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SOONER OR LATER ON ANY CLEAR, DARK NIGHT, AN ETHEREAL BAND CALLED THE MILKY WAY ARCHES ACROSS THE SKY. Although recognized since antiquity, philosophers and scientists could only guess at what it represented until fairly recently (see “How the Milky Way Galaxy got its name,” p. 33). With the invention of the telescope, it became clear that the Milky Way was the collective glow of stars too faint to be seen by the naked eye. More than a century later, English astronomer Thomas Wright suggested that this glowing band was precisely what one would expect to see if the Sun were embedded in a flat disk of stars.

We now know that the Milky Way is the primary structure of our galaxy seen edge-wise. Additional detail and especially the physical scale of the galaxy took another two centuries to work out. The process continues today as astronomers wrestle with conflicting evidence and make new discoveries. Much like mapping a fogbound city from a single intersection, scientists must decipher the galaxy’s structure while viewing it from inside a disk where dust clouds dim and block starlight.

The true scale of the Milky Way Galaxy — and, indeed, the universe as a whole — became dramatically clearer in the 1920s. That’s when a new generation of large telescopes coupled with photography revealed that “spiral nebulae” were actually entire galaxies like our own — “island universes” in the evocative parlance of the time. Surveys showed that most disk-shaped galaxies possessed winding spiral arms where young stars, gas, and dust were concentrated. Astronomers assumed our galaxy was a spiral too. In the 1950s, radio telescopes produced the first crude maps of the Milky Way’s spiral arms by tracking how gas clouds moved around the galaxy.

Over the past two decades, surveys using dust-penetrating infrared light have brought the general picture of our galaxy into better focus. These projects include the ground-based Two Micron All-Sky Survey and Sloan Digital Sky Survey (SDSS) as well as two NASA spacecraft, the Wide-field Infrared Survey Explorer (WISE) and the Spitzer Space Telescope. These observations have helped astronomers better define our galaxy’s spiral arms, take a census of star clusters and other phenomena in Giant clouds of gas and dust sprinkled with splashy star clusters adorn the Milky Way’s spiral arms, while the galaxy’s vast halo teems with darker matter. by Francis Reddy

Francis Reddy is the senior science writer for the Astrophysics Science Division at NASA’s Goddard Space Flight Center in Greenbelt, Maryland.

FAST FACT

27,200 LIGHT-YEARS

The Sun’s distance from the galaxy’s center

Scientists think our galaxy has four major spiral arms that wind their way out from a central bar. The Sun lies approximately 27,200 light-years from the center.
The Carina Nebula (NGC 3372) ranks among the Milky Way’s biggest star-forming regions. It lies about 7,500 light-years from Earth and burst to life when its first stars ignited some 3 million years ago. Today, it holds nine stars with luminosities at least a million times that of the Sun.

Exploration of Radio Astrometry (VERA), are using this capability to pinpoint the locations and motions of regions where new stars are forming in order to trace our galaxy’s spiral structure.

Movin’ out
The frontier of the galaxy lies at the outer fringe of the Oort Cloud of comets, about 100,000 astronomical units (AU); the average Earth-Sun distance) or 1.6 light-years away (see “From AU to light-year,” p. 34). Here, the Sun’s gravitational pull weakens to the level of nearby stars, and comets whose orbits take them this far may drift out of the Sun’s grasp entirely. Although some of these wanderers future star formation as shock waves compress surrounding gas.

How the Milky Way Galaxy Got Its Name

Spend some time under the stars any clear night far from city lights, and a ghostly "milky circle,” a description that also gave rise to our word “galaxy.” The Romans lifted the concept but gave it a twist appropriate for a civilization fond of road construction, calling it via lactica, the “milky way.” Galileo Galilei took the first step in understanding what it actually represented in 1609, when he and improved spyglass revealed that the pale light came from individual faint stars “so numerous as almost to surpass belief.”

Over the next two centuries, as astronomers began to understand that the Milky Way was part of an “island universe” that included the Sun and other visible stars, the name for a mythical cosmic pathway was transferred to our galactic home.—F.R.

At a distance of 1,350 light-years, the Orion Nebula (48) is the nearest large star-forming region. Our Sun likely formed in a cloud like this, one capable of producing 1,000 to 10,000 stars.

