Into the Heart


DARYL HAGGARD & GEOFFREY C. BOWER

WHEN ASTRONOMERS TUNED IN TO WATCH OUR GALAXY'S SUPERMASSIVE BLACK HOLE FEED, THEY FOUND MORE (AND LESS) THAN THEY EXPECTED.

THE MILKY WAY GALAXY'S nucleus is full of surprises. Scientists began to uncover exotic phenomena there more than 40 years ago, when they discovered the supermassive black hole, Sagittarius A* (Sgr A*, pronounced "saj A-star"), lurking at its core. Over the last several years, galactic-center happenings have been particularly spectacular and unpredictable. In 2012, observers reported a small, dusty object nicknamed G2 plummeting toward the black hole. All eyes (and telescopes!) turned to watch this little daredevil's destruction.

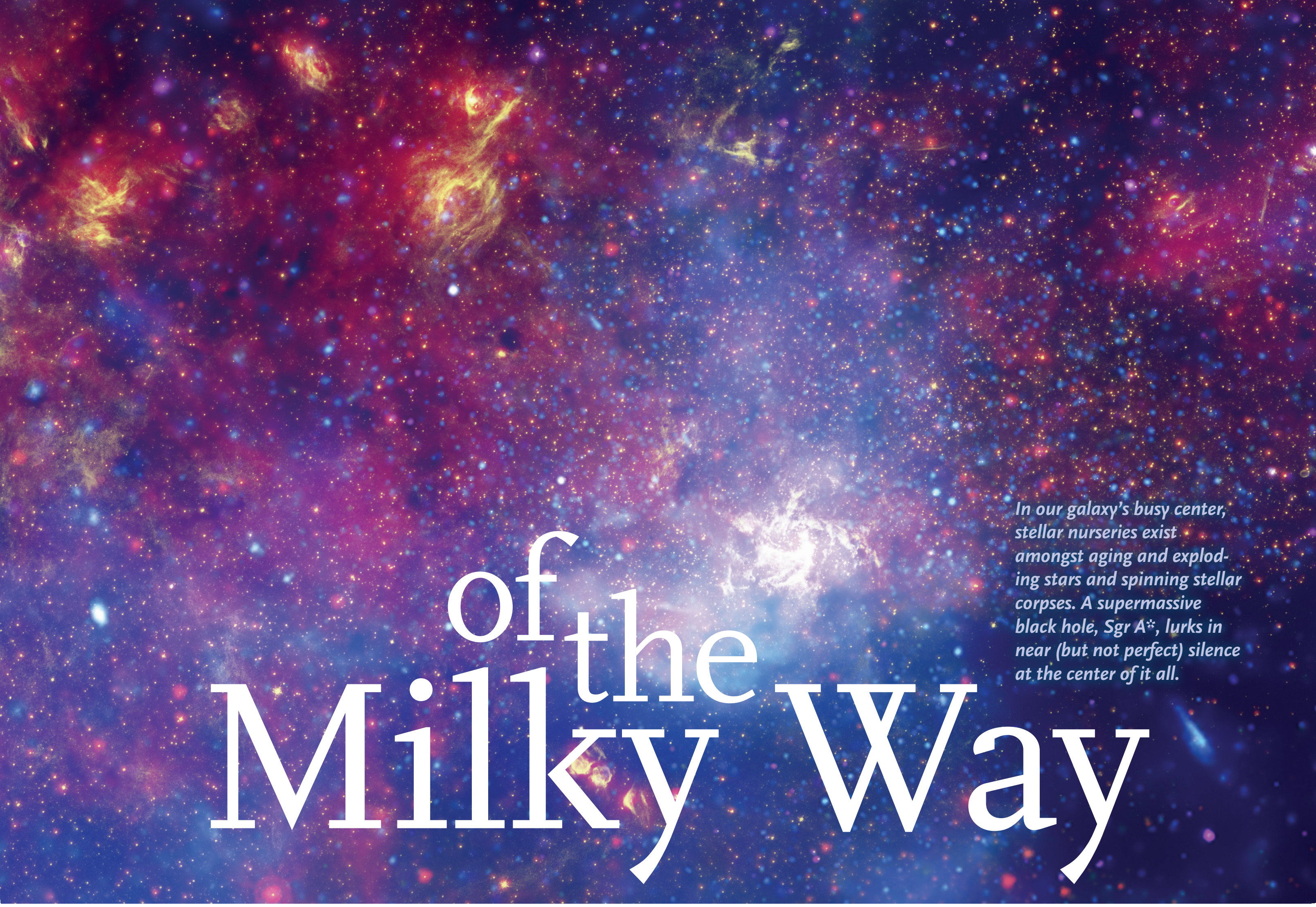
Across the globe, astronomers followed G2's fall, monitoring it across the electromagnetic spectrum for many months, hoping to discern the object's structure and fate. And then, before our telescopic eyes, something completely unexpected appeared. In early 2013, several months before G2's closest approach to Sgr A*, astronomers caught a bright X-ray outburst. But it didn't come from the black hole. The combined X-ray powers of the Swift, NUSTAR, and Chandra observatories quickly revealed that this newcomer was a *magnetar,* a young, highly magnetic neutron star — the first of its kind to be seen in the galactic center. Rapid radio follow-up conclusively placed this object at the distance of the galactic center, very likely in orbit around the black hole (though at a larger distance than G2).

