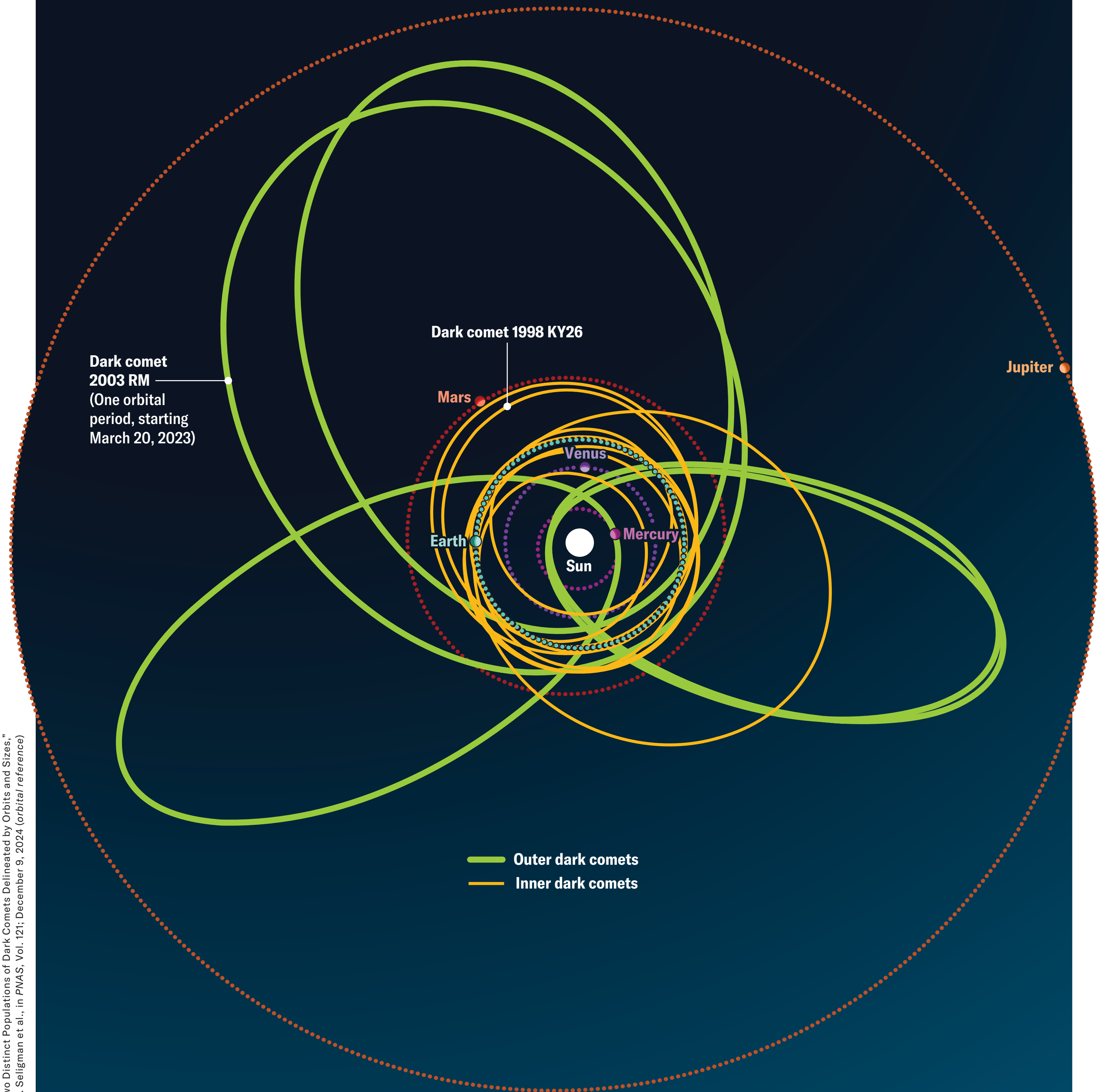
By this point, though, Seligman had noticed something exceedingly odd about these dark comets: they could be divided into two distinct families. One family, the outer dark comets—let's call them outies—seemed more reflective and larger, on the order of hundreds of meters in length or longer. Their family name comes from the fact that they linger closer to Jupiter and the outer solar system. Their elliptical orbits even resemble those of Jupiter-family comets; these objects orbit the sun in less than 20 years and were originally sourced from the Kuiper belt, a torus-shaped band of icy orbs beyond Neptune. Asteroid 2003 RM is one such outie.

