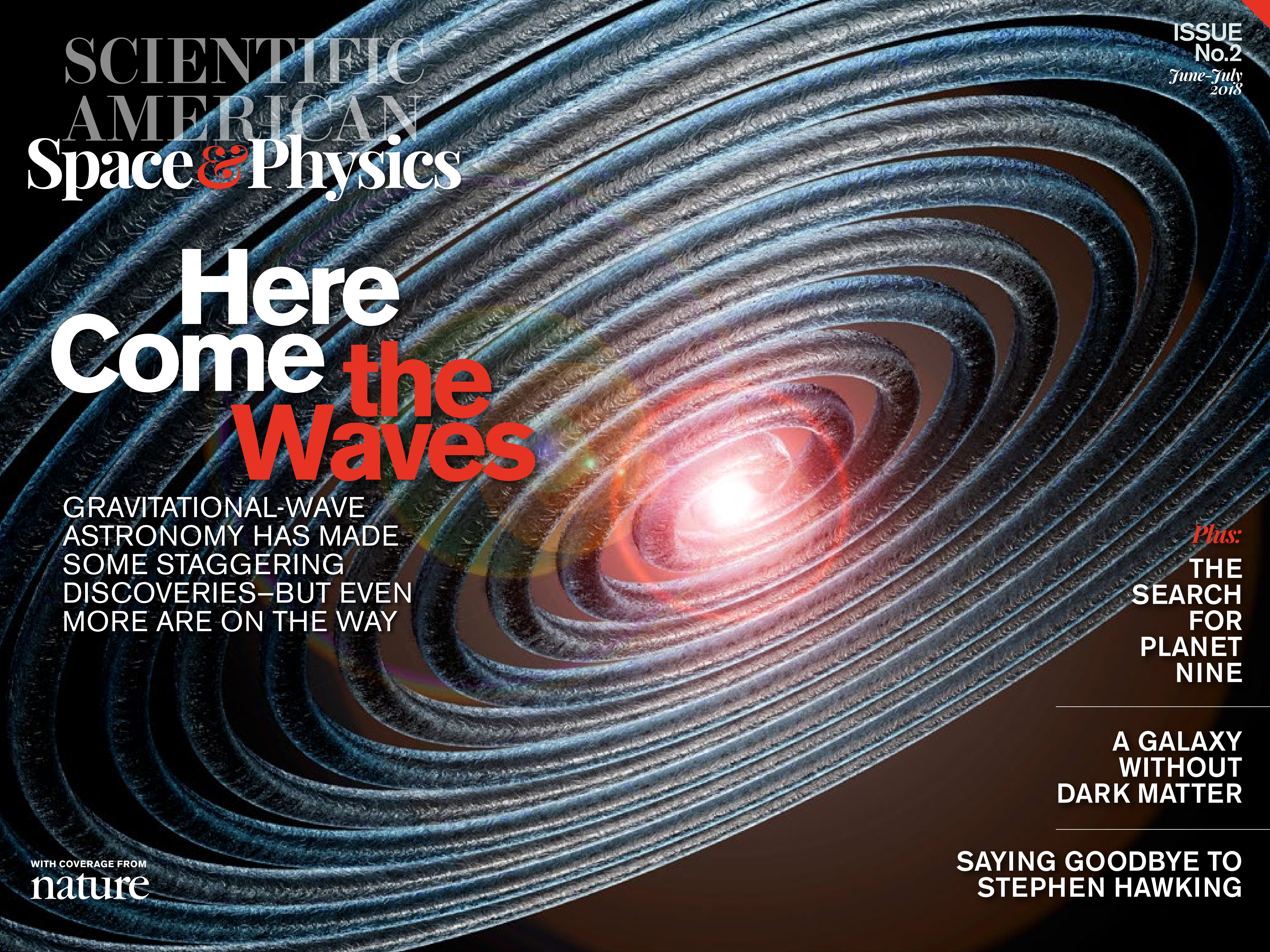

SCIENTIFIC AMERICAN
Space & Physics

ISSUE No.2
June–July 2018

# Here Come the Waves

GRAVITATIONAL-WAVE ASTRONOMY HAS MADE SOME STAGGERING DISCOVERIES—BUT EVEN MORE ARE ON THE WAY

*Plus:*

THE SEARCH FOR PLANET NINE

A GALAXY WITHOUT DARK MATTER

SAYING GOODBYE TO STEPHEN HAWKING

WITH COVERAGE FROM
nature

# Looking for Planet Nine, Astronomers Gaze into the Abyss

**Two years on, the search for our solar system's missing world is as frenzied as ever—and the putative planet is running out of places to hide**

***By Lee Billings***

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AN ARTIST'S CONCEPT of Planet Nine backlit by the far-distant sun. Thought to be lurking in the depths of the outer solar system, this world is predicted to be several times the mass of Earth, with a thick atmosphere surrounding a rocky core.

CALTECH; R. HURT (IPAC)

IT'S BEEN OVER TWO YEARS SINCE CALTECH ASTRONOMERS MIKE BROWN AND Konstantin Batygin made an explosive claim: based on the orbital motion of objects in the Kuiper Belt—a region beyond Neptune that is home to Pluto and other icy bodies—there must be a very big *something* much farther out, hidden save for its subtle gravitational tugs on the rest of the solar system.

Brown and Batygin's best models put this mysterious object at about 10 times Earth's mass, perhaps 20 times more distant from the sun than Neptune and currently drifting through what might be a 20,000-year orbit in a patch of sky near the constellation Orion. Brown and Batygin called it "Planet Nine," elevating it to the position once held by Pluto (which was demoted to "dwarf planet" status in 2006, when Brown discovered multiple Pluto-like worlds out past Neptune). Within months a small army of theorists and observers had thrown themselves into the search—which, so far, has come up empty. Planet Nine remains stubbornly in absentia.