After all this action, Sgr A* would not be outdone. Later, in September 2013 and again in October 2014, Sgr A* shot off two of the brightest X-ray flares we've ever observed. Rich data from the G2- and magnetar-monitoring campaigns offered an unprecedented multiwavelength view of these bright flares. These observations may hold the keys to understanding the environment around our nearest supermassive black hole.

The G2 Encounter

In 2012, a team of scientists led by Stefan Gillessen (Max Planck Institute for Extraterrestrial Physics, Germany) reported the discovery of G2, a faint infrared blob on a

of the Milky Way



In our galaxy's busy center, stellar nurseries exist amongst aging and exploding stars and spinning stellar corpses. A supermassive black hole, Sgr A, lurks in near (but not perfect) silence at the center of it all.*

NASA / JPL-CALTECH / ESA / CXC / STSCI

nearly suicidal slingshot orbit around Sgr A* (*S&T:* June 2013, p. 23). Already, astronomers could see that its path would take it within a couple hundred astronomical units (a.u., the distance between Earth and the Sun) of the black hole and deep into a hot, gas-filled environment.

Controversy ensued: was G2 a gas cloud, a gas-shrouded exoplanet, a star, or something altogether new?

Normally, Sgr A* is a notoriously quiet black hole, accreting only about a thousandth of an Earth mass every year. Early models for G2 estimated about 3 Earths' worth of mass in gas, assuming a simple spherical geometry. If a substantial fraction of this gas fell onto the black hole over the course of a few years, Sgr A* would morph into something akin to an active galactic nucleus (AGN), similar to those we observe in galaxies in the far reaches of the universe. To witness this transition would be spectacular.

But G2 might not be wholly gas. Other interpretations yield equally compelling possibilities. G2 could be a gas-shrouded exoplanet torn from its parent star during a close encounter in one of Sgr A*'s stellar disks, tossed into a plunging, *Interstellar*-style orbit around the black hole.

What is Sgr A*?

At a distance of 26,000 light-years, Sgr A* is our nearest supermassive black hole. Thanks to observations that monitor stars' orbits around this unseen dark object, we know its mass to excellent accuracy: between 3.8 and 4.8 million times the mass of the Sun.

Sgr A* feeds on winds blown out from massive stars in its vicinity. But for reasons we still don't understand, Sgr A* is an inefficient gas-guzzler. It swallows only a small fraction of an Earth mass per year (somewhere between 0.06 and 6 times the Moon's mass per year, as estimated from radio polarization measurements), blowing the rest back out into the galaxy. Its low-calorie diet leads to the surprising conclusion that the largest black hole in our galaxy is not a roaring lion but a cosmic pussycat, emitting about one-billionth of its maximum theoretical radiation.

Or perhaps it's a much more massive object: a star. If half the Sun's mass were buried inside G2's dusty, cool envelope, it could bind a puffy atmosphere and prevent it from being stripped as G2 passed near Sgr A*. But why the puffy shroud to begin with? One team, led by Andrea Ghez (University of California, Los Angeles), suggested that G2 could be the product of a stellar merger. Perhaps two low-mass stars slammed into each other, robbed the stars of their angular momentum, and sent the merger product plunging toward Sgr A*. This collision would disrupt the outer layers of the two progenitor stars and, until they had a chance to settle, leave a merged star with an extended, cold, dusty veil.

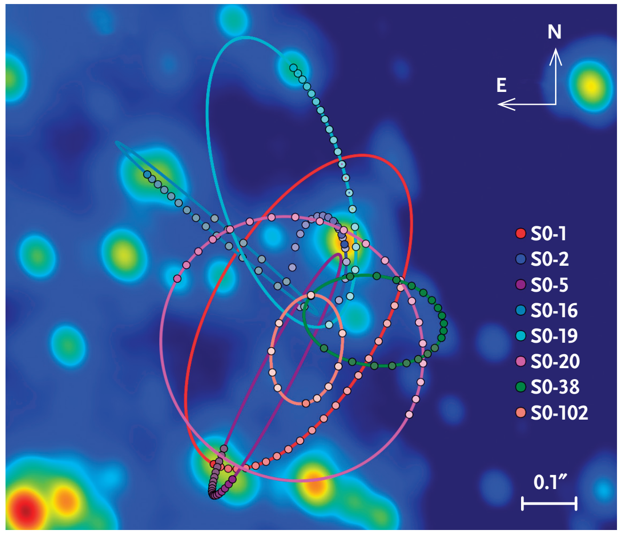
From the infrared images taken in 2012, as well as archival images of G2 dating back to 2004, observers soon concluded that the object's strongest interaction with Sgr A* would occur in the spring of 2014. Astronomers lined up to watch the encounter.

But despite continued infrared detections, radio, submillimeter, and X-ray observatories have come up dry so far. G2 didn't create the shock fronts we expected as it blasted through the hot gas around Sgr A*, nor has it yet bumped up Sgr A*'s accretion rate or created a jet.