Some stars barely shine at all. They never generate energy in their cores through true hydrogen fusion, the power source that heats stars for most of their lives, but when young they can produce energy by fusing a rare form of hydrogen, deuterium. Called brown dwarfs, they measure between 1.2 and 7 percent of the Sun’s mass. The companion to Scholz’s Star is a member of this class. With surface temperatures as cool as one-tenth the Sun’s, brown dwarfs are marginal stars that may be as numerous as the real things. More than 50 known stars and brown dwarfs reside inside 16 light-years of the Sun, but only 10 of them are visible to the naked eye.
FROM AU TO LIGHT-YEAR

Where the solar system ends, interstellar space and the galactic fron- tier begin. At the fringe of the Oort Cloud, perhaps 100,000 astronomical units (AU), the average Earth is about an AU away, comes as close as likely to be dislodged from the solar system as to continue in their slow orbits. From here on out, occupying distances in the manner commonly used within the solar system rapidly becomes unwieldy. It turns out that 63,241 AU equals the distance light travels in a vacuum over the course of one year: a light-year. The fringe of the Oort Cloud is about 1.6 light-years away. The closest star, Proxima Centauri, is a mere 4.22 light-years distant. And the Orion Nebula, the largest star-forming region, is about 1,500 light-years away off. According to relativity, no matter or information can travel faster than the speed of light in a vacuum. But there is a consequence to thinking about distance in terms of light travel time. The farther away we look, the longer light takes to reach us. At any given moment, we see Proxima Centauri as it looked 4.22 years ago and young stars in the Orion Nebula as they appeared more than a millennium ago. Applied to large numbers of galaxies at different distances, this time-machine effect gives astronomers a powerful tool for understanding how galac- tic as we own our galaxy and developed over billions of years. — F. R.

GALACTIC ARCHITECTURE

Early in the last century, the differences between open and globular star clusters guided astronomers into an overview of the Milky Way. Open clusters orbit in a disk-shaped volume that also contains nearly all of the galaxy’s gas and dust. Stars are born near the center. This disk is some 1,000 light-years thick and extends probably 75,000 light-years from the galactic center, placing the solar system a little more than a third of the way out in the disk. In the disk’s center lies a football-shaped concentration of new and old stars called the galactic bulge, which is about 12,000 light-years long. Although its exact size, shape, and viewing angle remain somewhat unclear, we see the bulge obliquely too far not to see from end on. Until recently, astronomers regarded the bulge as a separate object with a rotating structure. Now they are sure whether to classify our local patch of the galaxy as a branch of the Perseus Arm or a separate small galaxy. And the disk holds more surprises. A 2015 study of SDSS data led by Yan Xu at the Chinese Academy of Sciences in Beijing has even with stars its spread by more than five 50 percent over previous values. The number of stars in the disk had to drop off around 50,000 light-years from the center, but SDSS found what appeared to be a vast ring of stars about 10,000 light-years farther out. The new study shows this is an illusion caused by at least four ripples that displace stars in the disk above and below the galactic plane. When we look out of the galaxy from the solar system, the disk is perturbed a few hundred light-years, then down, and then down again, starting about 6,500 light-years from the Sun and reaching at least 50,000 light-years away. Additional ripples may yet be found. Small galactic orbit- ing structures may have produced the ripples. One in particular, known as the Sagittarius Dwarf Spheroidal, has passed through the disk multiple times and is gradually dis- solving into streams of stars as it orbits the Milky Way. Like a stone tossed into still water, the gravitational pull of a sat- ellite galaxy plunging through the disk could produce ripples. Simulations sug- gest that satellite galaxies tearing through the disk can play a role in creating spiral structure. And intriguingly, the newfound ripples align closely with the Milky Way’s spiral arms. The dark disk sits within a galaxy called the galactic halo, a place ruled by globular clusters and satellite galaxies, as astronomers have spotted at the edges of them. Our galaxy — indeed, most galaxies — may have been built by gobbling up many smaller galaxies. Today we see streams of stars linked to several small satellites, and the Milky Way appears to have swiped several globular clusters from the Sagittarius Dwarf Spheroidal. The larg- est and brightest galactic cluster, named Omega Centauri and located about 17,000 light-years away, has a more complex stellar makeup than others. Researchers suspect it is the leftover bulge of a dwarf galaxy long ago shredded by our own. Yet most of the Milky Way’s mass remains unseen. The motions of stars around our galaxy and others reveal a gravitational influence extending far beyond the structures we can see. Studies show that the Milky Way resides in a roughly spherical halo of invisible material known as dark matter — rays from the dark matter with light-year distances, or about six times the disk’s diameter. This stuff makes up 27 percent of the cosmos and the gravitational force it provides is the ordinary matter that structures to build galaxies like our own. The dark matter is a subject of ongoing research. New telescopes have Improved already provided major new insights, but many questions remain. As astronomers combine the results of this research over the next decade, an accurate 3-D portrait of the Milky Way will emerge, enabling us for the first time to view our island universe in the same way we see other galaxies as a complete cosmic object — a whole greater than the sum of its parts.
Strange hourglass lobes extend for 25,000 light-years on either side of our galaxy’s center. by Liz Kruesi