Unknown planets far from the sun are not a new idea; they perennially pop up in astronomy. Such claims trace back to the 1800s and fostered the discoveries of Neptune and Pluto. What makes Planet Nine different is how much more we now know about the outer solar system—a vast and stygian abyss in which hiding a planet is still possible, although getting harder all the time. Out there twirl frozen bits of flotsam left over from our solar system's earliest moments. A big planet's gravity can act like a thumb on a scale, subtly but substantially tweaking the movements of these so-called trans-Neptunian objects (TNOs). As astronomers use new telescopes and other instruments to rapidly map this last frontier of the solar system, they keep finding what seems to be a Planet Nine–shaped hole in it.

Brown and Batygin's proposed planet handily explains orbital oddities observed in some TNOs. In their initial paper the pair showed how a recently discovered population of TNOs, bizarrely orbiting nearly perpendicular to the plane of the known planets, could be coaxed and kept there by the gravity of a far-out hidden world. Other newfound TNOs move in a telltale filigree of orbital resonances, periodically perturbing one another in a web of complex patterns that hint at further interactions with some great, unseen mass. Planet Nine's gravitational influence could even serve as a solution to the long-standing mystery of why the sun's axis of spin is tilted six degrees askew to the orbits of the inner planets.

Planet Nine also aligns with an emerging awareness that the solar system's early days were a chaotic mess, in which the early formation of Jupiter and Saturn scattered smaller and more embryonic worlds into the sun or the interstellar void. In this picture Planet Nine might have been an outbound world that plowed through enough debris to slow down and get trapped in the solar hinterlands. Or it could have been an alien outcast from another star, gravitationally captured when it wandered too close to our own. In an indirect way it could even be responsible for our existence—scattered inward rather than outward, it might have disrupted Earth's orbit, preventing life's genesis here.

