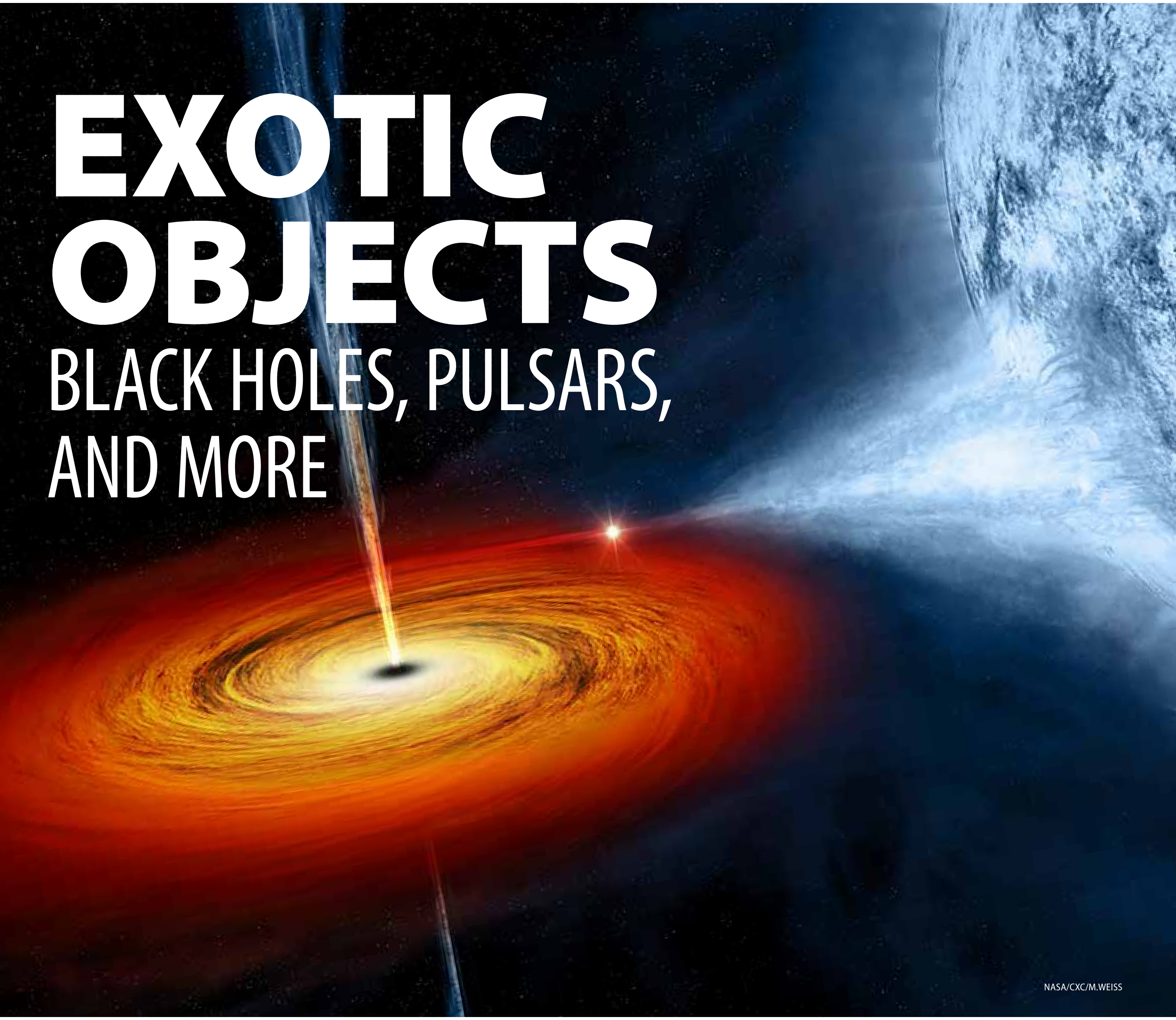
Astronomy magazine



EXOTIC OBJECTS

BLACK HOLES, PULSARS, AND MORE

NASA/CXC/M.WEISS

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A supplement to *Astronomy* magazine

A BRIEF HISTORY OF BLACK HOLES

The 1964 discovery of Cygnus X-1 filled in a missing piece of Einstein's puzzle and widened our understanding of the universe.

by Jeremy Schnittman

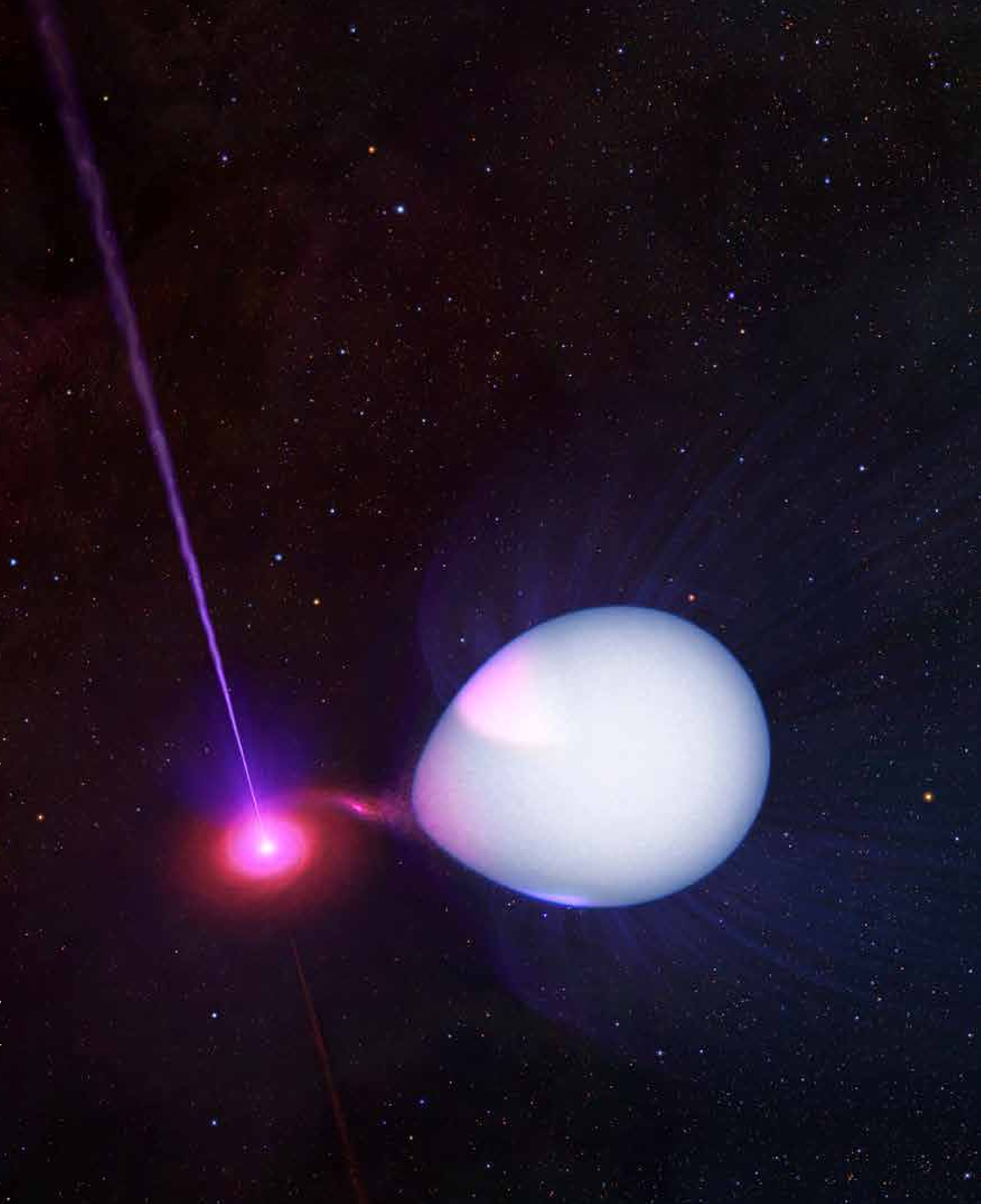
THE FOUNDATION FOR WHAT WE KNOW about black holes came during the Great War. Imagine the scene: December 1915. Europe and the world are struggling under the dark cloud of World War I. Somewhere on the eastern front, an older German artillery lieutenant huddles in his greatcoat, fighting to stay warm and dry at the bottom of a trench.

With numb and trembling fingers, he opens the latest dispatches from home. One particularly bulky package attracts his attention. That night, throwing caution to the wind, he risks using an electric light to read the long and detailed report. Little does he know that it will prove to be arguably the most important work of creative genius of the 20th century.

The author of this pivotal document was a theoretical physicist named Albert Einstein. The recipient was his colleague Karl Schwarzschild, the director of the Astrophysical Observatory in Potsdam and an accomplished theorist and mathematician. Despite his astronomical career, Schwarzschild, then in his 40s, joined the war effort.

Just weeks before, Einstein had completed 10 long years of dedicated work, successfully expanding his special theory of relativity to include gravitational forces along with electricity and magnetism. In four landmark papers published in the *Proceedings of the Prussian Academy of Sciences*, Einstein laid out the mathematical foundation of the general theory of relativity, still considered one of the most beautiful and elegant scientific theories of all time.

The pinnacle of this magnum opus was published November 25, 1915, with the concise title "The Field Equations of Gravitation." While perhaps a bit opaque to anyone without a firm grasp of tensor calculus, the field equations can be neatly summarized by the words of the great physicist John Wheeler: "Space-time tells matter how to move; matter tells space-time how to curve."



In this artist's depiction of Cygnus X-1, a stellar-mass black hole strips gas from the surface of its companion star as they orbit each other. Since the 1970s, it has since become the strongest black hole candidate, with scientists at near certainty that it is one. Initially detected in X-ray, it has since been studied in various other spectra. ADOLF SCHALLER FOR *ASTRONOMY*

Albert Einstein developed his theory of gravity, known as general relativity, in 1915. ALBERT EINSTEIN ARCHIVES

Karl Schwarzschild developed the idea for black holes from relativity's equations in 1916, just a year after Einstein published his theory. EMILIO SEGRE ARCHIVES

Much like M. C. Escher's famous picture of two hands sketching each other, the circular reasoning of Einstein's field equations makes them both elegant, yet also notoriously difficult to solve. At the root of this difficulty is Einstein's far more famous equation $E=mc^2$, which states that energy and matter are interchangeable. Because gravity is a form of energy, it can behave like matter, creating yet more gravity. Mathematically speaking, general relativity is a nonlinear system. And nonlinear systems are really hard to solve.