Douglas Finkbeiner was an outsider to the world of high-energy astrophysics. His expertise was dust — the galactic kind — and studying its microwave emission. But that different perspective allowed Finkbeiner and his colleagues to reveal one of our galaxy’s largest structures, known as Fermi Bubbles.

These enormous balloon-shaped features — each reaching out 25,000 light-years from the galaxy’s center — were discovered more than six years ago, yet they remain mysterious. Astrophysicists cannot say what created them. They have narrowed down how long ago these bubbles formed, and they are beginning to sort through their composition. And soon, researchers will have another observatory that should reveal even more.

It’s clear so far, though, that Fermi Bubbles are evidence of some past violent activity near our galaxy’s center. The movements of energetic particles have painted these structures in gamma rays and microwaves.

A microwave haze

In 2003, Finkbeiner first saw an extra signal in data from the Wilkinson Microwave Anisotropy Probe (WMAP) when the spacecraft scanned the sky for the Big Bang’s residual radiation. He was a postdoc at Princeton University at the time. After subtracting the many different sources of microwave radiation in the inner part of the Milky Way — for example, electrons spinning around magnetic field lines and spewing microwave photons, particle collisions, dimly glowing dust, and dust spinning billions of times each second — he still had a signal left over.

“It’s really hard to think of a word that hasn’t been used yet,” Finkbeiner says. “And so I called it the microwave haze.”

What’s blowing BUBBLES IN THE MILKY WAY?
He dove headfirst into the WMAP data, looking for what was causing these unexpected microwave signals in the inner galaxy. The idea that rose to the top was that the extra microwaves were created by the so-called synchrotron method. Magnetic fields thread the galaxy, and any electron moving through them would spiral around their lines. If the electrons are moving fast enough and the magnetic field is strong enough, the electrons will slow while spiraling and emit microwave radiation.

Those same high-energy electrons can also encourage gamma-ray radiation through a process called the Inverse Compton Effect. When ambi-
ent photons, like those produced by stars, encounter those electrons, the electrons can donate some of their energy to the photons. That boosts the photons’ energies to the gamma-ray level. “It all sounds very crystal clear now in hindsight, but at the time there were questions about whether the WMAP haze, as we were calling it, was even real,” says Gregory Dobler, a postdoctoral fellow working with Finkbeiner, who has since moved to Harvard.

The researchers modeled what they thought they would see from the upcoming Fermi Gamma-ray Space Telescope, launched in June 2008. The Fermi team was set to release its first year of data to the public in fall 2009, so Finkbeiner, Dobler, and then-graduate student Tracy Slatyer obsessively checked for updates. As soon as the data came out, they got to work analyzing it.

The timing couldn’t have been worse, though. Dobler’s postdoc position was winding down, and he was set to move to a similar position at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. “The data were available for download two days before I was going to drive across the country,” he says. “As I was packing up, we were feverishly writing code to make maps out of this gamma-ray data that was coming in.”

It paid off — they uncovered a haze of gamma rays. The scientists published their discovery of the Fermi Haze, as they called it, in the June 2010 issue of The Astrophysical Journal. But even while they were working on this paper, they saw a ghost of a signal. “It wasn’t just this diffuse, fuzzy blob that faded off into nothing as you went off the galactic plane, but a clear edge,” says Dobler. “It had this sharp edge, and it had this hourglass shape.”