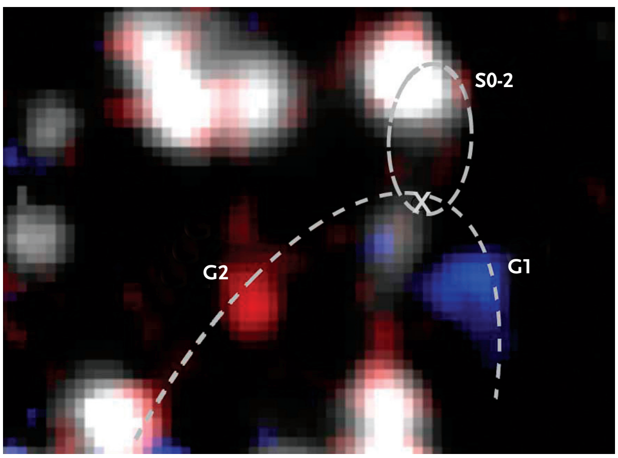
The lack of radio waves from a shock front means G2 is smaller than originally thought. Many think the size limits inferred from radio observations strengthen the stellar interpretation. The object could still be fairly big within those limits, similar in size to some of the largest known stars, so-called hypergiants, whose diameters can reach up to roughly 20 a.u.

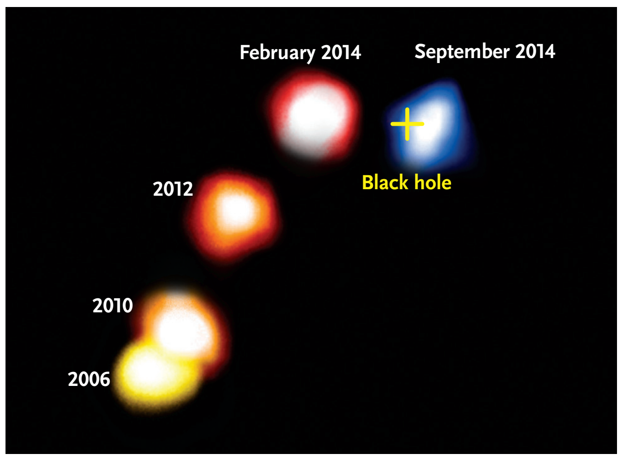
But the cloud idea isn't ruled out yet. It's just that if the object were a cloud, some force would need to act on it to limit its size. A strong magnetic field could deform the cloud, stellar winds might confine it, or we might be seeing the gaseous veil surrounding a merged star. The case remains wide open.

At the moment, observers are watching G2 as it re-emerges from behind Sgr A*. Ghez's team, using infrared images from the Keck telescopes, has seen the object reappear intact, which they say supports the star scenario. However, spectroscopic data collected from Gillessen's team suggest that the gas tail was significantly disrupted during the close encounter, evidence of tidal streams shorn from a cloud. Hope remains that we could still see an increase in accretion onto Sgr A* on long time scales, perhaps spread over several years.



CENTRAL STARS For about two decades, astronomers have used adaptive optics to monitor stars' orbital motions around the 4.3 million-solar-mass black hole sitting at the center of our galaxy. Dots mark stars' average annual positions.





WATCHING G2 *Left:* An archival image from 2006 reveals G2 (red), the dusty body discovered traversing the galaxy's center in 2011. (A similar object named G1 is shown in blue.) Even with adaptive optics, the Very Large Telescope (VLT) in Chile sees stars as blobs of near-infrared light (white/gray). Dashed lines show the orbits of G2 and a close-in star named S0-2, which zips around Sgr A* every 16 years. *Right:* In this composite VLT image, colors indicate G2's velocity: the object receded from us as it approached the black hole (yellow, orange, and red), now it's rounding the bend and coming back (blue). Both images are about 0.1 light-year across.

Can a Magnetar Probe General Relativity?

The discovery of a magnetar in the galactic center has opened up an opportunity for studying stellar evolution in the galaxy's frenetic downtown, understanding black holes, and perhaps even testing Einstein's theory of general relativity. In fact, astronomers have long sought to discover a pulsar in orbit around Sgr A*, which could provide an unprecedented measurement of the black hole's mass and spin, as well as test for deviations from our current theory of gravity.

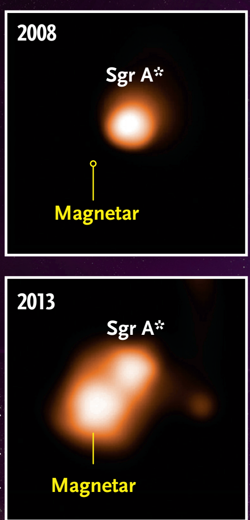
The power to make these exquisite measurements comes from the stability of these massive and energetically spinning objects. Pulsars are arguably the best-known clocks in the universe: a pulsar's period and its change over time are often measured to 10 significant digits, sufficient to track changes in the arrival time of individual pulses with accuracies better than 1 microsecond. So a pulsar orbiting a black hole is a relativist's dream — its pulses would trace the black hole's complex spacetime structure, and subtle but predictable changes in the pulses' arrival time would reveal the black hole's mass and spin.