It's easy to imagine Einstein's shock when, amid a dreadful war, Schwarzschild wrote back within a matter of days, describing the first known solution to Einstein's field equations. Schwarzschild modestly writes, "As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas." Einstein responds, "I have read your paper with the utmost interest. I had not expected that one could formulate the exact solution of the problem in such a simple way. I liked very much your mathematical treatment of the subject."

Tragically, less than a year later, Schwarzschild succumbed to a skin disease contracted on the front, joining the millions of WWI fatalities due to disease. He left behind a solution that completely describes how space-time is warped outside a spherical object like a planet or star. One of the features of this mathematical solution is that for very compact, high-density stars, it becomes much harder to escape the gravitational field of the star. Eventually, there comes a point where every particle, even light, becomes gravitationally trapped. This point of no escape is called the event horizon. As one approaches the event horizon, time slows to a complete standstill.

For this reason, early physicists studying these bizarre objects often called them "frozen stars." Today, we know them by the name first used by Wheeler in 1967: black holes. Even though the event horizon played an integral part in Schwarzschild's solution, it took many years before black holes were accepted as anything other than a mathematical curiosity. Most of the world's leading experts in general relativity in the first half of the 20th century were absolutely convinced that black holes could never form in reality. Arthur Eddington insisted, "There should be a law of nature to prevent a star from behaving in this absurd way."

But the bizarre nature of these new branches of physics strained even the most gifted intuition, so that even 50 years after Schwarzschild's landmark paper, there was still no consensus on the existence of black holes.

Complicating the issue was the concurrent development of quantum mechanics, a new field almost entirely characterized by cases of nature behaving absurdly. Physicists working at the intersection of quantum mechanics and general relativity began to appreciate how both fields were critically important to understanding very massive and dense stars. But the bizarre nature of these new branches of physics strained even the most gifted intuition, so that even 50 years after Schwarzschild's landmark paper, there was still no consensus on the existence of black holes.

Finding the unseeable

One thing was clear: If black holes did exist, they were most likely formed by the collapse of massive stars, unable to support their own weight after running out of nuclear fuel. The question most astronomers were focused on was, "How do we find them?" After all, black holes give off no light of their own. Astronomy needs light, and to make light, you generally need matter — the hotter and brighter, the better.

Fortuitously, the late 1960s marked the dawn of X-ray astronomy with a series of sounding rockets and satellites that could get above Earth's atmosphere, which otherwise blocks out all celestial X-rays.

During a short rocket flight in 1964, astronomers discovered one of the brightest X-ray sources in the sky, in the constellation Cygnus, dubbed Cygnus X-1 (Cyg X-1 for short). However, it didn't coincide with any particularly bright optical or radio source, leaving its physical origin a mystery. When NASA's Uhuru X-ray Explorer Satellite was launched in 1970, more detailed observations became possible, narrowing the uncertainty of its location. One of the first remarkable discoveries was Cyg X-1's rapid variability, on timescales shorter than a second. This strongly suggested that the physical size of the X-ray-emitting region was quite compact, much smaller than a typical star. What could pack so much power into such a small area?

Within a year, a stellar counterpart to Cyg X-1 was identified, allowing astronomers to confirm it as a binary system and estimate the mass of the companion by measuring the Doppler shift of the orbiting star's spectrum. The answer was a whopping 15 times the mass of the Sun, far exceeding any theoretical limit for white dwarfs or neutron stars. Altogether, the rapid time variability, large X-ray luminosity, and high mass estimate combined to make Cyg X-1 an excellent candidate for the first stellar-mass black hole. (Strong evidence for supermassive black holes also had been building for years, thanks largely to Maarten Schmidt's study of quasars. Their tremendous brightness and great distances combined to make a strong case for black hole accretion, the only imaginable energy source capable of such incredible luminosity.)

Cygnus X-1 (the brighter of the stars by the arrow) lies in a rich field near the plane of the Milky Way, and doesn't look like much at visible wavelengths. NOAO/AURA/NSF

Cygnus X-1 first came to notice when astronomers found it to be an intense source of X-rays. In this view from the Chandra X-ray Observatory, the high-energy radiation is colored blue. NASA/CXC/CFA

As more sensitive X-ray telescopes were launched in subsequent years, the case only grew stronger. We have now seen X-ray variability from Cyg X-1 on timescales as short as a millisecond, confining the emission region to an extent of hundreds of kilometers, just a few times the size of the event horizon. By observing X-rays from black holes, we can directly probe the properties of space-time predicted by general relativity.

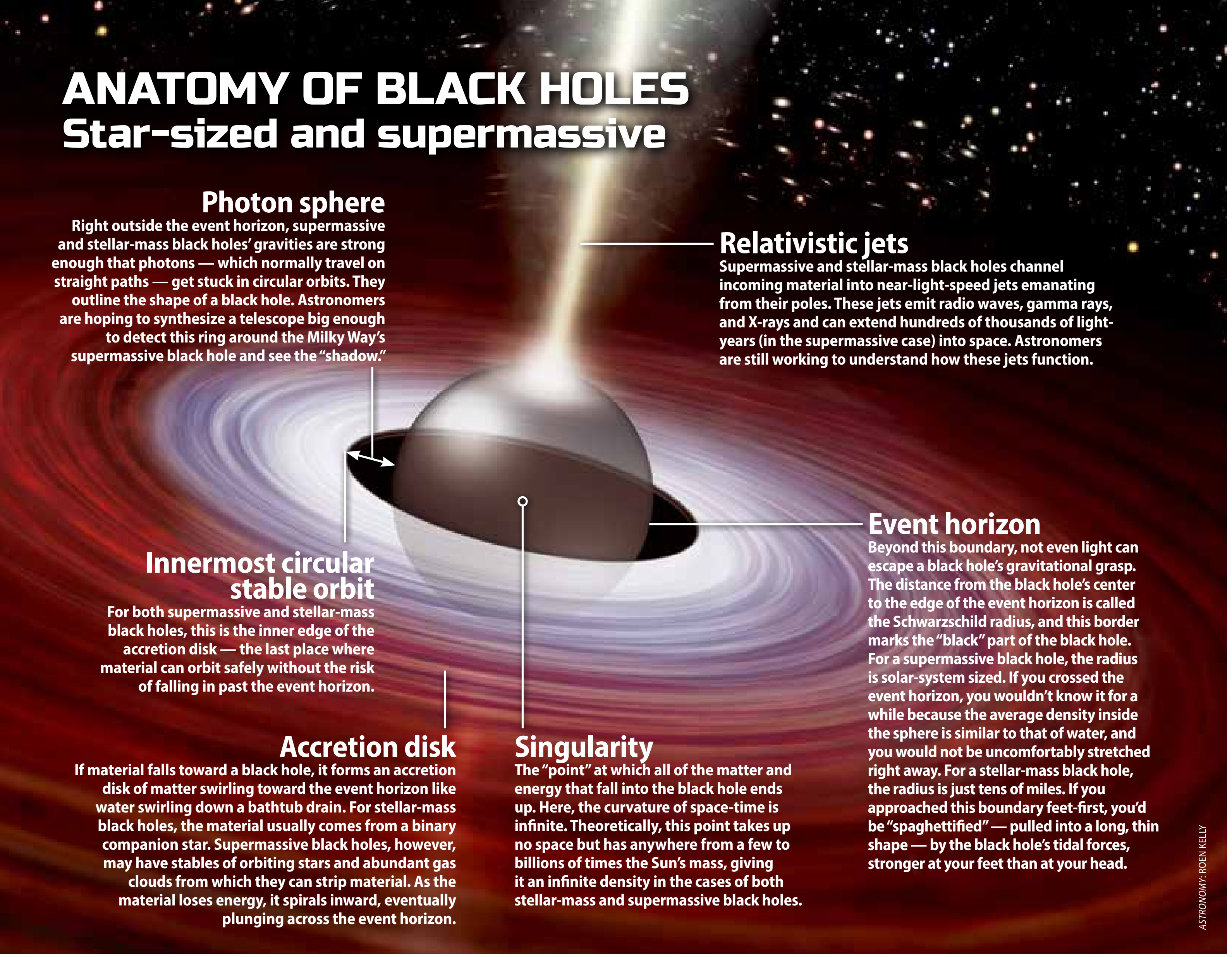
Staring down an event horizon

While stellar-mass black holes are some of the brightest X-ray sources in the sky, they are also some of the most fickle. In the 40-plus years since the discovery that Cyg X-1 is likely a black hole, only a few dozen more black hole candidates have been identified. Most of those have only been detectable during short, unpredictable outbursts lasting a month or so before they disappear again for decades. Compare that with their supermassive counterparts: The Sloan Digital Sky Survey alone has identified more than 100,000 quasars (the energetic centers of young, distant galaxies), each powered by an accreting supermassive black hole.

In addition to this most common "quiescent" behavior, astronomers have identified three other major states exhibited by stellar-mass black holes: hard, soft, and intermediate. These names describe the observable properties of the X-ray spectra in each state. We aren't yet entirely certain what physical mechanisms drive these different behaviors, but they are likely tied to two things: how much gas the black hole is accreting, and how strong the magnetic fields embedded in the gas are.

In astronomical jargon, a "hard" spectrum means we see more high-energy X-rays than low-energy, and "soft" is the opposite. Of course, even "low-energy" is a relative term, as these photons come from an accretion disk that is at a temperature of millions of degrees, compared with the corona, which boasts a temperature in excess of 1 billion degrees!

The intermediate state shows evidence of a thin, cool accretion disk surrounded by a hot, diffuse corona like the surface of our own Sun. In this state, the high-



energy X-rays coming from the corona shine down on the disk. Some of these X-rays get absorbed by the trace amounts of iron mixed in the disk's gases. The iron then shines just like the fluorescent gas in a neon light, giving off more X-rays at very specific wavelengths. Because the gas in the disk is orbiting the black hole at nearly the speed of light, the X-rays coming from the disk experience extreme Doppler shifts, appearing to a distant observer at shorter wavelengths when the gas is moving toward the observer and longer wavelengths when moving away. By carefully measuring the wavelengths of the X-rays from an accreting black hole, we can measure how fast all the gas is orbiting around it.