Further afield, surveys of planets orbiting other stars have shown the most common worlds in our galaxy bear a passing resemblance to the putative Planet Nine—so-called "super-Earths" that are midway in size between Earth and Neptune, and appear around most stars we examine. If Planet Nine is real, it could be more than just another planet on the block; it could be the missing link between our familiar solar system and those we now see elsewhere in the Milky Way.

"I try not to be religious about my own results. It's important to keep a skeptical eye," Batygin says. "But I actually feel more comfortable than I did two years ago, because the theory still holds up beautifully. The more we look, the more we see a solar system that makes no sense without Planet Nine."

## THE MOST MYSTERIOUS OBJECT IN THE SOLAR SYSTEM

IN THE MONTHS FOLLOWING the announcement, many of Planet Nine's most fervent seekers (Brown chief among them) predicted it would probably be found by the end of the following winter—that is, by now. In January of this year Brown was still bullish: based on "statistically rigorous calculations" incorporating all the available data, there is only a one-in-10,000 chance the planet is *not* out there, waiting to be found, he tweeted. In other words, Brown's best guess is Planet Nine has a 99.99 percent probability of being real.

Astronomer Scott S. Sheppard, a Planet Nine hunter at the Carnegie Institution for Science in Washington, D.C., recently ballparked the odds at 85 percent—an estimate consistent with his more conservative research style. In 2014, two years before Brown and Batygin's bombshell (and with far less fanfare), Sheppard and Gemini Observatory astronomer Chad Trujillo published their own claim of an undiscovered super-Earth in the outer solar system.

Sheppard and Trujillo's work concerned what may be—after Planet Nine—the second-most mysterious object in the solar system: a 1,000-kilometer-wide TNO called Sedna, discovered in 2003 by Brown, Trujillo and another colleague.