The magnetar in the galactic center is unfortunately too far away and too jittery to perform these kinds of measurements. At its distance, it will take at least 700 years to orbit Sgr A*. And due to instabilities arising from its strong magnetic field, a magnetar makes a poor clock — more like an old spring-wound wristwatch than a precision atomic timepiece.

Nevertheless, we plan to continue watching the magnetar over the coming years. With luck, it will remain bright enough to reveal whether its motion describes an orbit around Sgr A*.

Ordinary pulsars may not be found in orbit around Sgr A* (see page 21). Fortunately, this is not the end of our quest to use pulsars to probe fundamental physics around Sgr A*. Millisecond pulsars, which spin so fast they're close to breaking apart, are old neutron stars that have "spun up" by interacting with a companion star.

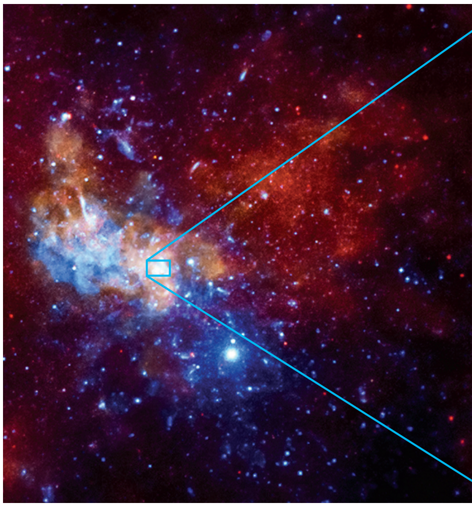
Current radio telescopes would miss any millisecond pulsars in the galactic center due to radio scattering. But a new generation of radio telescopes, including MeerKAT in South Africa and the Square Kilometer Array in South Africa and Australia, will have the sensitivity to detect these fast-spinning pulsars in Sgr A*'s vicinity and, if successful, help us test general relativity.



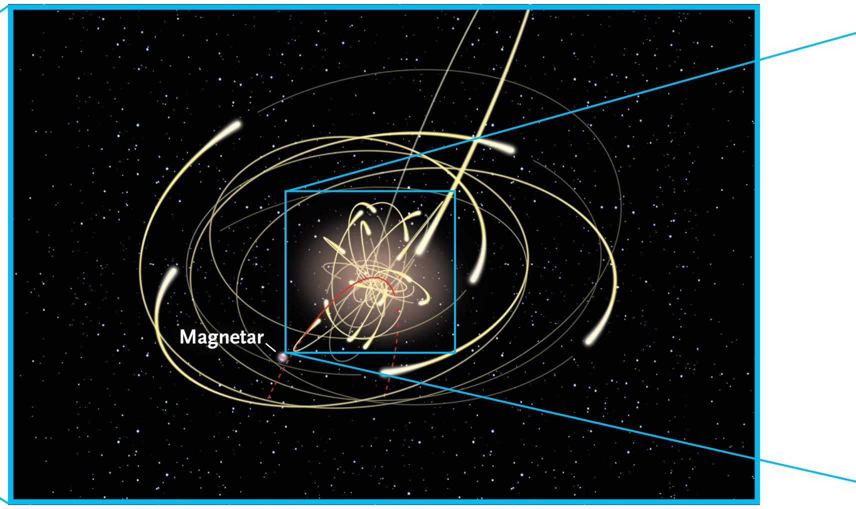
NASA / CXC / INAF / F. COTI ZELATI ET AL., MNRAS, 449, 2685, 2015

MAGNETAR A neutron star with extraordinarily powerful magnetic fields, SGR 1745-2900 lies as close as 0.3 light-year to Sgr A*. Chandra captured the magnetar's X-ray outburst in 2013 (*above*). An artist's conception (*right*) shows how an outburst might happen: a rupture in the neutron star's solid crust, accompanied by a rearrangement of the magnetic field, could release tremendous amounts of energy.

ART: NASA GSFC / S. WIESSINGER



INTO THE HEART This image from the Chandra space telescope captures X-rays from the busy galactic center in a view 50 light-years across. Red, green, and blue indicate low, medium, and high-energy X-rays, respectively.



STELLAR DISK + MAGNETAR Drawing from near-infrared data gathered by the Keck telescopes, this frame shows stellar orbits in the galactic center. Stars farther out tend to orbit clockwise in a disk, while the closer-in cluster contains stars on more chaotic orbits. The X-ray-emitting magnetar is a projected 0.3 light-year from the center. G2's current orbit follows the red track.

Due to the different nature of their data, the two teams might be looking at different sides of the same coin: even if the black hole yanked some gas off G2, there may yet be a star lurking within the gaseous envelope.

What of Sgr A* itself? Did the black hole notice all this action in its domain? In the midst of the G2 observing frenzy, Sgr A* offered up some surprises of its own.