Original spin

Considering the first solution to Einstein's field equations took Schwarzschild less than a week to derive, it must have felt like an eternity to wait nearly a half-century before the next black hole solution was discovered by New Zealander Roy Kerr in 1963. (Another solution, the Reissner-Nordstrom black hole, was published almost immediately after Schwarzschild's, but also is limited to spherically symmetric systems and mathematically almost identical.) Kerr made his formulation while at the University of Texas at Austin.

Unlike Schwarzschild black holes, Kerr black holes spin; they retain the angular momentum from the pre-supernova star from which they were born. This is extremely important astrophysically, since we know that nearly every celestial object rotates, from moons to planets to galaxies. So it is natural to expect that black holes rotate, too.

Evidence for this spin shows in how the black hole pulls everything around the horizon, essentially sweeping up space-time itself into a swirling vortex. This allows gas to move ever faster as it spirals closer and closer to the horizon, leading to more extreme Doppler shifts, and thus larger offsets in the X-ray spectra. In just the past few years since the launch of NASA's NuSTAR X-ray telescope, we have been able to use these spectra to measure spins of multiple black holes with unprecedented accuracy. NuSTAR's ability to see X-rays covering a much wider range of energies compared with previous missions also allows us to rule out other alternative models — like X-ray absorption by interstellar gas clouds — that had been proposed to explain the shape of the spectrum.

Measuring black hole spins not only teaches us about general relativity, but it also provides important insight into how massive stars evolve and collapse in supernovae. Because many of these binary systems are quite young (at least by cosmic standards — Cyg X-1 is "only" a few million years old), whatever spin we measure today is essentially the same spin that came from the original formation. From this point of view, they truly are "frozen stars," retaining a near-perfect memory of their violent birth.

An outrageous legacy

General relativity is one of the few fields in modern physics where theory has driven experimentation for almost the entire century. Einstein had a unique talent for not only proposing brilliant and fruitful thought experiments, but also real experiments that could test his theories. Perhaps his most famous prediction was how the gravity of the Sun would deflect the light from distant stars, an effect confirmed with spectacular success in 1919 during a solar eclipse, propelling Einstein to international celebrity. More impressive still was the 40-plus years between Schwarzschild's (unintentional) prediction of black holes and the discovery of Cyg X-1.

To borrow a phrase from theoretical physicist Kip Thorne, perhaps the most outrageous piece of Einstein's legacy was his prediction of gravitational waves, made a century ago, and triumphantly confirmed just this year by the Laser Interferometer Gravitational-wave Observatory (LIGO). In addition to confirming the basic idea that the "fabric" of space-time is not just a metaphor but a tangible substance, the LIGO discovery also provided a new test of general relativity in the most extreme environment — just outside a black hole. There were some surprises in store, as well: the discovery of stellar-mass black holes 30 times the mass of the Sun, twice as big as any seen before. For the cherry on top, LIGO was even able to measure the spin of the final black hole at 70 percent of the maximum Kerr limit, arguably the most accurate and precise measure of spin to date.

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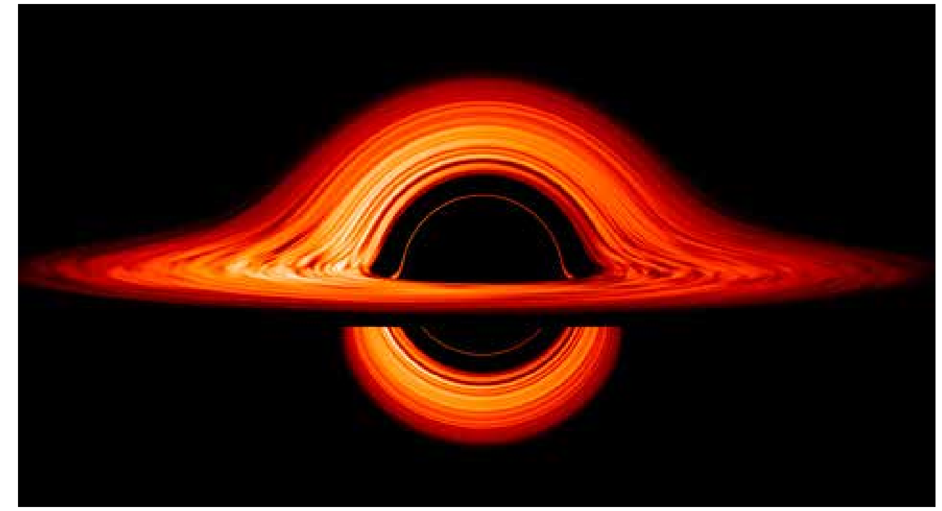
Building on this unprecedented track record of success, most astrophysicists fully believe that general relativity's description of the nature of black holes is the correct one. Lingering questions attempt to use our knowledge of black holes to improve our understanding of how gas, magnetic fields, and X-rays behave in the presence of such a tremendous gravitational force. This is the messy part of black hole research — Astronomer Royal Martin Rees famously described it as "mud wrestling" — and one where observation has been far ahead of theory for decades.



This simulation gives a realistic depiction of a black accretion disk, including the light-bending effects of relativity. NASA/JEREMY SCHNITTMAN

The first puzzle came right on the heels of the first detection of Cyg X-1. In 1973, from the most basic laws of conservation of energy and angular momentum, Igor Novikov and Kip Thorne derived a brilliant and elegant description of how gas slowly spirals in toward a black hole, releasing its gravitational potential energy as heat and radiation at temperatures of millions of degrees.

There are only two problems with the Novikov-Thorne model: It doesn't work in theory, and it doesn't work in practice. It doesn't work in theory because it doesn't explain how exactly the gas loses angular momentum. It doesn't work in practice because it doesn't agree with observations of high-energy X-rays coming from billion-degree gas.

Hot ionized gas experiences almost no friction or viscosity, so it should simply go around and around on perfectly circular orbits forever, never getting any closer to the event horizon. Novikov and Thorne fully appreciated this problem, and they absorbed it into their theory with a simple fudge factor, leaving the details to later work. In the end, it took almost 20 years to find the answer. In 1991, Steve Balbus and John Hawley discovered a powerful instability that comes from the twisting and pulling of magnetic field lines embedded in an accretion disk. Ionized gas is an excellent electrical conductor, which means it also can generate powerful magnetic fields. These fields, in turn, can pull back on the gas, slowing it down and allowing it to spiral in toward the black hole.

By 2001, supercomputers had become powerful enough to adequately simulate the Balbus-Hawley instability in accretion disks around realistic black holes, fully confirming their predictions. It took yet another decade before the simulations were sophisticated enough to include the effects of radiation, and study the interplay between the disk and corona. In doing so, we have finally reached the point where, starting from the most fundamental laws of nature, we can explain how the high-energy X-rays, first seen in 1971, are actually generated around real black holes.

In exactly 100 years, black holes have progressed from being a mathematical curiosity, to the subject of purely theoretical physics, to a central area of astronomy research, where theory and computer simulations confront experiments and observations on a daily basis. With the recent opening of the gravitational-wave window on the universe, in the coming years we fully expect to learn even more about the birth, life, and death of these remarkable objects. One thing we can say for certain: We will continue to be surprised by nature's exotic imagination!

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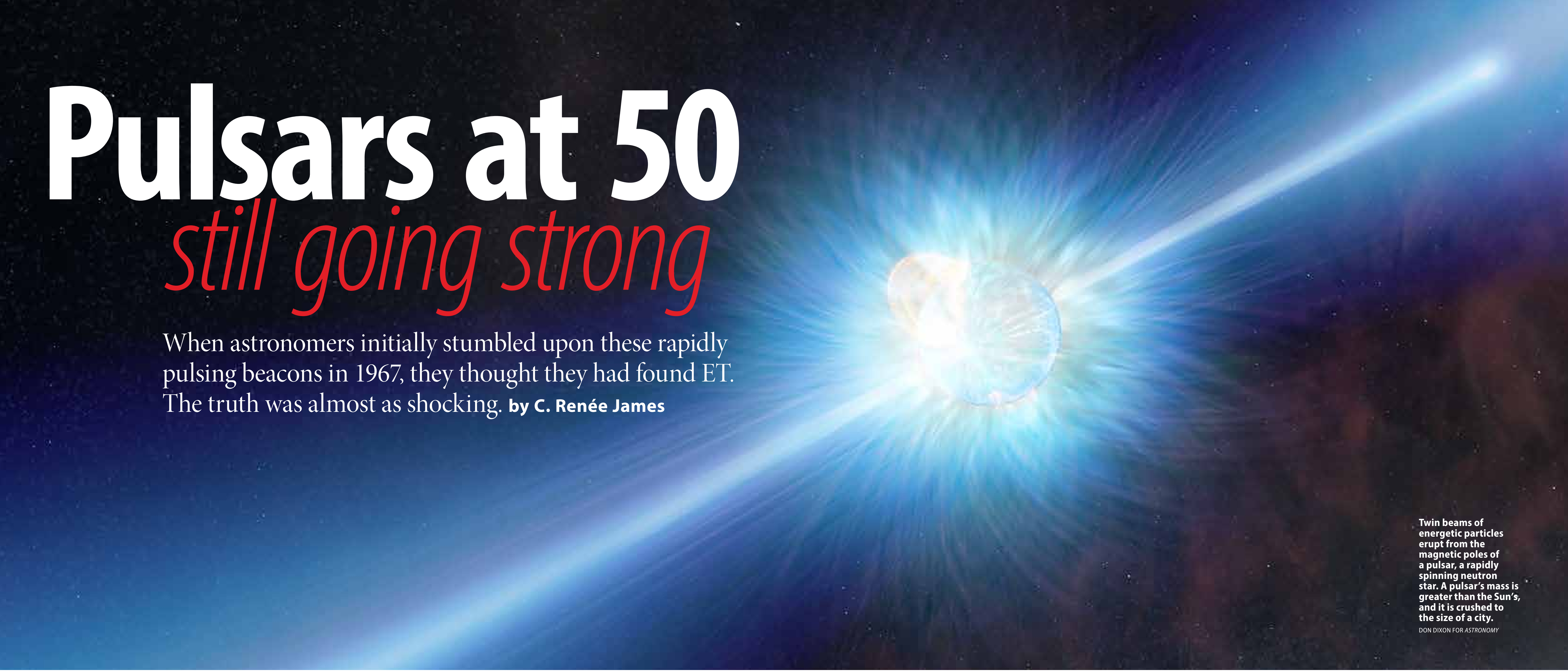
Pulsars at 50
still going strong

When astronomers initially stumbled upon these rapidly pulsing beacons in 1967, they thought they had found ET. The truth was almost as shocking. **by C. Renée James**



Twin beams of energetic particles erupt from the magnetic poles of a pulsar, a rapidly spinning neutron star. A pulsar's mass is greater than the Sun's, and it is crushed to the size of a city.
DON DIXON FOR *ASTRONOMY*

Fifty years ago, an unassuming bit of "scruff" appeared in Jocelyn Bell Burnell's radio telescope data. Although barely noticeable at first, the scruff quickly led to two Nobel Prizes, provided evidence that Albert Einstein's general relativity was right, rode on humanity's first interstellar vehicle, and became the inspiration for a watch, a car, and an album cover.