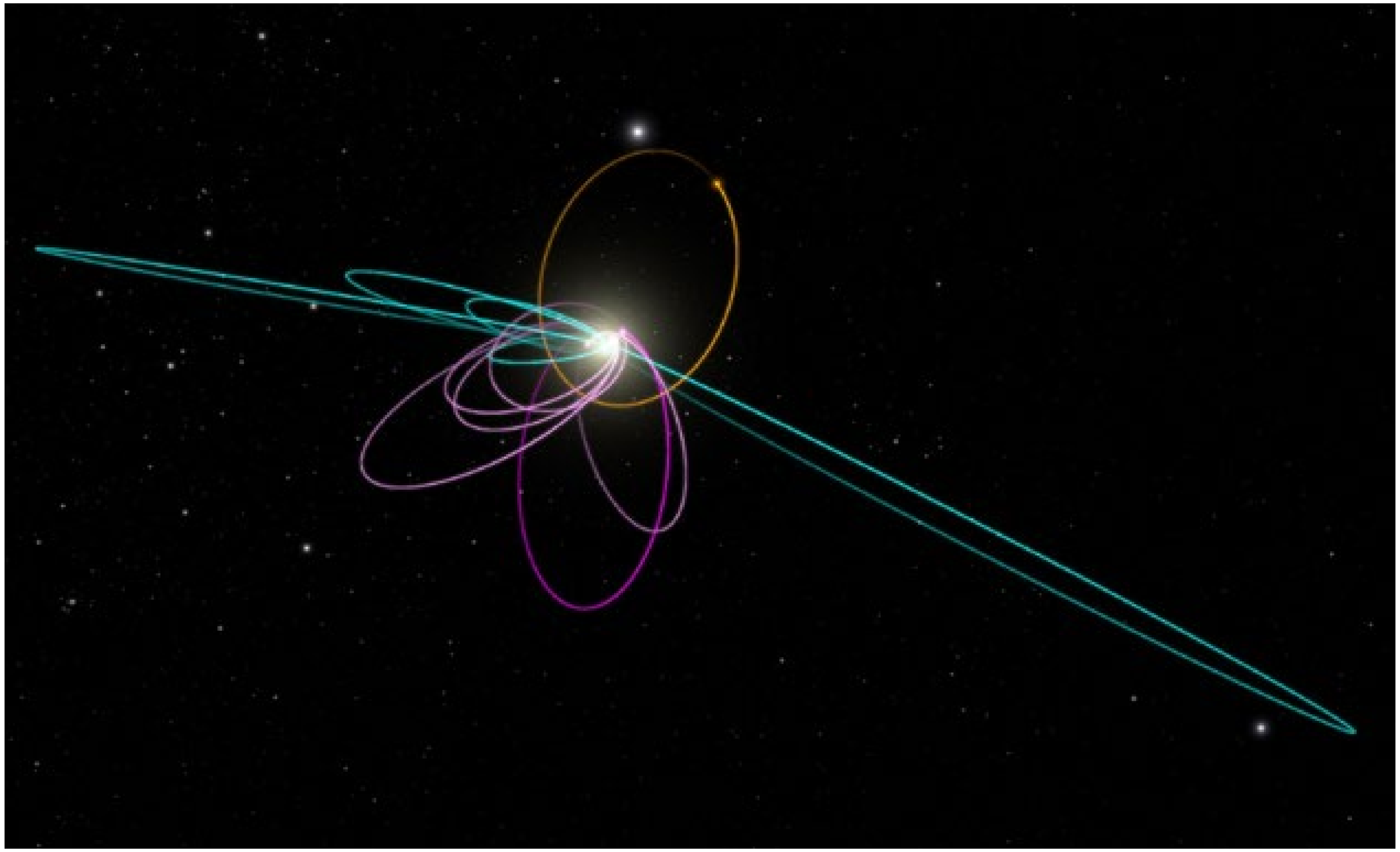
Sedna occupies a bizarre 11,400-year "eccentric" orbit: an elongated ellipse that takes it more than 20 times farther out than Pluto and never brings it closer than twice Neptune's distance from the sun. Such an extreme orbit is probably a scar from a violent past, a sign that long ago Sedna was gravitationally hurled from its standard circling onto a wild new trajectory. In the outer solar system such orbits tend to be tethered at one end to whichever giant planet originally did the hurling. But Sedna's was not attached to Neptune. It seemed detached from everything, and nothing else seen orbiting the sun shared its strange orbital properties—that is, until Sheppard and Trujillo discovered a second detached and eccentric Sedna-like (but much smaller) object, 2012 VP113.

One "Sednoid" could have been a fluke; two suggested the existence of a large, scarcely glimpsed population of detached objects. How did they get there? One possibility, proffered early on by Brown and others, was that such bizarre orbits came from a chance close encounter with a passing star in our solar system's infancy. But a single obscure detail made Sheppard and Trujillo suggest the cause was instead a hidden planet: the Sednoids shared an uncanny alignment with several other recently reported "extreme" TNOs. All lived in eccentric orbits at a high angle to the disklike plane where the known planets exist, periodically swooping through that plane in their orbits—and all swooped through that plane just as they made their closest approach to the sun. In the arcane parlance of astronomy, they clustered around a common "argument of perihelion."

Mike Brown (left) and Konstantin Batygin (right) finalize their first paper postulating the existence of Planet Nine in this photo from December 2015.

KONSTANTIN BATYGIN

"Normally arguments of perihelion should be random, having any angle between the full 0-to-360 range of possible orientations. But these were all quite improbably clustered together," Trujillo recalls. "One of the things that can confine them into a narrow range like that is the presence of a massive planet farther out.... Scott and I did



At present, the clustered orbits of objects in the Kuiper Belt beyond Neptune provide the best evidence for Planet Nine's existence. Sedna's orbit (purple) as well as the orbits of several other objects (pink) suggest they have been pushed out by the hypothesized planet (orange). Planet Nine's gravitational influence could also explain another population of objects (blue) orbiting perpendicular to the plane of the solar system.