If the emission really had defined a sharp edge, then that suggests that whatever is causing the gamma rays exists only in the Milky Way’s center — and the center inflated the enormous balloon of gamma-ray radiation.

With those huge structures were finally discovered in Fermi data, scientists named them Fermi Bubbles. It looks like something at the Milky Way’s center inflated the enormous bubbles — but what, and when? In 2014, their find netted Finkbeiner, Slatyer, and another collaborator, Meng Su, the Bruno Rossi Prize, the top award in high-energy astrophysics.

Critics speculated that the researchers missed other sources of gamma-ray emission in the sky. So Finkbeiner and his team labored to improve their background models. And they turned doubters into believers when they found the distinct bubble structure.

On either side of our galaxy’s plane lies a 25,000-light-year-tall balloon of gamma-ray radiation. These huge structures were outflows from the galactic center. These outflows could be enormous jets from the supermassive black hole after it eats nearby material, like those seen at the centers of large galaxies across the universe.

Astronomers have found that the material in jets rushing away from other black holes travels at millions of miles per hour. As the jets slam into nearby gas, the interaction has many consequences, including depositing energy, causing the gas to light up, and compressing it into shock fronts. Or the bubbles could come from a burst of massive-star formation near the Milky Way’s core. That would give a double dose of energy to inflate
Scientists are watching a distant quasar — the active core of a galaxy — as its light passes through the Milky Way's northern Fermi Bubble. It used this light to analyze the speed, composition, and mass of the outflow. Scientists are unsure how the bubbles formed, but evidence points to a violent event at our galaxy's center several million years ago.

**Below** Fermi has two main instruments. Its Large Area Telescope can identify and precisely place gamma-ray sources across a wide section of sky. The Burst Monitor keeps an eye out for gamma-ray bursts from all directions.

The Hubble Space Telescope watched a distant quasar — the active core of a galaxy — as its light passed through the Milky Way’s northern Fermi Bubble. It used this light to analyze the speed, composition, and mass of the outflow. Scientists are unsure how the bubbles formed, but evidence points to a violent event at our galaxy’s center several million years ago.

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**In the ultraviolet**

To break the stalemate, astronomers have turned to ultraviolet light. The Space Telescope Science Institute’s Andrew Fox and colleagues are using the brilliant centers of active galaxies, called active galactic nuclei (AGNs), as storefronts behind the Fermi Bubbles to sample small sections. When light passes through the gassy bubbles on the way to the Hubble Space Telescope, the gas can imprint the light with its calling card.

The astronomers split up each AGN into its color, or wavelengths. Different elements absorb light at different, specific wavelengths, and so the scientists can see what’s in the bubbles’ gas. They have identified silicon and carbon — elements created in the cores of massive stars. That means the material inside the bubbles must have been processed through stars, Fox says. But those wavelengths can reveal something else, too. “The features that we look for tell us whether the gas is moving toward us or away from us,” Fox says. “We are able to use this technique to measure exactly how fast gas is moving at different positions in the Fermi Bubbles.”

Using these newfound velocities, a bright ageon’s location on the bubble, and some basic geometry, Fox’s team calculated that the material in the structures is between about 2 million and 4 million years old. So whatever blew these bubbles did so relatively recently.

So far, the astronomers have looked at 10 AGNs in the northern galactic hemisphere: Four follow a rough line upward from the galactic center and lie behind the northern bubble, and six lie outside of it. This means they could sample the movement of the material at four different locations. “We can see the gas decelerate and slow down as we go up into the Fermi Bubble,” says Fox. What exactly is slowing the gas, however, is a mystery. They also found that, just as the gamma-ray and microwave emissions abruptly stop about 25,000 light-years out, so does this flowing material.

The next step in their research is to study the southern bubble, which is much more difficult. That’s because there are far more — for example, the Magellanic Stream of material being pulled from the Magellanic Clouds into the Milky Way — lies in the way and contaminates the data. Separating the two bubbles’ signals from the intervening material will take extra time and attention, but it must be done.