The objects revealed by the scruff — dubbed "pulsars" — turned out to be smaller than a city but more powerful than the Sun. And if everything goes right, they soon will help us detect the most colossal events in the cosmos and even help us navigate to the stars.

Despite its meteoric rise to fame, the pulsar had an unpromising start. In July 1967, Bell Burnell noticed a quarter-inch-wide radio signal barely rising above the background noise on the recordings. It would have been easy for anyone else to ignore, but Bell Burnell had almost single-handedly strung 120 miles of wire to create the 4.5-acre radio telescope at Mullard Radio Astronomy Observatory near Cambridge, England, making her fast friends with everything it had ever picked up. She was not about to let anything escape her attention, no matter how scruffy.

Fortunately, the scruff showed up more than once. In fact, as she pored over the miles of charts, the keen-eyed graduate student spotted the signal on about 10 percent of the printouts, arriving four minutes earlier each day. Keeping time with the stars, the source definitely was not terrestrial. But what was it?

She persuaded her Ph.D. adviser, Antony Hewish, to speed up the paper feed so she could better scrutinize the odd signals. For weeks, miles of charts streamed through. As the piles of paper grew, so did Hewish's frustration. Finally, on November 28, 1967, as they were about to pull the plug on the search, the signal returned.

Now, instead of a bit of scribbly fuzz, a series of regularly spaced shallow bumps appeared, each separated from its neighbors by 1.3373 seconds. These precisely timed, rapid radio blips telegraphed information about uncharted astrophysical territory. Because known stars could not change brightness so rapidly, the scientists knew they were looking at an unfathomably dense, small object. Or did they dare suggest, could it be something artificial?

LGM or not?

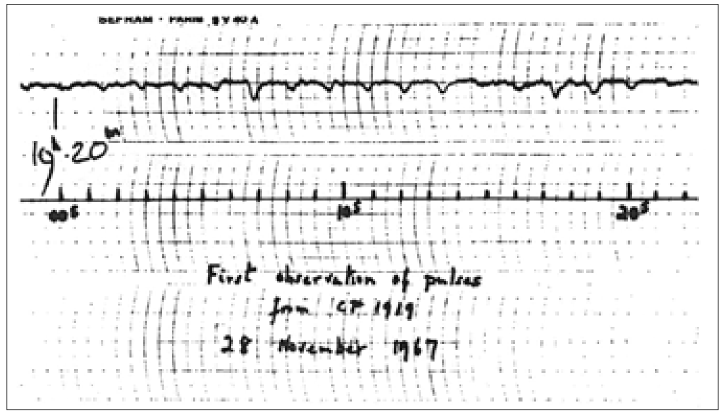
Although Bell Burnell and Hewish agreed that the latter explanation was highly unlikely, unusual signals are a siren song to astronomers. Despite healthy skepticism, most people are open to the possibility that someone, or something, in this vast universe might try to make contact. And so Bell Burnell gave the object the tongue-in-cheek nickname "LGM-1," for "Little Green Men."

The next step was to look for Doppler shifts, telltale changes in the signal's wavelength that let astronomers know an emitting object's comings and goings. These new data would let them know if the signal had been broadcast from a planet orbiting a star. Before that investigation even got off the ground, however, another similarly regular signal joined LGM-1. Then another. And another.

At that point, Bell Burnell recalls, they gave up on the idea of aliens. "It was extremely unlikely that there would be four separate lots of Little Green Men, all, at

C. Renée James *is a science writer and physics professor at Sam Houston State University in Huntsville, Texas. Her latest book is* Science Unshackled: How Obscure, Abstract, Seemingly Useless Scientific Research Turned Out to Be the Basis for Modern Life *(Johns Hopkins University Press, 2014).*

Jocelyn Bell Burnell appears in front of one of the large radio telescopes at Cambridge University's Mullard Radio Astronomy Observatory in 1968. CAMBRIDGE UNIVERSITY



Above: This bit of "scruff" — the slight dips seen in the top row of data — represents Jocelyn Bell Burnell's initial detection of pulses from the pulsar CP 1919+21 (now known as PSR B1919+21) from November 1967. CAMBRIDGE UNIVERSITY

Left: Jocelyn Bell Burnell stands among the more than 1,000 posts and 120 miles of wire and cable that formed the radio telescope she used to discover pulsars in the late 1960s. CAMBRIDGE UNIVERSITY

the same time, signaling to the inconspicuous planet Earth using a stupid frequency and a daft technique," she said.

Although the signal proved not to be an extraterrestrial greeting, it was a tremendous astronomical discovery in its own right. The researchers soon found out that whatever it was, it kept time to better than 1 part in 10 million, either rotating or pulsating (they weren't sure which) more than 60,000 times per day. On top of this, it was emitting enough power across interstellar distances to be detected even by 1967 instruments.

The neutron star connection

This sort of activity required a phenomenal source of energy. Astronomers Fritz Zwicky and Walter Baade hinted at one back in 1934, when they hypothesized that an exploding massive star — they called it a "supernova" — might leave behind a dense core composed mainly of neutrons.

It was a wild idea with seemingly little chance of verification. How would anyone ever detect a city-sized ball of neutrons, even one at a temperature of a million degrees? For the most part, astronomers ignored Zwicky and Baade's prescient paper and quietly assumed that massive stars died by blowing themselves to smithereens.

Then came LGM-1, which soon became CP 1919+21 and ultimately PSR B1919+21. If the object were physically pulsing, growing and shrinking, Bell Burnell and Hewish computed a density equivalent to a mountain squeezed into a thimble: 10 trillion grams per cubic centimeter, the same density as a ball of neutrons.

Since it was a pulsating signal from a stellar source, science journalist Anthony Michaelis christened the object a "pulsar" in 1968. Although scientists were still several months from understanding whether the object was pulsating or rotating, the moniker stuck.

It was admittedly a catchy name. Less than three years after Bell Burnell's discovery, the Hamilton Watch Co. began developing the Pulsar watch, capitalizing on nature's seemingly perfect timekeepers. The first Nissan Pulsar, which was — what else? — a compact car, rolled off the assembly line in 1978.

In 1979, pulsars slipped effortlessly and largely unrecognized into popular culture. Next to the entry in the 1977 edition of *The Cambridge Encyclopedia of Astronomy* was an image of successive stacked pulse profiles from PSR B1919+21. The simple but enigmatic portrait of squiggles might have remained in that

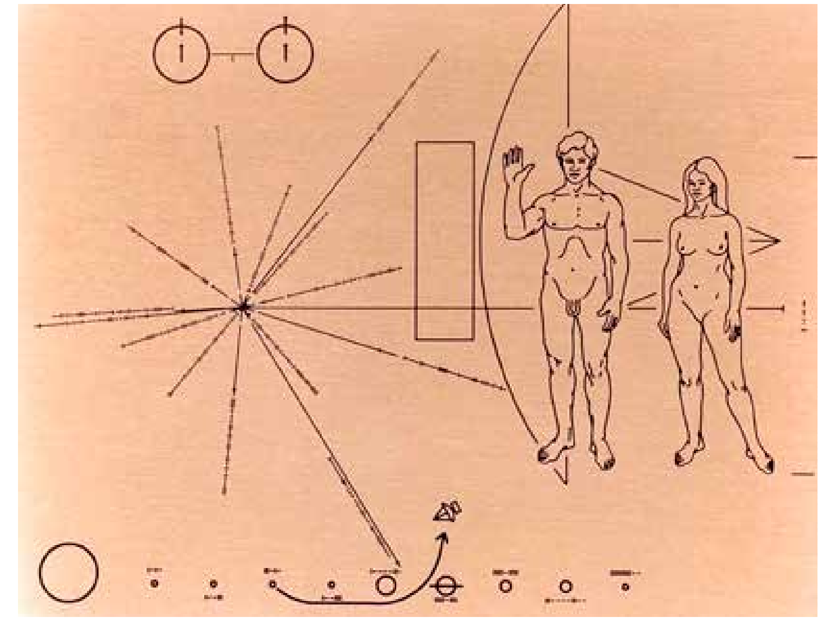
AN EARLY WARNING OF PULSARS

U.S. Air Force Staff Sgt. Charles Schisler knew something was odd in the radar signals he was monitoring. It was summer 1967, and the signal had been showing up for weeks, keeping time with the stars by rising four minutes earlier each night.

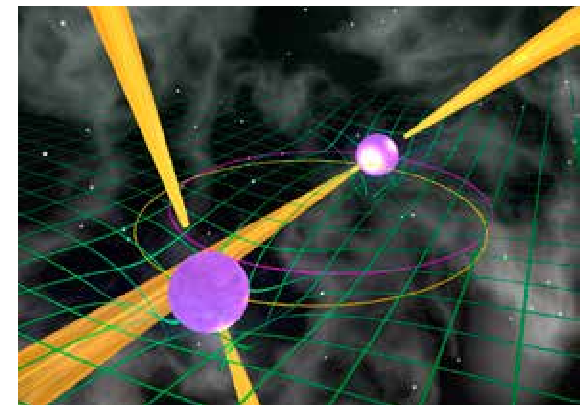
Unfortunately, his employer wasn't at all interested in this sort of signal. The Ballistic Missile Early Warning System at Clear Air Force Station in Alaska was built to detect incoming warheads, not pulsars. As a result, Schisler wasn't at liberty to announce his discovery or do any formal follow-up observations.