CALTECH/R. HURT (IPAC)

a few simple simulations that suggested this was a possibility, but we didn't go into much detail—we were primarily just reporting the discovery of 2012 VP113."

Two years later Brown and Batygin's papers burst into view, building on Sheppard and Trujillo's work with hundreds of simulations predicting a mass and orbit for the possible world—a treasure map for planet-hunting astronomers. The Planet Nine hypothesis was born, along with a friendly but fierce rivalry that persists to this day.

"This is science at its finest," Sheppard says. "We noticed something weird going on out there and showed why it could be due to a big planet. Then they built on that and actually got an orbit for this thing. I don't think we have anything to prove, but it would be fun to find the planet. Whoever happens to point their telescope at the right spot at the right time will do it."

## A NEEDLE IN A CELESTIAL HAYSTACK

MOST HUNTERS AGREE that if Planet Nine were anywhere near the point closest to the sun, it would be bright enough to have already been found. Instead it is probably near aphelion—the outermost sweep of its orbit, where it moves the slowest and thus spends most of its time. Seen in Earth's sky, it might now appear as a tiny dot somewhat dimmer than one of Pluto's midsize moons, gliding almost imperceptibly against a starry backdrop. Fainter TNOs have already been found, meaning Planet Nine should be within reach of many telescopes around the world. But, as Batygin puts it, "the amount of real estate that is available for the planet to hide in is astronomically vast." That means some 400 square degrees of sky, or 2,000 times the area covered by the full moon.

To have a decent chance at discovery within this immense space, one needs a very large light-gathering mirror to peer deeply into the sky for dim objects as well as a wide field of view to quickly scan large chunks of the heavens for a needle in a celestial haystack. Only a few telescopes on the ground (and none yet in space) boast both.

Brown and Batygin use the facility best suited for this search—the 8.2-meter Subaru Telescope on the summit of Mauna Kea, a dormant Hawaiian volcano. Sheppard and Trujillo do, too, while hedging their bets with observations at several other large telescopes. Using Subaru's new wide-field, 870-megapixel Hyper Suprime-Cam, either team can cover six full moons' worth of sky per image. Each takes snapshots of the firmament across several consecutive nights, then uses a computer to look for any uncatalogued objects that slowly change position.

The search can only take place at certain times of year, chiefly during the Northern Hemisphere's autumn and winter, when the general region where Planet Nine might live is high in the sky. So these rivals tend to observe almost back-to-back, one team arriving practically as the other is packing up to leave. Earlier the two teams shared data and split the survey region into parcels that one or the other would observe. But now they keep to themselves, blindly overlapping their monitoring of any given piece of sky—not out of distrust but simply to ensure the collective search is as thorough as possible. Instead of observing any given segment of sky just once, the rivals are opting to watch each one twice or more by virtue of their independence.

High-altitude weather sometimes fouls the narrow observational windows, and both teams' recent observing sessions at Subaru have been decidedly unlucky. Near-continual snow and hail blotted out the sky for Brown and Batygin on one fruitless run last December; their final night was particularly grim, when an igloo-like shell of ice frozen to Subaru's protective dome prevented them from even accessing the telescope. On another trip in January poor weather prevented Sheppard and Trujillo from making 70 percent of their planned observations. During Brown and Batygin's most recent outing in February persistent high-altitude winds smeared the stars into pancakelike shapes, scuttling the search. "I like pancakes," Brown quipped on Twitter, "but not this many." Plagued by poor weather, what began as a sprint to the finish has turned into a longer slog.

The Milky Way and the constellation of Orion rise above the Subaru Telescope atop the dormant volcano Mauna Kea in Hawaii. Subaru is the premier observatory searching for Planet Nine, which is thought to lurk somewhere in this broad swath of sky.