**The X-ray factor**

Not everyone is convinced the microwave haze seen in 2003 was the first hint of Fermi Bubbles. Instead, they point to an earlier paper by Jos Bland-Hawthorn and Martin Cohen that focused on X-ray data from the ROSAT (Roentgen-Gamma observatory), which launched in 1990. The researchers saw a figure-eight shaped outline centered on the galaxy’s core, but they interpreted the signal as coming from the dissipated shell of a star sitting in the foreground.

The more recent X-ray observatory XMM-Newton has produced a tantalizing detection of the edges, Slater says, but astronomers don’t yet have enough X-ray data about the bubbles to help further narrow the structures’ source. Some balloon structures also show up in radio waves, although the shapes are slightly askew. Ettore Carretti, then at CSIRO in Australia, used observations from the Parker Radio Telescope to hunt for Fermi Bubbles. His team measured these structures’ magnetic field strengths and the energy contained within them.

In their January 2013 Nature article, the team members calculated that multiple generations of exploding massive stars over about 10 million years would best fit the radio observations. “This setup of the outflow — and gas is expected to explode as supernova, the outgoing material — traveling at supersonic speeds — creates shock waves laced with magnetic field lines. The waves sweep up electrons and accelerate them to higher energies.”

**Virtual bubbles**

Astronomers can’t go back in time a few million years to watch what actually produced the bubbles. Their solutions so theorists are building computer simulations that model the different possible processes in hopes of reproducing today’s gamma-ray and microwave structures. These models are giving scientists insight that they wouldn’t get from observations alone.

The models must match the bubbles’ edges, shape, and size — in gamma rays, microwaves, radio waves, and X-rays. They also need to match an oddly flat gamma-ray energy spectrum (meaning the intensity of light is basically the same at energies 1 billion times that of visible light and at energies 100 billion times as intense). Then there’s the unexplained brightness profile. The amount of gamma radiation throughout the structures is nearly identical no matter if astronomers look 2,000 light-years from the galactic center or 20,000 light-years into the bubble. How could an electron created at the center of the galaxy keep its energy as it moves so far out?

Karen Yang, a postdoctoral fellow at the University of Maryland, spent the last few years making complex 3-D computer simulations of the Fermi Bubble formation. She and her colleagues looked at jets emanating from the central supermassive black hole about 1 million years ago. These carried high-energy electrons from the galactic center to between 15,000 and 30,000 light-years above or below it. Their model created the same size and shape of the Fermi Bubbles, along with the sharp gamma-ray edges. The simulations also reproduced the smooth bubble surface, uniform surface brightness of the observed bubbles, and the ROSAT X-ray arcs surrounding the bubbles,” Yang says. Their models also match with the microwave emission and radio measurements.

However, she adds that no simulation — from her group or other teams — has matched all observations. The flat gamma-ray spectrum, for example, is a characteristic that no one can yet create in a computer. It seems that more observations are necessary. And soon, astronomers will have another X-ray telescope to make them.

**Waiting for data**

In February 2017, Russia and Germany will launch their partnership mission, the Spectrum-Roentgen-Gamma observatory. Its eROSITA telescope (short for “extended ROSAT Survey with an Imaging Telescope Array”) is the primary instrument on board, and it will map the full sky in a similar energy range of what ROSAT did, but with 20 times the sensitivity. The all-sky survey also will capture X-rays at slightly higher energies than ROSAT. The full eROSITA survey will take nearly four years.

What Finkbeiner is most looking forward to is the spectral information that eROSITA will provide to teach astronomers about the temperature of the material along the shock front at the bubbles’ edges. They hope to learn about the densities of the bubbles and the material it’s raining into, plus information about its speed, which should corroborate what Fox’s team has revealed in its ultraviolet observations. All of this information will help astronomers understand what the source or sources are.

“No, you may be concerned that even after all that, we won’t really know whether it’s an AGN or a starburst, and that may be true,” Finkbeiner says. No matter what the data reveal, astronomers will have even more crucial information to solve the puzzle. “We’re just hoping it’s a much better image of what’s going on.” And of course, a bit of luck wouldn’t hurt, either.

**Quasar clues**

Quasar clues

Whatever blew these bubbles did so relatively recently.