It wasn't until 40 years later that information from the Early Warning System became declassified, and Schisler felt comfortable revealing that he had observed not just one pulsar, but a dozen or so. Even then, Schisler was quick to point out that his detections never hinted at the pulsing nature of these sources, a key to understanding the objects responsible for the signals. That honor still goes to Jocelyn Bell Burnell. — *C. R. J.*

These enigmatic squiggles represent pulses from CP 1919+21 recorded with the Arecibo radio telescope. Harold Craft Jr. created this visualization for his doctoral thesis. It became a part of pop culture when Joy Division used it on the cover of the band's debut album, *Unknown Pleasures*. HAROLD D. CRAFT JR.



Top: The Pioneer 10 and 11 spacecraft each carried a plaque describing the Sun's location for any extraterrestrial intelligence that might find the probe. Carl Sagan and Frank Drake used the positions and periods of 14 pulsars (the lines emanating from the star left of center; the horizontal 15th line gives the direction to the Milky Way's center) to mark the spot. NASA



Above Left: PSR J0737–3039 is the only known double pulsar, a binary system in which both objects are pulsars. The two orbit each other once every 2.45 hours. Scientists are using the pair, illustrated here along with the underlying fabric of space-time, to test Einstein's theory of general relativity. MPIfR/M. KRAMER

encyclopedia and in obscure journal articles if it hadn't caught the eye of Peter Saville, who decided that it would make the perfect cover art for Joy Division's 1979 album *Unknown Pleasures*. These days, plenty of people recognize the image that's been featured on everything from T-shirts to tattoos, but few realize it represents the first pulsar discovered.

So what exactly are these objects that have captured the attention of astronomers, watchmakers, car companies, and album art designers? The simplest description is that they are rapidly rotating, highly magnetized, city-sized, collapsed cores of dead, high-mass stars — the neutron stars Zwicky and Baade proposed.

But this portrayal utterly fails to convey the bizarre and extreme character of a pulsar. Nature crams up to three times the mass of the Sun into its tiny volume, making its surface gravity second only to that of a black hole. Its magnetic field strength can be a quadrillion times Earth's, far exceeding anything scientists can create in a laboratory.

This mega-magnetism whips up charged particles in the vicinity, causing them to swarm around the magnetic poles and emit beams of intense radiation. These beams become a sort of lighthouse beacon, sweeping across the universe as the neutron star spins. On the off chance that Earth happens to lie in the beam's path, we see a quick blip with every rotation.

Pulsars are laboratories of extreme physics, and their discovery opened up an entirely new field. The find was so significant that just seven years later, Hewish would share the Nobel Prize in Physics "for his decisive role in the discovery of pulsars." The exclusion of Bell Burnell, who treated even the smallest, most unusual bit of data as significant, has been hotly debated ever since.

Astronomers estimate that up to a billion massive-star remnants should exist in the Milky Way, but only a million or so are pulsars. So far, only about 2,300 have turned up. Pulsars aren't permanent, after all. As the rotation, magnetic field, and local supply of electrons peter out over a few million years, so does the lighthouse beam. During a human lifetime, however, a pulsar's timing is typically as precise as an atomic clock's, changing by about a billionth of a second per year.

The presence of a stellar companion, though, can wind them up and turn them into even better timing devices. In 1982, astronomers discovered the first millisecond pulsars, objects whirling around at more than 100 times per second. The current record belongs to PSR J1748–2446ad, which rotates 716 times per second. Not merely curiosities, these speed demons may help future astronauts find their way.

Toward a pulsar GPS

Astronomers hatched the idea to use pulsars as navigation tools on the heels of their discovery, but in 1972, it literally was etched in gold. As scientists were putting the finishing touches on the Pioneer 10 spacecraft for its journey through the solar system and beyond, they wondered if they could convey the craft's "home" to any extraterrestrials it might come across. If only there were some way to indicate our position relative to

A pulsar spinning 30 times per second powers the emission from the Crab Nebula supernova remnant (M1). The pulsar is the bright dot in the heart of the central, hollowed-out region. This composite image shows visible light as red and X-ray radiation as blue. NASA/HST/CXC/ASU/J. HESTER ET AL.

objects with precisely known properties, like a sort of galactic GPS.

"Pulsars are the obvious answer," Carl Sagan declared. And with just three weeks left to design and etch the gold plaque that would ultimately be affixed to Pioneer 10 and its twin, Pioneer 11, he and Frank Drake created a map of the Sun relative to 14 pulsars. They also included a code indicating universal constants that intelligent aliens should be able to decipher. With the map and the spin-down rate of each pulsar, extraterrestrials would know not only where we are, but also when we launched the probe.

Maybe. "The data for one pulsar on the plaque is wrong, and so the aliens would need to sort that out!" jokes pulsar researcher George Hobbs at Australia's Commonwealth Scientific and Industrial Research Organization.

What about us? Could we ever use pulsar GPS as we leave the safety of Earth? Our current GPS, which uses Earth-orbiting satellites, obviously wouldn't help us navigate to Mars, much less to other star systems. Looking to the future, Hobbs and his colleagues have explored the feasibility of using pulsars as navigation tools.

The idea is straightforward in principle. On Earth, we know when to expect pulses from pulsars. And because light takes time to travel, those arrival times depend on our exact location. Complicating matters is the fact that pulsars, well, pulse — frequently. The universe hosts an infinite number of places where you can expect a pulse from a given pulsar at a particular time, but by observing several pulsars, you can quickly narrow the set of places you might be.

It takes a bit of computational gymnastics to settle on the right one, but Hobbs and his colleague You Xiaopeng have performed those acrobatics with data from millisecond pulsars and successfully pinpointed the location of the 64-meter Parkes radio telescope in Australia to within 0.6 mile (1 kilometer). They even confirmed that Earth revolves around the Sun, just in case anyone was still on the fence about that.

"The main challenge is being able to detect pulsars without a huge telescope," says Hobbs. "Of course, you're not going to launch the Parkes telescope into space!"

Even if you did, it wouldn't be of much use. A single radio dish can observe only one pulsar at a time, but, as is the case with terrestrial GPS, you need simultaneous information from several different clocks. A single X-ray telescope might do the trick, however, and several teams around the globe have jumped on the X-ray pulsar navigation bandwagon.

"The Europeans seem to have a crazy package to see if they can navigate aircraft [with pulsars]," says Hobbs. "And the Americans and Chinese are both undergoing research into deep-space navigation with pulsars."

A time for pulsars

Pulsar timing should prove useful for more than navigation. When he's not wrestling with issues of pulsar GPS, Hobbs and others are looking to these neutron stars to help us listen in on the most gargantuan cosmic events.

We can thank Einstein for the idea that our universe is an interwoven tapestry of matter, space, and time. According to his theory of general relativity, when matter moves, the rest of the tapestry ripples predictably in response. On September 14, 2015, the Laser Interferometry Gravitational-wave Observatory (LIGO) directly detected gravitational waves for the first time. Two black holes, each about 30 times the mass of the Sun, collided over a billion years ago, causing space to literally (and measurably) contract and expand.

But many people aren't aware that pulsars have been whispering rumors about gravitational waves for decades, giving astronomers confidence that they would ultimately detect them directly. In 1974, Russell Hulse and Joseph Taylor Jr. at the University of Massachusetts, Amherst, announced the discovery of a pulsar in orbit around another non-pulsing neutron star. It was the first of its kind: two extreme objects locked in a frantic dance, whirling around each other every 7.75 hours. The system pulls relentlessly at the fabric of the universe, which, in turn, saps energy from the pair. The lost energy spreads into the universe as gravitational waves.

The scenario might sound vaguely familiar. This binary pulsar — PSR B1913+16 — is performing a small-scale version of the tarantella executed by LIGO's famed colliding black holes. Long-term observations show that PSR B1913+16's orbit is shrinking by about 3.2 millimeters per circuit, with the two neutron stars scheduled to collide in just 300 million years. The system provides researchers with an extreme gravitational laboratory, one for which Hulse and Taylor received the 1993 Nobel Prize in Physics.

Pulsars probe gravitational waves

Pulsars can do more than merely insinuate the existence of gravitational waves, however. Because rotating neutron stars make exquisite clocks, they can be the endpoints of a galactic LIGO setup. LIGO detects passing gravitational waves by measuring how they compress and stretch the instrument's arms. These waves should do the same to the space between pulsars and Earth. Astronomers would then measure subtle variations in the pulse periods, and those changes would depend on the pulsar's direction. LIGO has only four observational arms: two in Livingston, Louisiana, and two in Hanford, Washington. With pulsars, astronomers can have as many observational arms as there are observed pulsars.

It's an elegant and simple plan, one that officially got underway more than a decade ago with the creation of the International Pulsar Timing Array (IPTA). But IPTA is after much bigger quarry than the stellar-mass black hole mergers seen by LIGO. It's trying to listen in on collisions of supermassive black holes. Paradoxically, this task is even more challenging than detecting the mergers of star-sized black holes.

Paul Lasky, a member of both gravitational wave teams, explains the process: "When two galaxies collide, the black holes in their cores will eventually sink to the center of the merged galaxy, and those two black holes will eventually merge themselves." It would seem that the sheer magnitude of such an event would make it easy to detect, but the resulting gravitational waves would have a phenomenally low frequency.

"The period of the waves is approximately one to 10 years," says Lasky. "This means that you need to observe for that amount of time to actually detect a single period." So even with a decade of observing under their belts, astronomers aren't too concerned that IPTA has yet to detect a merger of supermassive black holes.

There is one puzzling gap in IPTA's results, however. If you throw a large rock into a perfectly calm pond, you will see symmetric ripples radiate from the entry point. But the universe has thrown lots of rocks of varying sizes into the cosmic fabric over billions of years, and that should create a jumble of interacting ripples, or what scientists call the stochastic background. "The fact that we have not seen this stochastic background in more than a decade of observations is slightly at odds with theoretical predictions," says Lasky.

Still, with the resounding success of LIGO, gravitational wave scientists now can look more deeply into phenomena that until recently were on the fringe of observational astronomy, just as pulsars were a half-century ago. And there is every reason to believe that in the next 50 years, pulsars will continue to play a starring role in our understanding of the universe.

Not bad for a bit of scruff.