Inflows, Outflows, and Flares

X-ray observations confirm that Sgr A* feeds off stellar winds. But most of that mass never makes it all the way to the gaping maw. Daniel Wang (University of Massachusetts, Amherst) led a team that studied X-ray emission around Sgr A*. The researchers reported that less than 1% of the material flowing toward the black hole successfully makes the journey inside — the other 99% blows back out into the surrounding environment.

In the process, our delicately snacking black hole belches X-ray flares: mild bursts occur roughly once a day, and bright spikes appear every 10 days or so. Thanks to G2 monitoring in 2013 and 2014, one of us (Haggard) led a team that discovered two of the most impressive X-ray flares ever seen. Over the course of a couple of hours, each released several hundred times the X-rays normally seen from this region.

Simultaneous multiwavelength observations (when they exist) generally show infrared and radio-wave spikes accompanying X-ray flares. But the inverse isn't true — a typical day sees four times as many infrared flares as X-ray flares. So it's not clear how emissions at different wavelengths relate to each other.

Because of these uncertainties, we still don't understand the flares' origin. A reordering of magnetic fields could create flares in a way similar to those seen from our Sun. Or the black hole's extreme gravity might shred the occasional asteroid that comes in a little too close.

The X-rays brighten and fade within a couple of hours. If they arise in the accretion disk, then their source must lie just outside the black hole's event horizon, the point of no return for material and light entering the black hole. Since that puts the escaping X-rays within an a.u. from the black hole, in the thick of whatever gaseous flow feeds Sgr A*, the flares are unlikely to be connected to G2's closest approach at roughly 150 a.u.

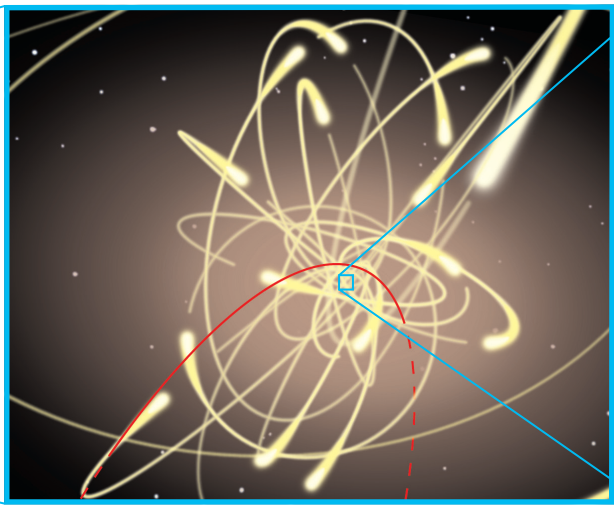
Nevertheless, a recent study of 150 Chandra and XMM-Newton observations spanning 15 years, led by Gabriele Ponti (Max Planck Institute for Extraterrestrial Physics, Germany), shows that bright flares became more frequent about six months after G2 made its closest approach to the black hole. Coincidence? Maybe — other black holes show similar flare clustering.

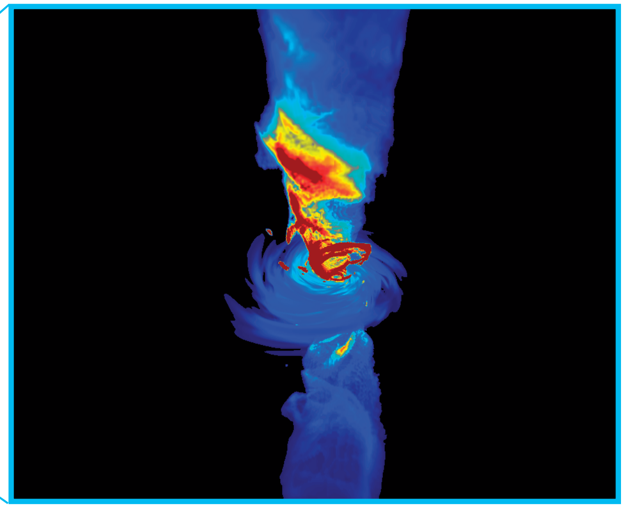
Continued multiwavelength monitoring of Sgr A* is our best hope of pinpointing the source of the flares.

Discovery of an Exotic Pulsar

The same monitoring that followed G2's approach and captured two brilliant flares led to another surprise on April 24, 2013. As G2 approached Sgr A*, daily monitoring of the black hole with the Swift satellite jolted scientists with the announcement of a bright X-ray outburst. Observers around the world rushed to their telescopes to capture a more complete picture of the anticipated disruption of the G2 cloud.

But the picture quickly became much more complex. The X-ray outburst lasted for hours, then days — much longer than the typical 1- or 2-hour duration of an X-ray





S&T: G. DINDERMAN, SOURCES: X-RAY: NASA / CXC / UMASS / D. WANG ET AL.; STARS: NCSA / UCLA / KECK; BLACK HOLE: M. MOSCIBRODZKA ET AL., A&A, 570, A7, 2014, REPRODUCED WITH PERMISSION © ESO

CLOSING IN ON G2 This frame, a few tenths of a light-year on a side, zooms in on the central cluster of stars, suffused by the gentle glow of hot, X-ray-emitting gas that's on its way toward the black hole. G2's observed orbit followed the red solid line; the dashed line extrapolates a bit beyond observations.