The astronomers split up each AGN into its color, or wavelengths. Different elements absorb light at different, specific wavelengths, and so the scientists can see what’s in the bubbles’ gas. They have identified silicon and carbon.
For 24 terrifying minutes, Fiona Harrison and her team watched the spikes in electric current. Each burst indicated that another one of their space telescope’s tinker-toy-like sections had exited its holding cell and locked into place. With the 57 sections fully deployed, a school-bus-sized mast now separated the telescope’s main optics from the cameras that would focus and collect the highest-energy X-rays for the first time.

Harrison is the principal investigator for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission and a professor of physics and astronomy at the California Institute of Technology. She says she felt a combination of elation and nervousness while watching data from each step of the deployment. What she calls her “24 minutes of terror” — likened to the Mars Curiosity team’s “seven minutes of terror” during the rover’s landing sequence — followed nine days after NuSTAR launched June 13, 2012.

Before they sent the X-ray telescope into space on a rocket attached to the belly of Orbital Sciences’ Stargazer aircraft, mission scientists had to test everything. The spacecraft was shaken and put through extreme temperatures. But no one can easily check how something will work in a gravity-free environment. So the NuSTAR team never tested the mast’s delicate structure unfolding with all of its instruments. Instead, the first time the entire spacecraft was deployed was after they launched it into space.

The researchers weren’t sure if it would operate properly when the time came. “But it did; it worked perfectly,” Harrison says. In the three years since that harrowing summer day, the observatory has given Harrison and her colleagues incredible views of the supermassive black hole at the center of our galaxy.

NASA's bargain X-ray space telescope, NuSTAR, is revealing hidden secrets from the supermassive black hole at the center of our galaxy. by Liz Kruesi
the high-energy universe. Some of NuSTAR’s most exciting discoveries have been at the very center of our Milky Way Galaxy. There, in an area a few hundred light-years wide surrounding a supermassive black hole, astronomers can explore some of the most extreme objects in the cosmos.

The black hole laboratory

The crown jewel of our galaxy is a black hole packing the mass of more than 4 million Suns. Like any black hole, this one, called Sagittarius A* (pronounced “A-star”), isn’t directly visible. Instead, astronomers know it exists because they’ve tracked the orbits of nearby stars around it. And they’ve watched radiation outbursts as material circles the gravitational drain and is swallowed as a snack.

But Sagittarius A* and the stars used to discover its presence are not alone in the galactic center. This region — about ⅛° by ⅛° on the sky, or some 230 light-years on either side — contains thousands of objects. The dense cores of stars, filaments of hot magnetic gas, clouds of cold gas and dust, the scattered remains of dead massive stars — all are crammed around this supermassive black hole.

Astronomers look to the galactic center to study one of the most extreme environments in space. So it’s no surprise that the region is one of NuSTAR’s primary targets.

This telescope detects the most energetic form of X-rays, which astronomers call “hard” X-rays. Specifically, NuSTAR gathers photons thousands of times more energetic than those of visible light. Harrison’s team accomplishes this thanks to the observatory’s twin telescopes, each composed of 133 concentric reflective cylinders that capture and guide X-ray photons to an associated camera. 33 feet (10 meters) away. Both cameras pack four cadmium-zinc-telluride detector chips, which convert high-energy photons of light into electronic signals.

But NuSTAR is actually a fairly simple observatory — scientists point toward a target and collect the light on those detectors. In that collected light, they get a photograph of the sky, the energy spectra (each color’s intensity) for everything in the field of view, and specific timing information about when each photon fell on the detector. In a way, it’s three instruments in one.

The ability to collect this much information for each observation has been crucial for NuSTAR scientists, especially when studying targets that change rapidly. Several of the observatory’s major findings at the galactic center required this data haul.

Bright flares, long screams

Our galaxy’s supermassive black hole lets out frequent blasts of energy. The Chandra X-ray Observatory spotted the first flares from Sagittarius A* in 1999. Since then, astronomers have seen the black hole outburst an average of twice a day in infrared and once per day in low-energy “soft” X-rays. But they still have no idea what’s causing these flares.

Despite these extremes, the Milky Way’s supermassive black hole is relatively weak in comparison to the active galaxies astronomers have turned up in recent years. But its proximity makes it an ideal place to learn about all galactic cores.

“Here is by far the closest supermassive black hole, and we’re still really scratching our heads to figure out why it is such an incredibly faint source,” says Boston University’s Joe Neilsen, who uses Chandra to study these flares. “These bright flashes of radiation have to be telling us something really interesting about the immediate neighborhood of the black hole.”