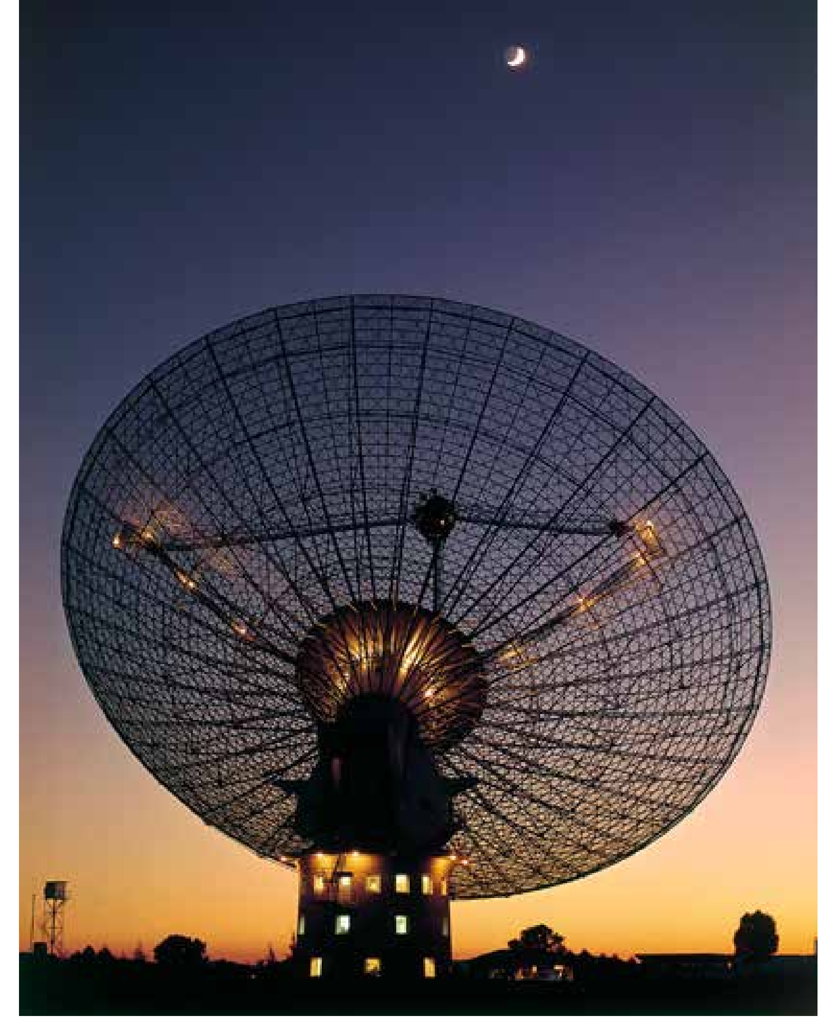
THE PULSAR HOUND OF PARKES

Although it was up and running by 1961, the 64-meter Parkes radio telescope in New South Wales, Australia, was not the first to find evidence of pulsars, or even ferret out the first millisecond pulsar. In fact, the radio scope, nicknamed "The Dish," came quite late to the pulsar game.

The telescope — one of the antennas that received the Apollo 11 TV transmissions from the Moon — amassed just eight pulsar discoveries by 1973 and added only about 300 more over the next quarter-century. But once scientists installed a new receiver in 1997 that provided much wider sky coverage, The Dish leapt into action. It would detect more than 100 pulsars per year for the next seven years, outpacing all other radio observatories put together.

The Dish's most significant discovery arguably came in 2004, when it revealed a double pulsar system. A step beyond Hulse and Taylor's pulsar-neutron star binary, the double pulsar allows astronomers to probe Einstein's general relativity further while exploring an eclipsing pulsar system.

All told, The Dish has discovered about two-thirds of the 2,300 or so known pulsars. In addition, it plays a leading role in the International Pulsar Timing Array, the development of pulsar GPS, and bringing pulsar science to a new generation through PULSE@Parkes, an educational program for high school students. — *C. R. J.*



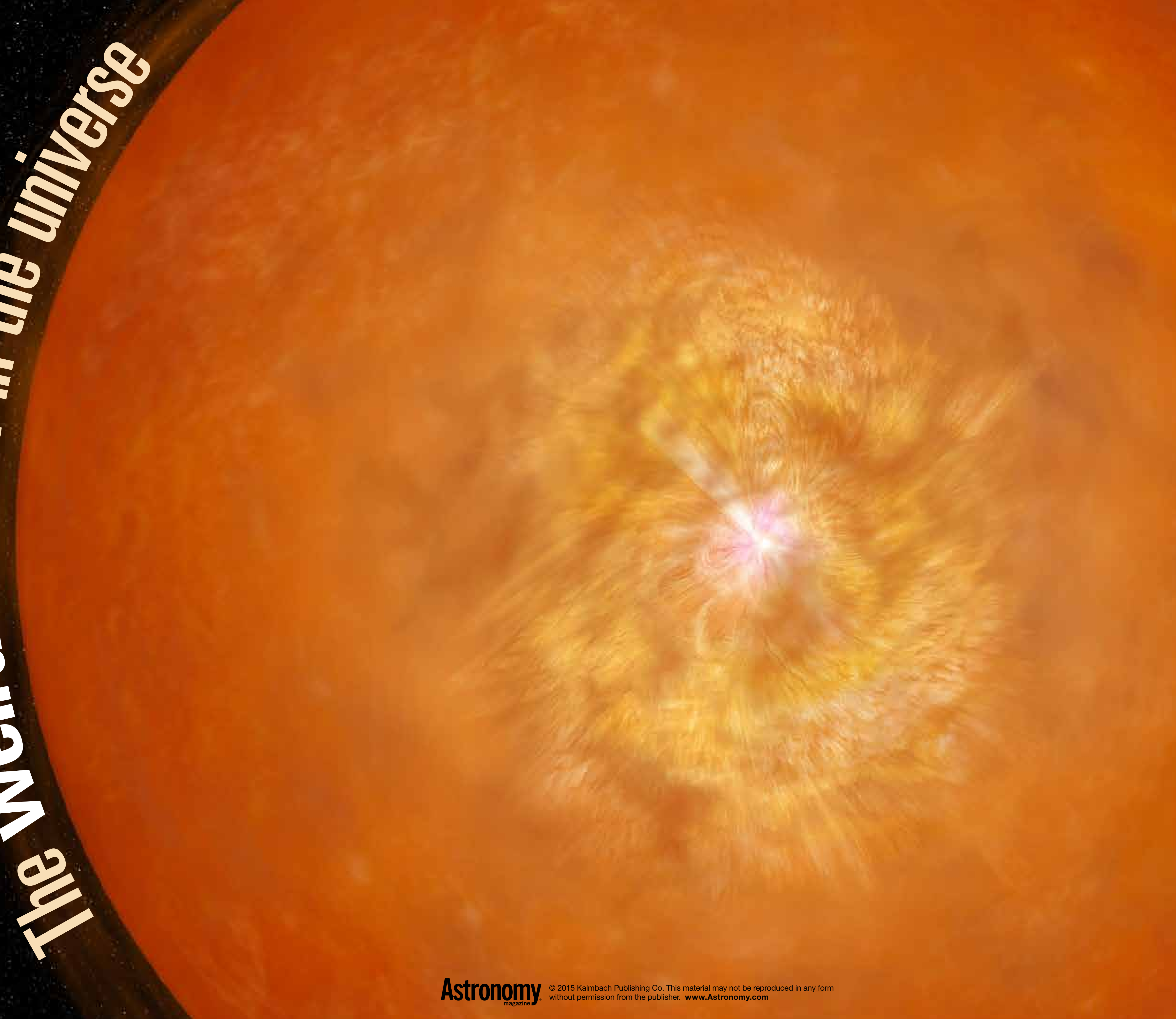
The 64-meter Parkes radio telescope — aka "The Dish" — has discovered about two-thirds of our galaxy's known pulsars. CSIRO

The weirdest star in the universe

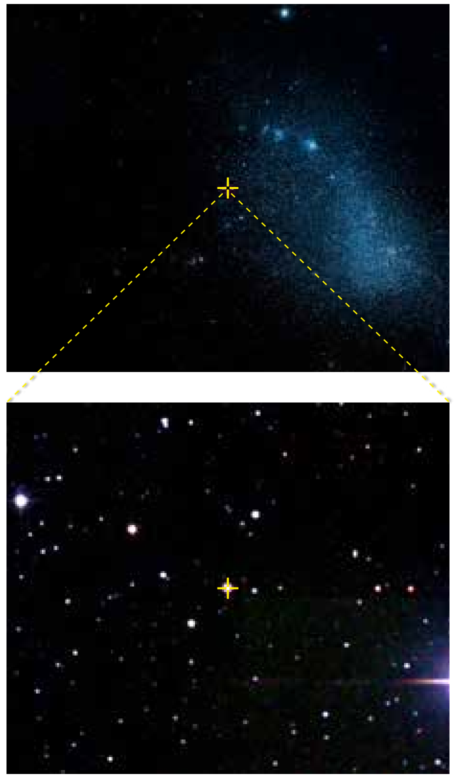
Astronomers dreamt up the idea of Thorne-Żytkow objects — dead stars inside dying stars — in the 1970s. Only recently have they tracked one down.

by Yvette Cendes

In an infinite universe, even the most bizarre thought experiments by astronomers — perhaps conceived late at night, perhaps proposed simply to see how weird stars can get — can come to pass. Imagine a massive star, near the end of its life and puffed up to the red supergiant phase, with a tiny neutron star, the skeletal remnant of an even more massive star, at its core. No one knows quite how this Frankenstar might form or how long it would live, and the fusion process would be anything but normal, yet the physics checks out. This mysterious star, called a Thorne-Żytkow object (TZO), could exist. But does it? Amazingly, 40 years after its conception, astronomers think they might have found one of these stars, and it has the potential to upend our understanding of stellar evolution.



A neutron star — the tiny (not to scale here), mostly dead remnant of a massive star — hidden inside a dying red supergiant becomes an entirely new stellar oddity called a Thorne-Żytkow object.
DON DIXON FOR *ASTRONOMY*



▲ **Emily Levesque and collaborators used the 6.5-meter Magellan II Clay Telescope at Las Campanas Observatory in La Serena, Chile, to observe the spectrum of HV 2112 and unlock its hidden nature as a Thorne-Żytkow object.** LAS CAMPANAS OBSERVATORY/CARNEGIE INSTITUTE OF WASHINGTON

◄ **At first glance, HV 2112 looks like an ordinary — if bright — red supergiant, shining clearly in this Spitzer infrared image of one corner of the Small Magellanic Cloud.** SPITZER/JPL/NASA/CENTER DE DONNÉES ASTRONOMIQUES DE STRASBOURG

A working theory

TZOs are named after Kip Thorne and Anna Żytkow, two astronomers who worked out detailed calculations of what this strange system would look like in 1977 at the California Institute of Technology. They proposed a completely new class of star with a novel, functional model for a stellar interior. Scientists had explored the idea of stars with neutron star cores when neutron stars were first thought of in the 1930s, but their work lacked a detailed analysis or any firm conclusions.