Then we have the inner dark comets, or innies. These are smaller—all 50 meters or less in diameter—and have circular orbits that stick within the inner solar system. An object called 1998 KY26, which may be just 10 meters across, is an example of an innie.

The team suspects the outies are easier to explain. These shinier objects with cometlike orbits are probably icy comets with limited—and therefore very difficult-to-detect—outgassing and dust release. If so, they may provide a new answer to a long-standing question. "How do comets die?" Fitzsimmons asks. "We know some of them spectacularly fall apart, break apart," particularly if they do an Icarus and fly too close to the sun. But the seemingly minimal cometary activity of the outies lends support to another mechanism: suffocation.

Odd Orbits

Almost a decade ago astronomers started noticing unusual space rocks—they moved like comets but looked like asteroids, without the tails of gas and dust that shape the motion of comets. Since that initial discovery, scientists have spotted more of them, and now we know of at least 14 of these so-called dark comets. In an effort to understand them, researchers have divided the known population into two camps: "innies," which are all under 50 meters wide and travel in circular orbits in the inner solar system, and "outies," which are larger and follow elliptical orbits that take them closer to the outer solar system.



Source: "Two Distinct Populations of Dark Comets Delineated by Orbits and Sizes," by Darryl Z. Seligman et al., in *PNAS*, Vol. 121; December 9, 2024 (*orbital reference*)

Graphic by Jen Christiansen

A Japanese spacecraft is already on the way to visit a dark comet—and the commanders of that mission didn't even realize it until recently.

If, as outies approach the sun, their vaporizing water ice releases enough buried dust into space, a lot of it may tumble back down onto the comet's icy nucleus. If the ice is continually smothered by dust, then it will be increasingly insulated from the sun's glare. After some time only small patches will, very briefly, get vaporized and release puffs into space. Perhaps eventually none of the ice will be exposed at all. "They're covering themselves in a blanket of dust and saying, 'That's it, I've given up being a comet. I want to be an asteroid now,'" Fitzsimmons says.

The innies are more troublesome to explain—which makes them more beguiling. One conundrum is that if they spend all their time in the inner solar system being frazzled by the sun, how can they have any ice left to fuel their sporadic accelerations? But "the real strange thing is their size," Fitzsimmons says. "We have never seen an active comet nucleus smaller than a few hundred meters across." A minuscule nucleus is extremely vulnerable to annihilation, either via heating or by spinning itself up into a self-destructive pirouette. And yet there the innies are.

Seligman isn't sure how closely the innies and outies may be related. One possibility is that the outies sometimes tumble into the inner solar system, and the innies are a late-stage version of them that's racing toward a dehydrated demise. Alternatively, the innies could be main-belt comets—which do have observable comas and tails—that have been scorched for such a long time that they're almost completely desiccated, rendering them unable to showcase almost any cometary activity.

Having 14 of these dark comets to study is a boon to the team. The collection still leaves them with more questions than unequivocal answers, but by this point the wider implications of dark comets are starting to become clear.

Models suggest a small fraction of Earth's water was made within the planet and erupted onto the surface via volcanism. Where did the rest come from? "The obvious candidate is comets," Hainaut says. But because comets spend most of their time in the Kuiper belt or the considerably more distant Oort cloud, they seem too far away to have done the job. Dark comets might offer a closer source. "It's very easy to bring stuff from the asteroid belt to Earth," Hainaut says—and main-belt comets, along with the inner dark comets, handily fit the bill.

The existence of dark comets might also have ramifications for planetary defense, the science of preventing dangerously large asteroids and comets from crashing into Earth. One of Farnocchia's primary occupations as a member of NASA's Center for Near-Earth Object Studies is to find potentially hazardous asteroids before they find us—so it's in his (and everyone's) interest that we know how to calculate the slightly less predictable orbits of dark comets.

In other words, if you find a larger near-Earth asteroid that nobody has identified before, that's a great start. "But if you don't know where it's going to be, that won't matter," Seligman says.

Farnocchia, a planetary defense veteran, isn't too concerned. The automated software that's designed to both detect and then precisely track the motions of near-Earth asteroids (and comets) far into the future may not yet fully account for the novelty of dark comet–style accelerations. But on the scale of a human lifetime, "you'd still be able to connect the dots," he says.

Dividing the dark comets into two families in 2024 was a marked step forward, but the scientists hunting them down were still left furrowing their brows in confusion. "What is going on?" Farnocchia asks. What are these objects, and why can't we spy any of their jettisoned dust?