The data they have so far match many different scenarios, from rocky objects being torn apart to magnetic field lines twisting and breaking. “In principle, if you combine [our] data with data from Chandra and other observatories, we should be able to figure out what the mechanism is by which these flares are being produced,” says Columbia University’s Chuck Hailey, who leads the NuSTAR galactic plane survey. But because the intensity of the energy from such an outburst drops steeply at higher energies, NuSTAR needs the brightest flares. “Something above 40 times the quietest, or sleeping, state of the supermassive black hole is what we want” for a thorough analysis, Hailey adds.

And astrophysicists were lucky, at least at first. In NuSTAR’s first four months, the telescope spied two brilliant flares about 50 times brighter than the black hole’s baseline and two fainter ones closer to about 20 times the intensity. But they’ve pointed the telescope at Sagittarius A* several more times and only seen faint flares.

One of the main complications with finding the flares is that there’s another “annoying” source at the galactic center. In this region lies many binary systems, each containing a neutron star and a lower-mass companion Sun. As the companion dumps material onto the neutron star, that material heats up and emits X-rays. Astronomers have known since 2003 that one of these binaries sits just 3 light years from Sagittarius A*. And in May 2013, this object decided to show off.

“It seems to be letting out a particularly long scream,” says Hailey. Luckily, such an X-ray binary is intermittent, and it will quiet down again. When it does, NuSTAR researchers will look back at Sagittarius A* and await additional flares. Hailey is positive the telescope will capture them. “There’s no doubt in my mind that over the next couple of years, we’re going to see some bright flares.”

Until then, scientists are looking for the echoes of Sagittarius A*’s past flaring. Large nearby gas and dust clumps, called molecular clouds, reflect X-rays from previous flares. That reflected light takes a longer path to get to Sagittarius A* to Earth, so astronomers see this light echo decades to centuries later. By studying data from Chandra and other X-ray telescopes, scientists recently realized that the black hole let out several larger flares or a gigantic one hundreds of years ago.

“It is possible that Sagittarius A*’s activity is unusually quiet now but it was more active in the past,” says Columbia University’s Kaya Mori, who is leading an analysis of the nearby molecular clouds. The NuSTAR team doesn’t have any definitive results yet, although they plan to release a peer-reviewed paper soon.

NuSTAR watched X-ray flares burst from the supermassive black hole at the Milky Way’s center over the course of several days in 2012. The hottest material, which reached up to 180 million degrees F (100 million degrees C), is shown in white. 

Contributing Editor Lia Kuehn’s coverage of black holes in Astronomy magazine won her the 2013 David N. Schramm award for high-energy astrophysics science journalism.

NuSTAR is giving astronomers a fresh look at the universe thanks to its unique view of the electromagnetic spectrum. No other spacecraft has focused light in the high-energy X-ray region. 

Energies of electromagnetic radiation have to be telling us something really interesting about the immediate neighborhood of the black hole.
Whatever G2 is, it swung nearest the black hole in early 2014. As it came about 240 times the Earth-Sun distance from Sagittarius A* and rammed through the black hole’s dense environment, astronomers expected G2 would feel a shock and light up before being torn apart by the black hole’s gravity. So they kept turning their X-ray, radio, and infrared telescopes toward the galactic center to see the first sign of this interaction. When Swift caught the brightest flare it had ever detected at the galactic center, astronomers were ecstatic they were about to watch the G2 show.

Two days later, NuSTAR came on the job. The hard X-ray scope detected bursts of X-rays spaced 3.67 seconds apart — a strong sign that the blast Swift saw was not a result of the G2 interaction but instead from an extremely magnetized type of neutron star called a magnetar. These neutron stars spin relatively fast, giving you an estimate of the magnetic field strength of the surrounding magnetic field. The clincher piece of evidence came when Mori’s team measured a small change in the pulsation period, called the spin-down rate. “The spin-down rate, combined with the period, gives you an estimate of the magnetic field strength of the neutron star,” explains Victoria Kaspi, a neutron star expert at McGill University in Montreal. “And that’s what seals it.”