The origin of a TZO goes like this: For reasons not yet clear, the majority of the massive stars we observe in the universe are in binary systems. These stars are several times more massive than our Sun (at least eight times bigger, though stars as large as hundreds of solar masses have been observed) and spend their fuel much more quickly. The largest stars in the universe burn all their fuel in just a few million years, while a star the size of our Sun burns for several billion. In a binary system where the two stars' masses are unequal, then, the larger of the two runs out of fuel and dies before its partner. The massive component explodes in a fiery supernova as bright as an entire galaxy. When the fireworks are over, this future TZO system is already exotic — the normal, lower-mass star is now paired with a rapidly rotating neutron star with a radius as tiny as 6 miles (10 kilometers), composed entirely of neutrons packed so tightly that they test the extremes of quantum mechanics.

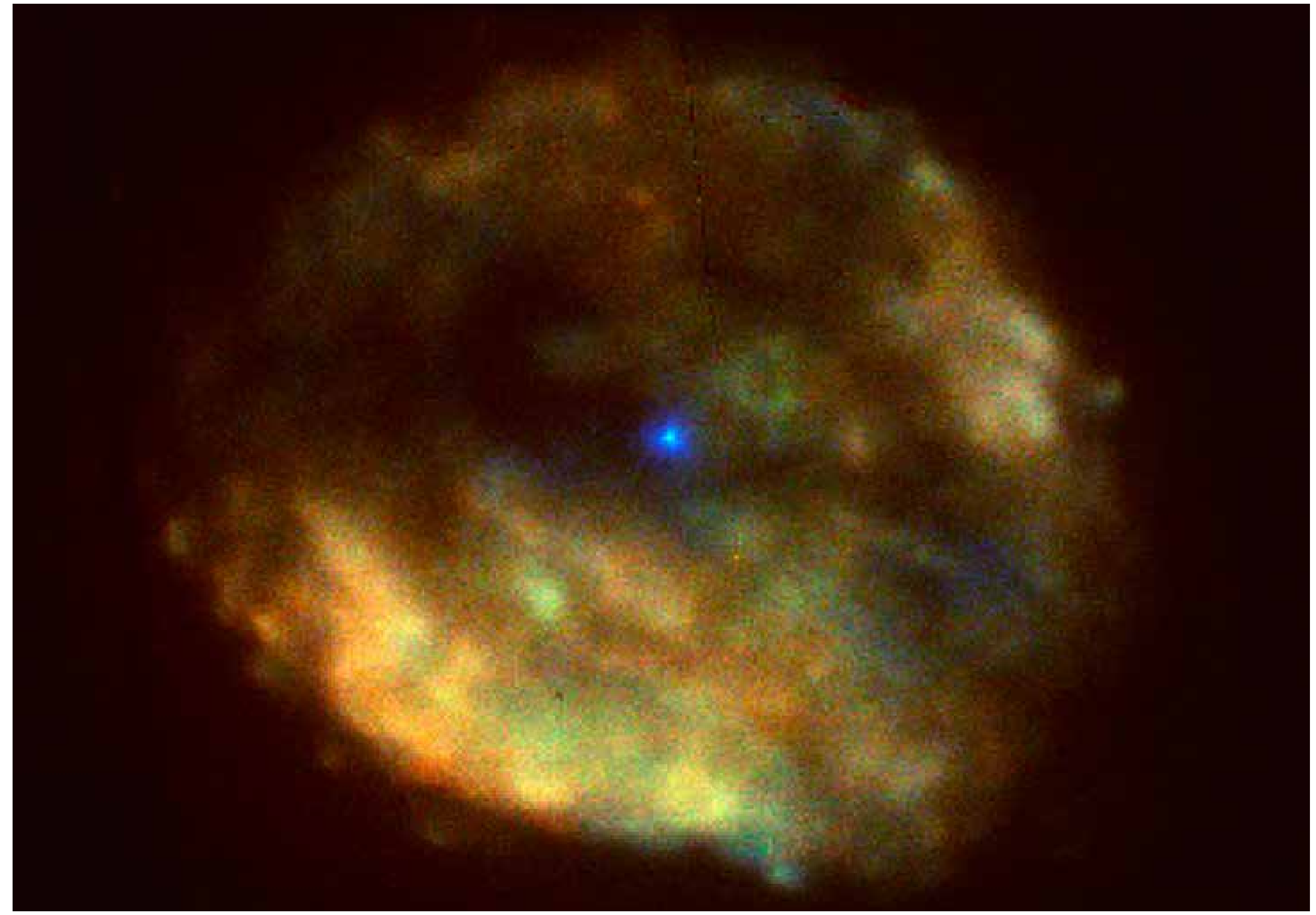
TZOs are important because they have the potential to tell astronomers where some of the more exotic elements in the universe come from.

Astronomers already have observed many such neutron star/normal star systems. As the two orbit each other, gas from the normal star can flow onto the outer layers of the neutron star, causing bright X-ray flares. These flares are millions of times more luminous than the X-rays emitted by normal stars and are in fact some of the brightest sources of X-rays in our galaxy.

But such systems raise a question: What ultimately happens to a system where a neutron star and a regular star orbit each other, but their orbits are unstable? This could occur for a variety of reasons, such as the supergiant's puffed-off gas layers dragging down the neutron star and causing it to spiral in or as a result of the supernova explosion that tore apart the first star. In many cases, the neutron star will get a gravitational "kick" that ejects it from the system. But for others, the binary system may reach a final stage of evolution wherein the neutron star orbits closer and closer to its companion, which by this stage is nearing the end of its own life and is a red supergiant star. Eventually, the two stars merge, the red supergiant swallowing the neutron star, and a TZO is born.

In a galaxy the size of our Milky Way, containing hundreds of billions of stars, such mergers should be happening routinely. In fact, scientists have proposed that as many as 1 percent of all red supergiants might actually be TZOs in disguise. "Mergers between a neutron star and a star are common," confirms Selma de Mink, an astronomer at the University of Amsterdam whose research focuses on stellar evolution. "The question is, what does that look like? For me, that is the big excitement — this happens all the time, but we have no clue." She explains that some sort of transient and observable event should occur at the moment of the merger — perhaps there is a flare of energy in the X-ray or a

Yvette Cendes *is a Ph.D. candidate in radio astronomy at the University of Amsterdam. She is on Twitter @whereisyvette.*



This neutron star X-ray source hidden inside a supernova remnant stumped astronomers for years while they tried to explain its slow rotation period. The solution might in fact be that it is the "ghost" of a Thorne-Żytkow object. SA/XMM-NEWTON/A. DE LUCA (INAF-IASF)

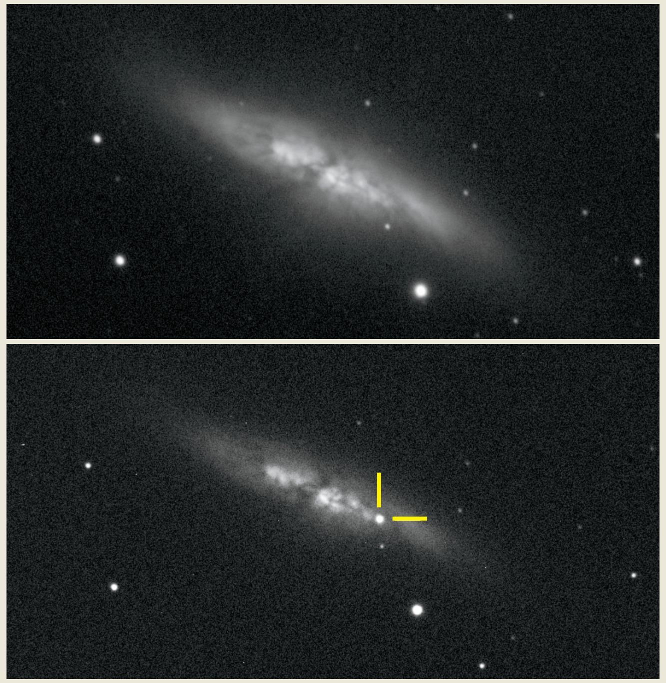
nova explosion in visible light. Theorists are working on various models, but as yet there is no consensus on what scientists would see at the birth of a TZO.

Made of star stuff

TZOs are important because they have the potential to tell astronomers where some of the more exotic elements in the universe come from. Hydrogen, helium, and trace amounts of lithium were created immediately after the Big Bang. All the heavier elements in the universe, though, formed not at the dawn of the cosmos, but within the heart of a star. Some of these elements we know and love from our daily lives — carbon, oxygen, and iron, to name a few — are produced inside stars through regular processes that are fairly well understood. But the origin of some particularly heavy elements, such as molybdenum, yttrium, ruthenium, and rubidium, is less clear. "These elements are not household names, but still you might want to know where the atoms that make up our universe came from," jokes Philip Massey, an astronomer at Lowell Observatory in Arizona whose research includes the evolution of massive stars.

Theory suggests that these elements might be created in TZOs. A neutron star inside a red supergiant leads to an unusual method for energy production: The object's burning is dominated not by the standard nuclear fusion that occurs in other stars, but instead by thermonuclear reactions where the extremely hot edge of the neutron star touches the puffy supergiant's gas layers. These reactions power the star and also create those heavy elements. Convection that circulates hot gas in the star's outer layers transports these new elements throughout the star and ultimately even to its surface, where a keen-eyed observer with the right telescope might just spy them.

The XMM-Newton satellite discovered the X-ray source scientists now believe may be the remnant of a Thorne-Żytkow object (shown above) after the red supergiant tore itself apart with its stellar winds. ESA



Astronomers saw a type Ia supernova explode in the relatively nearby Cigar Galaxy (M82) in January 2014. These two images were taken only a month apart and highlight the brilliance of the new supernova. UCL/UNIVERSITY OF LONDON OBSERVATORY/STEVE FOSSEY/BEN COOKE/GUY POLLACK/MATTHEW WILDE/THOMAS WRIGHT

DOUBLE STANDARDS

Binary stars end their lives in all kinds of dramatic and interesting ways, and as with all stars, the specifics of their stories depend mostly on the mass of the stars involved. Thorne-Żytkow objects (TZOs) may be astronomical oddities, but one of the most famous examples of binary stars that end their lives in an explosive and illuminating fashion resembles a TZO at two different stages. Type Ia supernovae are stellar explosions used as "standard candles," or distance indicators, by astronomers because they explode with a predictable amount of energy, which means their brightness varies neatly with their distance from us.