Although extremely powerful optical telescopes have so far failed the researchers, two others will soon be able to aid their quest. The first is the Vera C. Rubin Observatory, a gigantic, wide-eyed digital camera being assembled on a mountain ridge in Chile. It will come online later this year, and within just a few months it will find millions of new asteroids and plenty of comets—almost certainly increasing the known dark comet population and giving the team more of these aberrations to study.

The second, if the researchers can convince the powers that be to give them some time to use it, is the James Webb Space Telescope (JWST). Its infrared scope can see things other observatories cannot—including the normally invisible water-vapor outgassing of comets. "JWST is really the only telescope we could use to measure their outgassing coma," says Aster Taylor, a Ph.D. student of planetary astrophysics at the University of Michigan and a dark comet aficionado.

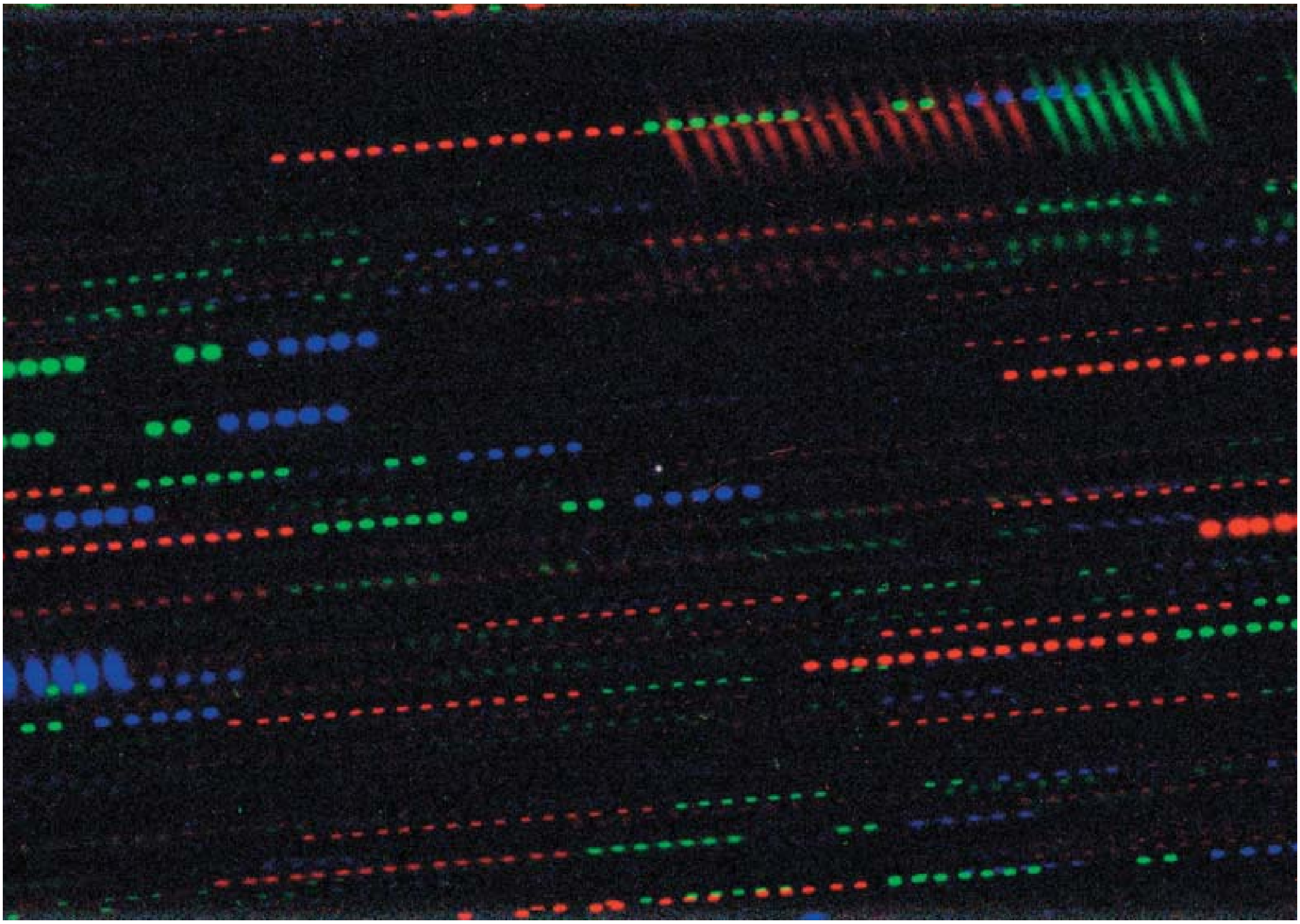
In 2023 JWST confirmed the presence of water vapor around a main-belt comet for the first time. The dust presumably shooting off dark comets may be elusive, but the researchers could use JWST to look for outgassing instead. "If they find water emission, that really does nail it," Fitzsimmons says—case closed.