SUPERMASSIVE BLACK HOLE This frame from a recent simulation shows 1-millimeter radio emission from around Sgr A* as it accretes from a small gas flow and spews a jet. The view spans 6 astronomical units, a distance slightly larger than Jupiter's orbit around the Sun.

flare from Sgr A*. Radio telescopes in the United States and Japan, on the other hand, didn't see the expected jump in radio emission, which typically follows Sgr A*'s bright X-ray flares. This was clearly not an ordinary enhancement of activity around the black hole.

Two days after the initial outburst, NASA's NUSTAR X-ray telescope discovered that the emission was not steady but in fact pulsed every 3.76 seconds. Radio telescopes in Australia, the United States, and Germany confirmed radio pulsations with the same period shortly after that. Within five days of the initial outburst, the sharp eyes of the Chandra X-ray Observatory demonstrated that the pulsed emission arose not from Sgr A* but from a compact object only 3 arcseconds, or 0.3 light-year, away from the black hole.

This rapid response of space- and ground-based telescopes across the electromagnetic spectrum provided unambiguous evidence that this outburst came from an exotic compact object known as a *magnetar*.

When massive stars with less than 25 solar masses burn through all their nuclear fuel, they explode in a supernova, leaving behind a crushed object composed almost entirely of neutrons. This remnant packs one to two times the mass of the Sun into a sphere comparable in size to a small asteroid, only 10 kilometers (6 miles) in diameter. Moreover, the neutron star is born spinning as fast as 600 revolutions per second. If the jet of radiation spewed out of its magnetic poles sweeps across our line of sight, we call it a pulsar due to the jet's lighthouse effect.

Pulsars are exotic enough in their own right, but magnetars are stranger still. Possessing magnetic fields 100 times stronger than that of a typical pulsar, they're rare: astronomers have discovered thousands of pulsars in the galaxy, but only 30 or so magnetars. Where their strong fields come from isn't known, but the magnetic energy appears to drive magnetars' characteristic X-ray flashes. Dramatic rearrangement of the fields at the star's surface leads to explosive heating, creating a thermal hot spot that cools slowly over time.

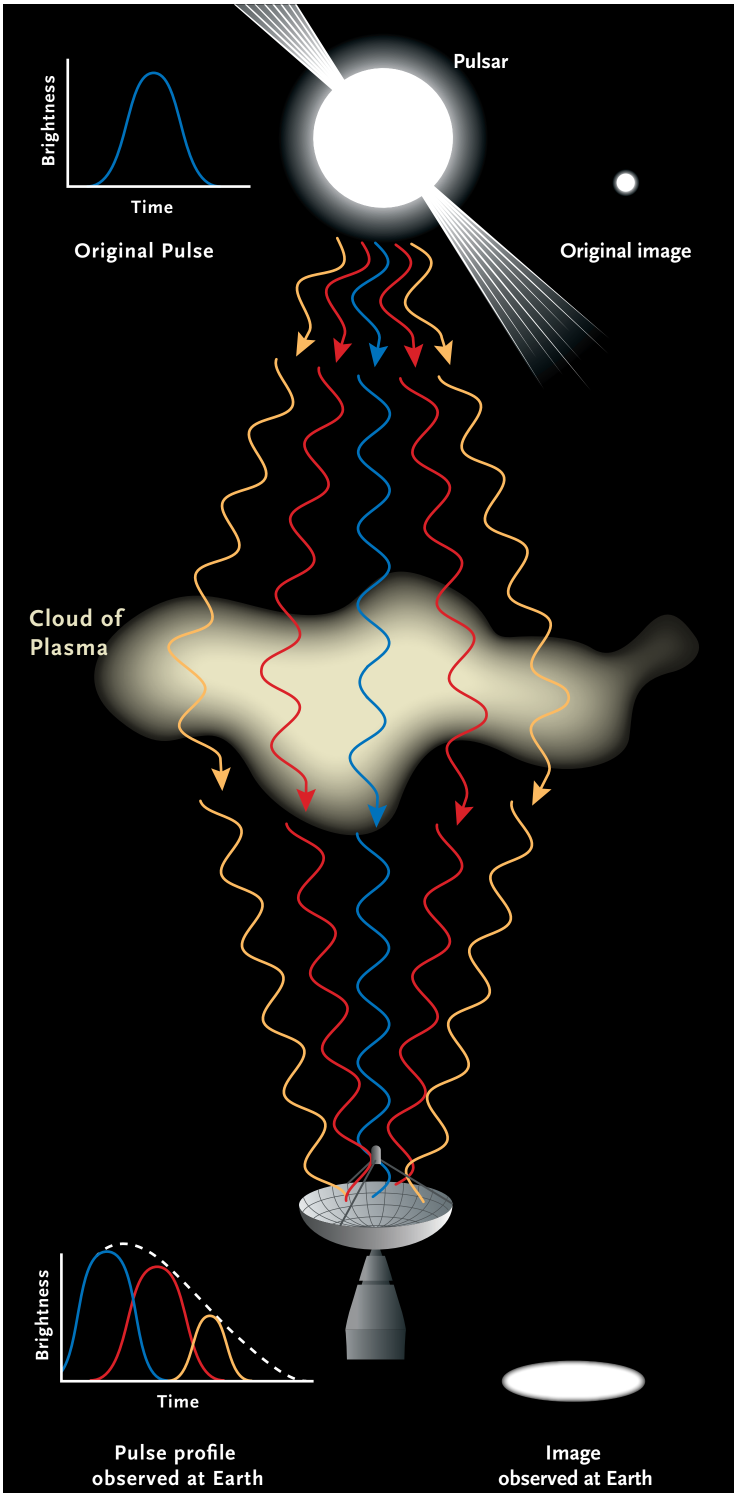
The galactic center magnetar is still cooling off two years after its initial outburst, its X-rays steadily declining in intensity. Mysteriously, its radio emission, which radiates from charged particles racing around the pulsar's strong magnetic field, has remained steady.