SEBASTIAN EGNER, SUBARU TELESCOPE AND NAOJ

### FROM THE ARCHIVES

ONE OF THE MOST SWEEPING data sets now narrowing down Planet Nine's possible hiding places does not come from a telescopic search at all—but rather from NASA's Cassini orbiter at Saturn, which plunged into the ringed planet in September 2017 after a 13-year stay. That was long enough for the spacecraft to have recorded any faint perturbations a faraway planet could induce in Saturn's motion around the sun. After Batygin and Brown's announcement a team at the NASA Jet Propulsion Laboratory, led by the physicist William M. Folkner, searched for such anomalies amid the positional data Cassini beamed back during its mission, but found none. This means if Planet Nine exists and is about 10 Earth masses, it must be on an even longer, more eccentric orbit than thought and nearing an aphelion perhaps twice as far out as was first forecast in 2016. That great distance would make it even harder to see. Alternatively, it could be smaller than 10 Earth masses and still close to Brown and Batygin's canonical predicted orbit.

Or it could simply not exist.

"The stinging possibility here is that Planet Nine is just frickin' far out, and then we have to wait for a new generation of better telescopes to find it," Batygin says. "Another possibility I try not to think about too much is that it's in the galactic plane." That's the disk of the Milky Way that arcs like a glowing backbone through the night

Cerro Tololo Inter-American Observatory (CTIO) sits beneath a shower of stars in this long-exposure photo. Multiple teams use instruments on CTIO's Blanco Telescope (leftmost dome) to hunt for Planet Nine. If the planet continues to elude astronomers into the 2020s, the last, best hope for finding it will be the Large Synoptic Survey Telescope, a facility now under construction near CTIO.

REIDAR HAHN FERMILAB

sky. A fraction of Planet Nine's proposed orbit passes through this region, where the dim, glacially creeping planetary dot could hide in a thick fog of background stars.

Only one near-future facility can easily pierce the Milky Way's luminous veil: the Large Synoptic Survey Telescope (LSST), a behemoth of an observatory with an 8.4-meter wide-field mirror hooked up to a three-gigapixel camera. Currently under construction in Chile and set to begin its survey in 2022, during each night's observations the LSST will capture 20 terabytes' worth of panoramic views of the sky overhead to create a celestial time-lapse movie of unprecedented depth and detail. Its expansive view is likely to uncover hundreds if not thousands of additional extreme TNOs, providing a flood of hard data to further test Brown and Batygin's hypothesis. Even if Planet Nine is rather dim, particularly far away and in front of the galactic plane, the most crucial evidence for or against its existence should pop out of LSST's colossal database within a few years of the survey's debut—presuming it is not found before then.

In the meantime Cassini's is not the only archival data being used in the ongoing search. A team led by astronomer David Gerdes at the University of Michigan is taking a different approach: looking for the planet within the accumulated images from the Dark Energy Survey (DES), a project now in its fifth and final year. Designed to map an eighth of the night sky, DES's view coincidentally overlaps with Brown and Batygin's best guess for Planet Nine's approximate celestial location. The project's workhorse is the Dark Energy Camera, a 570-megapixel instrument with a field of view twice as large as that of Subaru's. It is mounted on the four-meter Victor M. Blanco Telescope at Cerro Tololo Inter-American Observatory in the Chilean Andes, just a short hike away from LSST's construction site. The DES equipment can cover twice as much sky as Subaru in any given snapshot. But because its telescope is about half the size, it must take much longer exposures—a situation that arguably gives Subaru a slight edge.

Other broadly similar archive-based searches are in various stages of completion—chiefly one overseen by the University of California, Berkeley, astrophysicist Peter Nugent using data from a small telescope at Palomar Observatory and another from Berkeley astronomer Aaron Meisner and colleagues using data from NASA's space-based Wide-field Infrared Survey Explorer (WISE). There is even a "citizen science" Web site devoted to letting anyone—even you, dear reader—pore through WISE images for the elusive planet. And behind all the observations a vast and diverse ecosystem of numerical simulations hums along on powerful supercomputers, trying to further narrow the search for Planet Nine by modeling its gravitational effects on the solar system across multibillion-year timescales.