But two different kinds of binary systems give rise to these explosions. In one case, the system is a mass-mismatched binary, similar to but less extreme than the early stages of a TZO. The more massive star rushes through its lifetime but, instead of exploding, fades into a hot, dense white dwarf. The other star lags behind and, either as a Sun-like star or a red giant, starts to leak material onto its white dwarf companion. When the white dwarf has gorged itself on enough star stuff to overcome a precise 1.4-solar-mass limit, it explodes as a supernova.

In the other scenario, the two stars begin their lives more evenly matched and both progress to the white dwarf stage. As with TZOs, the exact catalyst is unknown, but something causes these partners to spiral toward one another and crash together, again lighting up in a supernova explosion.

While these may sound like very different events, from a distant spectator's point of view through a telescope, the differences between these two scenarios are subtle.

Astronomers are still working to figure out how many of our standard candles are caused by each of these processes. — *Korey Haynes*

Hunting for TZOs

But tracking these mysterious objects down is not an easy task. "To an outside observer, TZOs look very much like extremely cool and luminous red supergiants," explains Żytkow, now at the Institute of Astronomy at the University of Cambridge in England. This means they are nearly indistinguishable from the thousands of other normal, bright supergiant stars that many surveys observe. "However, they are somewhat redder and brighter than stars such as Betelgeuse in the constellation Orion," she says, naming the famous red supergiant familiar to stargazers.

The only way to distinguish a TZO from a regular bright supergiant is to look at high-resolution spectra — patterns of light astronomers use as stellar fingerprints — to find the specific lines caused by the unusual elements more abundant in TZOs than in typical stars. Such work is severely complicated by the massive number of complex spectral lines from other elements and molecules in the star, which easily number in the thousands. "It is a needle in a haystack kind of problem," says de Mink.

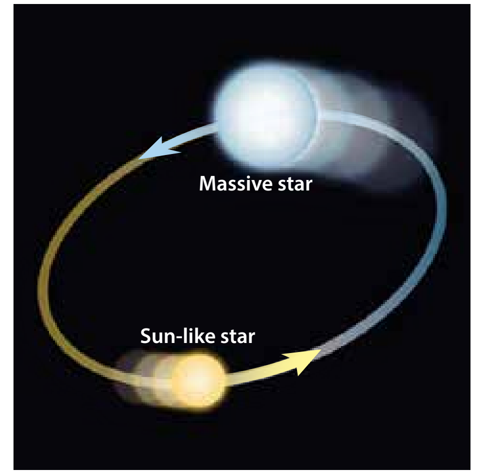
"Since we proposed our models of stars with neutron cores, people were not able to disprove our work. If theory is sound, experimental confirmation shows up sooner or later." — Anna Żytkow

Despite this, a team of astronomers thinks they might have found the first needle. Nearly four decades and several unsuccessful searches have passed since Żytkow initially worked on the theory behind TZOs. When she saw new research on some unusually behaving bright red supergiants, however, she was intrigued. Emily Levesque, an astronomer at the University of Colorado at Boulder, spearheaded the work with Massey, whom she has been researching red supergiants with ever since an undergraduate summer internship in 2004. Two years later, they discovered several red supergiant stars in the Magellanic Clouds — satellite galaxies of our own — that were unusually cool and variable in brightness. This avenue of research eventually attracted Żytkow's attention, so she asked whether the team had considered the possibility that these stars might be TZOs.

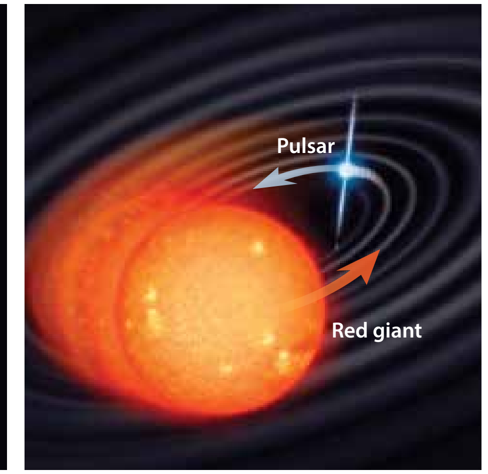
The potential to find the first TZO was exciting, but identifying a candidate from within the sample of red supergiants would require higher-resolution spectra than ever taken before. Levesque, along with her former mentor Massey and additional collaborator Nidia Morrell of the Carnegie Observatories in La Serena, Chile, secured time to observe a sample of several dozen red supergiants both in the Milky Way and in the Magellanic Clouds using the 3.5-meter telescope at Apache Point Observatory, New Mexico, and the 6.5-meter telescope at Las Campanas Observatory, Chile, respectively. They observed each of the stars with some of the most powerful spectrographs available and then began the meticulous task of identifying the various emission lines in the data and working out the relative elemental abundances in each star.

"It wasn't immediately obvious at a glance if we had a TZO," Levesque recalls, "but there was one star that jumped out at us." A star called HV 2112 in the Small Magellanic Cloud had a particularly bright hydrogen emission line astronomers saw even in the raw data they glanced at as it came in. In fact, it was so unusual that it prompted Morrell to joke at first look, "I don't know what it is, but I like it!"

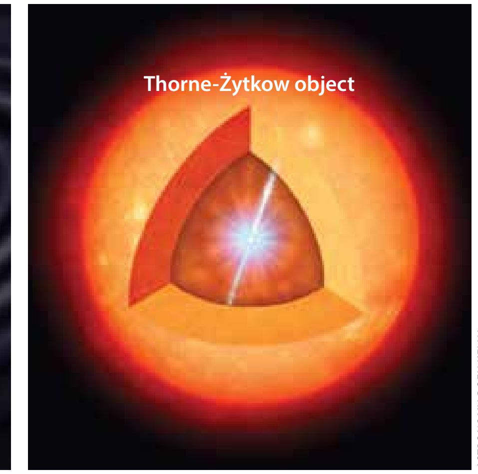
How to make a TZO



A Thorne-Żytkow object (TZO) starts its life as a normal binary star. One partner is close in mass to the Sun while the other is significantly hotter and more massive (images not at all to scale). The heavier star burns through its fuel quickly and explodes as a supernova.



After the supernova, the massive partner leaves behind a tiny neutron star (even less to scale!). The Sun-like star consumes its hydrogen fuel more slowly and expands into a red supergiant. At some point, the stars' orbits become unstable, and they begin to spiral toward each other.



The stars circle each other on decreasing orbits until they merge. The moment of the merger should be observable, but astronomers aren't sure exactly what to look for. From most perspectives, the newly formed TZO now appears as a normal, if bright, red supergiant.

ASTRONOMY: ROEN KELLY

It turns out there was much more to like about HV 2112 — it had unusually high concentrations of the elements lithium, molybdenum, and rubidium, which are predicted TZO signatures. While finding a star with an unusual abundance of one key element can happen for a variety of reasons, this was the first time astronomers saw all the critical elements in the same star; the team published their results identifying HV 2112 as a TZO candidate in the summer of 2014. "It could still turn out not to be a TZO in the long run," explains Levesque, "but even if not, it's definitely a very weird star."

This discovery was also satisfying for Żytkow, who was instrumental in pushing for telescope time and analysis of the spectral lines. "Work on the discovery of a candidate object which Kip Thorne and I first predicted many years ago is great fun," Żytkow says. "Since we proposed our models of stars with neutron cores, people were not able to disprove our work. If theory is sound, experimental confirmation shows up sooner or later."

Revisiting stellar evolution

While finding a "star within a star" sounds intriguing in itself, the discovery of a TZO is particularly interesting to astronomers for what its existence can tell them about stellar evolution. Major research advances in recent years in areas such as stellar convection allow astronomers to update their models for TZOs. These changes may yield new elemental abundances for observers to watch for. Astronomers also want to know whether TZOs can explain where some of the heavy elements come from: Rough estimates so far suggest there could be enough TZOs to explain their formation, but the numbers are highly uncertain.

With only one observed TZO in their stable, how do astronomers estimate how many TZOs are still in the wild, waiting to be discovered? This is not easy to answer: For one thing, no one is sure how long TZOs can be stable. Some models predict that they would be very short-lived objects — lasting only a few thousand years — either due to being torn apart by extremely strong stellar winds or collapsing into a black hole. "Computationally, this is one of the hardest things out there to model," says de Mink, "so we aren't sure."

Research also has focused on finding the remnant of a TZO after it has died. Recently, an international team of astronomers examined the abstrusely named X-ray source 1E161348–5055, which has perplexed scientists since its discovery several years ago. Initial results suggested its power comes from a neutron star — 1E161348–5055 is in fact located in a supernova remnant estimated to be just 2,000 years old — but its rotation period is 6.67 hours. Such a young neutron star should be rotating thousands of times faster; this slow period is more indicative of a neutron star that is several million years old. Several theories have been suggested over the years — perhaps the neutron star has a stellar companion, or perhaps it has an unusually high magnetic field — but no one has explained this mysterious X-ray source to everyone's satisfaction.

A TZO ghost may fit the bill. As a TZO, it might have burned for up to a million years. But a TZO's outer layers are not as dense as a normal star's, meaning this envelope of material is prone to dissipating over reasonably short time scales. The strong stellar wind common in larger stars could be all that's needed to blow the outer envelope away. This would leave behind a shell similar to a supernova remnant and a neutron star that is far older than its environment suggests — exactly what astronomers see in 1E161348–5055.

Looking deeper

Astronomers also are considering whether some parts of our galactic neighborhood might be easier hunting grounds for TZOs. Globular clusters present a particularly appealing target. Stars in a globular cluster all formed around the same time, are densely packed, and are old, meaning they have few of the heavy elements that enrich newer stars. A crowded globular cluster hosts the ideal circumstances to give a neutron star the needed "kick" to merge with a red supergiant star, and the unusual spectroscopic lines would stand out more easily in the metal-poor population.

As spectrographs and telescopes improve and surveys probe ever deeper into our celestial surroundings, TZO-hunters will keep trying to learn more about these weird stars, how they form and how they die, and how many others are waiting to be discovered. As Levesque explains, "It is very exciting to see what's out there."