Competition for JWST is fierce, and the team's initial dark comet–surveying proposal was rejected. The scientists have a new JWST proposal under consideration, "so we hope we will get that this time," Seligman says. Even if they don't see any outgassing, they can still use the space telescope to get an idea of the mineral content on the dark comets' surfaces, which may reveal the presence of ice.

What's got the dark comet hunters particularly animated, however, is that a Japanese spacecraft is already on the way to visit a dark comet—and the commanders of that deep space mission didn't even realize it until very recently.

Japan's Hayabusa2 mission is one of the all-time asteroid-hunting greats. Its goal was to retrieve a pristine sample of a carbon-rich asteroid named Ryugu and bring it to Earth so cosmochemists could learn whether ancient asteroids contained the building blocks of both planets and biology. It succeeded beyond all expectations. In 2018 it reached Ryugu. The following year it fired a bullet at the asteroid to excavate a crater, exposing buried primeval matter, before flying down toward it and scooping up some of those grains.

After safely delivering that invaluable treasure to Earth in 2020, Hayabusa2 flew back into space—and its extended mission began. This time it was taking on a planetary defense role. It was now named Hayabusa2# (the # indicates "sharp," as in musical notation; here it stands for Small



ESO/K. Meech et al.

The faint white dot (*center*) surrounded by star trails in this image by the Very Large Telescope and the Gemini South Telescope is 'Oumuamua, an interstellar asteroid that originated beyond the solar system.

Hazardous Asteroid Reconnaissance Probe). It is now flying to two nearby asteroids that are smaller than Ryugu but still in the size range of space rocks that could imperil Earth, just to check them out. It will zip by the first asteroid, named Torifune, in July 2026, and in 2031 it will rendezvous with a far smaller object—1998 KY26.

That's right: it's one of the inner dark comets. "I'm surprised," says Yuichi Tsuda, project manager of Japan's Hayabusa2 mission. The rock was originally chosen because it's small, it's spinning incredibly rapidly, and, unlike larger asteroids, which tend to be rubble piles, it's just a single rocky shard. "We thought it's very important to study for planetary defense," Tsuda says. When it was chosen as a target several years ago, his team hadn't come across any of the research into dark comets.

In 2023, desperate to collect more information about his rising tally of dark comets, Seligman searched online for more information about each of them. When he looked up 1998 KY26, a torrent of academic papers flooded his screen. "When I put it together, I was like, 'Oh, wow!'" he says, laughing. "It was super lucky—serendipitous. It was like the cherry on top." Finally, a dark comet is about to be brought into the light.

Tsuda and his team are still working out what to do when the spacecraft reaches 1998 KY26. They might try to orbit the dark comet and scan its surface for any cometlike ices and minerals. They could use their remaining bullet to blast a crater in its side, revealing its internal composition. Hayabusa2# might even end its extended mission by attempting a risky landing on the frantically spinning rock.

Whatever the choice in the end, the dark comet team can't believe its good fortune. "Our Japanese friends are going to have lots of fun," Hainaut says.

FROM OUR ARCHIVES
The Hunt for Planet Nine. Robin George Andrews; January 2025. ScientificAmerican.com/archive

For the time being, dark comets will remain mysterious. "It's hard to explain how they exist in the first place," Fitzsimmons says. "That's just Mother Nature being cleverer than we are. That's what astronomy's all about, figuring out how Mother Nature does stuff. How did that get there?"

There is a chance that all this work will amount to little. "[What] if observations come back, and we don't see anything?" Seligman wonders—no outgassing, no dust, but persistent cometlike accelerations. "What are we going to think?" Or perhaps by 2031 the Rubin Observatory will have found dozens of other dark comets, JWST will have found crystal-clear evidence of outgassing, other telescopes will have finally detected telltale dust plumes, and Hayabusa2# will have made a dark comet its final resting place among the stars.

It's likely that the dark comet team will soon have answers, and our solar system will become just a little bit more predictable. "I don't think I've emotionally prepared myself for that," Seligman says. He lets out a sigh. "It's fun for it to be a mystery." ●