"We are carpet-bombing the sky to see what falls out," Gerdes says. "Two years on, the first thing we can say about Planet Nine is that it's not low-hanging fruit, but we're still shaking the tree."

## OVERCOMING BIAS

AND SO THE SEARCH GOES ON, sustained by a steady trickle of smaller discoveries: TNOs with weird orbits that seem to fit the patterns theorists insist such a planet would create.

Many have come from the Outer Solar System Origins Survey (OSSOS), a recently completed project using a 387-megapixel camera on the 3.6-meter Canada-France-Hawaii Telescope, which sits near Subaru on Mauna Kea. During its four-year run OSSOS found several new extreme TNOs by deeply staring at a few-hundred-square-degree chunk of sky. Surely, then, Planet Nine's metaphorical thumb on the outer solar system's scale should have left fingerprints all over the OSSOS data. And indeed, in a paper published last summer, the OSSOS team announced three of their newfound extreme TNOs were consistent with the clustering patterns underpinning the Planet Nine hypothesis—but a fourth one was not. Including this outlier in their analysis and accounting for potential biases in their observations, the team concluded the TNO clustering first identified by Sheppard and Trujillo in 2014 could well be illusory.

That is, due to the seasonality of observing runs and inclement weather on Mauna Kea and other major mountaintop observatories, OSSOS and other surveys might simply have an easier time finding extreme TNOs in the region of sky that supports the Planet Nine hypothesis. If so, given that the total number of known extreme TNOs is still very low—anywhere from 10 to just under 30, depending on which definitions are used—the true, more typical distribution of such objects would only become clear after many more are found and any biases accounted for. "We cannot reject a uniform distribution [of extreme TNOs] with our new discoveries," says Michele Bannister, an astronomer and OSSOS team member at Queen's University Belfast in Northern Ireland. "We can't say there's no Planet Nine, but we can say that its proposed effects are not present at a statistically significant level in our independent data set.… It's an increasingly big ask to continue hiding a 10-Earth-mass planet out there, now that all these surveys are being completed."

> **"We are carpet-bombing the sky to see what falls out."**
> *—David Gerdes*

Few if any prominent Planet Nine hunters are swayed, however. Brown and Batygin reject the OSSOS team's implication that other TNO searches are unreliable due to vaguely defined biases, and they note that even if biases are rampant, their effects should average out when collectively considering surveys with widely divergent methodologies. If all but one survey (OSSOS) shows clustering, they say, that clustering is likely genuine.

Gerdes, the leader of the archival DES search, acknowledges all present surveys suffer some degree of observational bias that must be carefully accounted for. But he says the jury is still out as to their significance. According to a 2017 analysis by his team, there is only a few-percent chance the orbital alignments they have observed among the extreme TNOs would occur in the absence of Planet Nine. "Is 'a few percent' large or small?" Gerdes asks. "It depends on your definition—if there was a few percent chance of rain, you'd go ahead with the picnic. If a few percent of all airline flights crashed, you'd never get on a plane."

If the prize is a new planet—and with it a whole new understanding of the solar system—even Planet Nine's naysayers concede a significant chance of failure would be worth the risk. "You have to be most careful around the most alluring hypotheses," Bannister says. "They are seductive because they are beautiful. It would be enchanting—amazing—to have an extra planet to study. We would observe it with all our telescopes. We would write proposals to send spacecraft there very quickly. But we can't forget we are talking about a realm of the solar system that is still very hard to explore. We must take care with what the data tries to tell us, because we are mapping the deep."

Regardless of whether or not Planet Nine exists, Bannister says, its unfolding story is really a tale of discovering how our little corner of the cosmos truly came to be. "We will write the history book of our solar system based on what we find out there in the next several years, and it is already clear the system we see today is not as it was formed," she says. "That won't change whether we have nine planets instead of eight."