The Missing Pulsar Problem

The galactic center is full of young, massive stars of exactly the type that one would expect to go through a

Sgr A* and Friends

Galactic Nucleus	Black Hole Mass (in solar masses)	Accretion Rate (solar masses per year)
Sgr A* (quiet nucleus)	3.8 – 4.8 million	10^{-7} – 10^{-9}
M87 (active but low-luminosity nucleus)	3 – 6 billion	< 0.001
3C 273 (quasar, very active nucleus)	0.9 – 2.4 billion	4 – 10



S&T: GREGG DINDERMAN; SOURCE: G. BOWER

PLASMA-SMEARED PULSE When a spinning neutron star emits an earthward pulse, some radio waves travel directly to us. But most of its photons encounter free electrons floating in clouds of plasma, which force radio waves on detours. By the time scattered photons converge on an earthbound detector, the pulsar's point-like image has smeared out. Moreover, the longer paths of scattered photons delay their arrival times, smudging the pulse profile in time as well.

supernova phase and result in a neutron star or black hole. Some of these stars have been used to study the gravitational field of Sgr A* as they orbit the black hole. Theorists have suggested that there might be thousands of pulsars close to Sgr A*, leading to numerous searches at radio wavelengths.

But none of these searches has uncovered a pulsar any closer to the center than about 80 light-years, a distance too far away for them to be gravitationally bound to Sgr A*. This absence of radio pulsars has proved puzzling and made the magnetar's discovery all the more surprising.

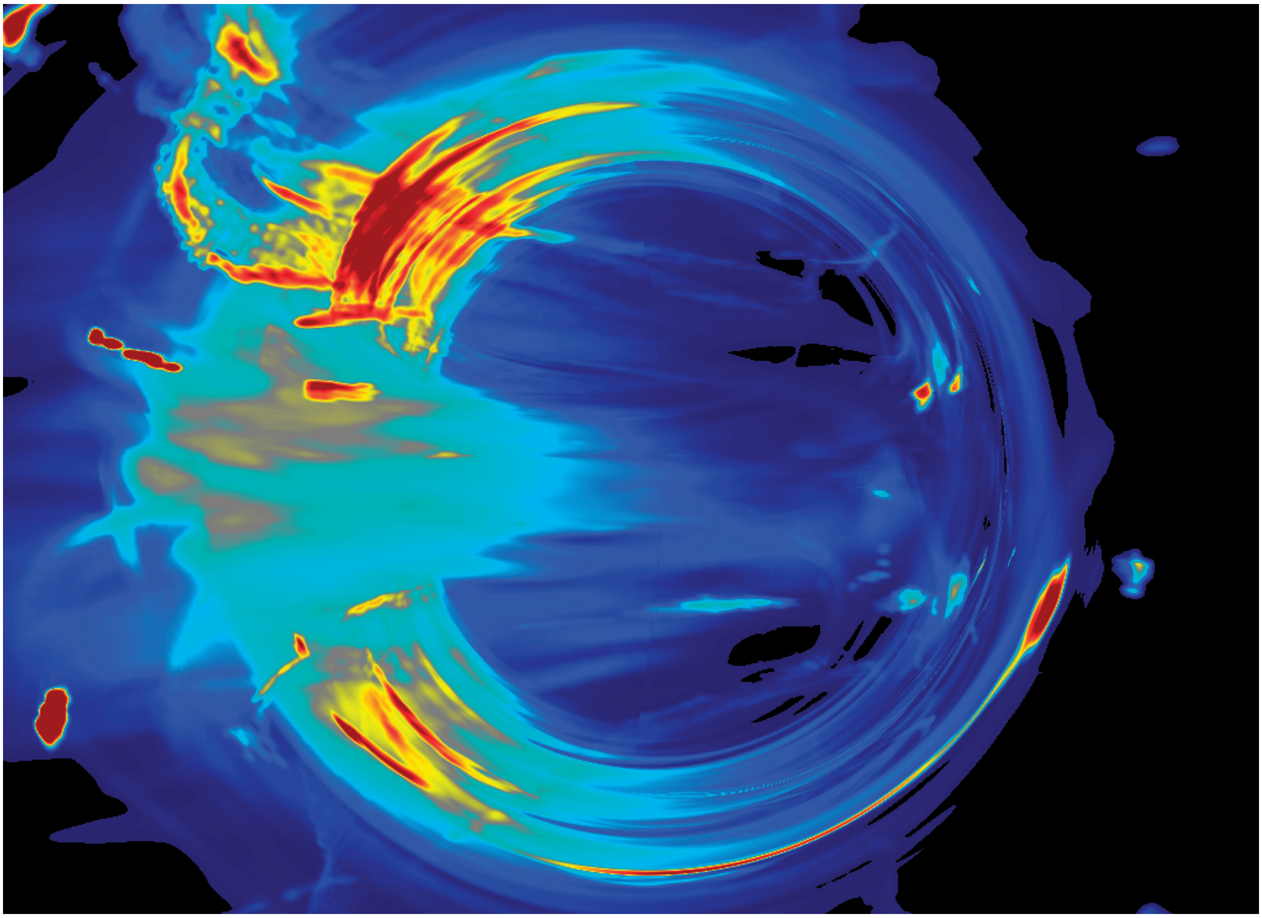
For the past two decades, the leading explanation has been not the absence of pulsars but the cloaking of their signal. Dust obscures the galactic center at visible wavelengths even as radio waves pass right through. But plasma, ionized gas between Earth and the galactic center, scatters radio waves and blurs images of radio sources such as Sgr A* (see box at left). The blurring has the effect of smearing individual pulses of radiation. If that smearing in time is longer than the pulse period of a particular pulsar, then the pulsar will cease to appear as a pulsed source and we won't detect it in our searches.