Magnetars are the most magnetic objects in the universe. They have magnetic fields hundreds to thousands of times stronger than normal neutron stars, which are already extremely magnetic. Each time that cracked spot on the surface spins into view, telescopes detect the energy. A neutron star called a magnetar. These neutron stars spin relatively fast, giving you an estimate of the magnetic field strength of the surrounding magnetic field. The clincher piece of evidence came when Mori’s team measured a small change in the pulsation period, called the spin-down rate. “The spin-down rate, combined with the period, gives you an estimate of the magnetic field strength of the neutron star,” explains Victoria Kaspi, a neutron star expert at McGill University in Montreal. “And that’s what seals it.”

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A stellar graveyard?
One of the best gifts a new telescope can give astronomers is an unexpected discovery. And that’s precisely what NuSTAR has done. Most of the X-ray-emitting objects in the galactic center throw out only soft X-rays. For example, Chandra and Europa’s XMM-Newton had detected a haze of soft X-rays in the Milky Way’s central region. The light from this soft X-ray haze fades out at higher energies. While astronomers aren’t positive yet what this haze is, the most likely source is the combined blazar of hundreds of white dwarfs — the still glowing cores of once Sun-like stars that are stealing material from companion stars. Each of these white dwarfs holds about half the Sun’s mass in an Earth-sized sphere. While a postdoctoral fellow at Columbia University, Kerstun Perez was studying one of the rare galactic center objects that don’t disappear at higher-energy X-rays. To concentrate only on this nebula, called G359.95–0.84, she had to subtract out the other signals from NuSTAR’s data. But the object still appeared far too bright in these hard X-rays, says Perez, who’s now at Haverford College in Pennsylvania. She and her colleagues checked everything else the signal could be — stray radiation in the background, smeared light from the nebula, and even the Chandra and XMM soft X-ray haze that, maybe, doesn’t fade out as expected. But the signal was still there. They discovered a bright haze in the central 13 by 26 light-years around Sagittarius A*, but “it’s probably not really truly diffuse in the sense of being gas,” says Harrison. The astrophysicists have four potential sources for this new-found emission, but none is a perfect fit. “[All four] go against the common knowledge of how those objects work,” says Perez. Three of the four theories include compact objects in binary systems stripping material from their neighbors, like the pesky object that’s frustrating X-ray scientists looking for Sagittarius A* flares. As this material piles up, it ignites and glows in X-rays. There could be so many of these binary systems that NuSTAR can’t resolve them individually and thus sees them as a fog. One of these exciting possibilities is an abundance of neutron stars and stellar-mass black holes. Swift, however, has been staring at the galactic center nearly every day for the past 9.5 years, and it’s seen only a few such systems near Sagittarius A*. “We’re saying we would need to hide a thousand of them,” says Perez.

The fourth possible source of this hard X-ray emission is high-energy material flowing from the region very near Sagittarius A*. This might be bright flares from the black hole, and that light is interacting with nearby dense molecular cloud material. The problem with this suggested source is that the geometry of the clouds doesn’t quite match the location of the emission that NuSTAR sees.

Out of all the theories, Perez finds the many black holes option the most exciting. But such a situation also would point to perhaps the most interesting questions. For a star to form a black hole at its death, it needs to start out extremely massive — at least 30 times our Sun’s mass. How would so many massive stars get to the very center of the galaxy? And why hasn’t any other X-ray telescope seen more than a few black holes binary in the nucleus?

In the meantime, scientists are using NuSTAR data to tally the point sources — like individual stars — that lie just about 8° degree (about 115 light-years) north of the galactic center. They also will compare the spectral properties of those resolved sources to the emission.

“It’s kind of like nibbling around at the edge of the emission to see if we can take it out. It’s not as simple as detecting something that have the same properties as what we see right at the center of the galaxy,” says Hailey. These major observations only scratch the surface of what NuSTAR has seen in the 1 million seconds it has so far stared at the X-ray glow of the galactic center.

The observatory has now extended its mission that will run until at least the end of 2016. Hailey says NuSTAR will spend roughly the same amount of time aimed toward the galactic center as it did in its primary mission.

After all, this is a fabulous location to study. “The galactic center is a fun place to look in high-energy X-rays just because almost anything that can emit in high-energy X-rays is there,” Perez says. A region crowded with exciting celestial objects, all within a few fields of view of today’s best instruments — it’s the perfect astrophysical laboratory.