The smearing effect is strongest at long radio wavelengths and diminishes rapidly at shorter wavelengths. But perversely, typical pulsars become fainter at shorter wavelengths, making them much harder to detect.

One of us (Bower) used the Very Long Baseline Array, a transcontinental network of radio telescopes, to measure the effects of scattering on the radio waves coming from Sgr A* and the magnetar. We have long known that Sgr A* is one of the most heavily scattered objects in the galaxy, and new observations show that the magnetar suffers exactly the same fate, leading to a blurred image of the magnetar. This isn't surprising because the two objects are so close together.

But the second measurement, measuring how much the magnetar's individual pulses smeared in time, was quite surprising. Current understanding suggested that pulses might smear by as much as 100 seconds at a wavelength of 30 cm, much longer than the typical pulsar period. But our observations showed that the magnetar's pulses are smudged by only 1 second at 30 cm, and even less at shorter wavelengths. If the "missing" pulsars are in the galactic center and behind the same amount of material, previous surveys should have easily seen through the fog of interstellar plasma to find them.

So why have past searches failed? And why was the first pulsar discovered in the galactic center a rare magnetar? Perhaps these facts tell us that the extreme conditions in the galactic center, such as strong magnetic fields and dense gas, drive the formation of stars and neutron stars that are more highly magnetized than their ordinary cousins throughout the Milky Way. Some have suggested far more exotic ideas: neutron stars might accrete dark matter, which should be prevalent



HUNGRY BLACK HOLE This simulated radio image, about 1 a.u. across, gives an edge-on view of gas flowing around and into the black hole. The black hole's gravity bends radiation from this flow into an apparent ring-like structure. Simulations like this guide expectations for the Event Horizon Telescope.

in the galactic center, then implode into black holes. Or more prosaically, perhaps the scattering effects of the interstellar medium are more complex and time-variable than our current models can account for.

What's Up Next?

The galactic center is often described as the kitchen sink of the galaxy: a medley of anything and everything in the cosmos. And it's clear that the banquet isn't over yet. A new suite of observatories, combined with recent happenings in the galactic center, promise new discoveries and deeper understanding.

Among the most promising new tools available to astronomers is the project known as the Event Horizon Telescope (EHT, *S&T:* Feb. 2012, p. 20). This network will bring together an array of powerful radio telescopes in California, Hawai'i, Arizona, Mexico, Chile, Spain, France, Greenland, and Antarctica to image Sgr A* at millimeter wavelengths with an angular resolution comparable to the black hole's event horizon.

EHT images will reveal the inward accretion flow as well as the outflow (if there is one) on an unprecedented scale, potentially showing material that circles the black hole on the innermost stable orbit with a period of 20 minutes or less. When combined with X-ray studies of flares, we will be able to trace the flow of gas from the outer edge of the accretion flow all the way to the edge of the event horizon.

Even more importantly, the EHT will explore the structure of spacetime on those same scales, imaging the strong gravitational lensing effects that lead to a "shadow" and ring of emission around the black hole. Short of the discovery of a pulsar in close orbit around Sgr A*, these observations will provide the most compelling test of general relativity and our best view ever of the supermassive black hole at the heart of the Milky Way. ✦

__Daryl Haggard__ is an assistant professor at McGill University, where she studies the interplay between supermassive black holes and their host galaxies. __Geoffrey C. Bower__ is an astronomer at the Academia Sinica Institute of Astronomy and Astrophysics, where he investigates transient radio sources, black holes, and instruments and techniques for radio astronomy.