Astronomy magazine

# OUR HOME
## THE MILKY WAY

CONTENTS



ESO/B. TAFRESHI

A supplement to *Astronomy* magazine

## THE MILKY WAY

# Earth's home galaxy

**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**

**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 edgewise. 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

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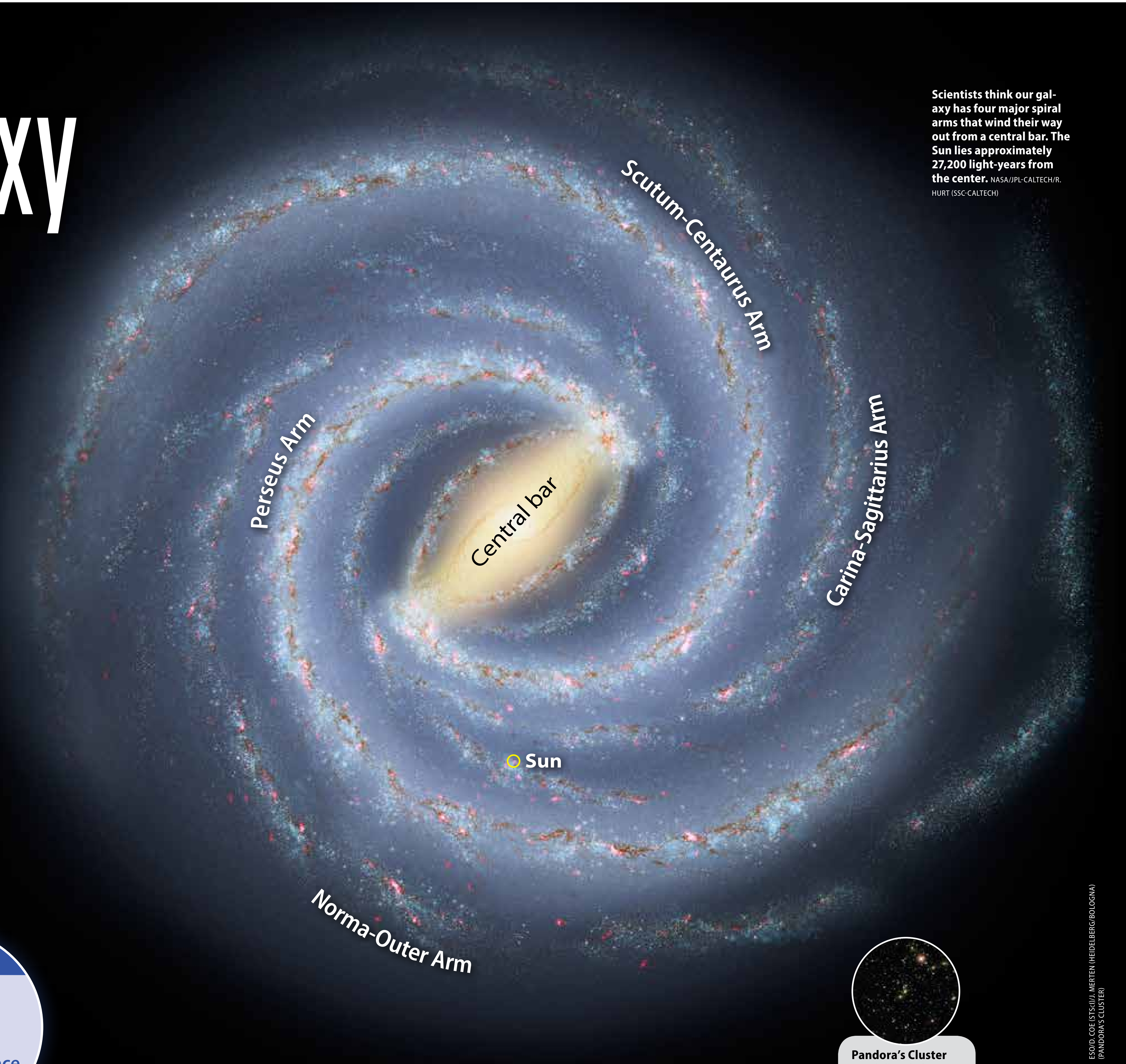



**Scientists think our galaxy has four major spiral arms that wind their way out from a central bar. The Sun lies approximately 27,200 light-years from the center.** NASA/JPL-CALTECH/R. HURT (SSC-CALTECH)

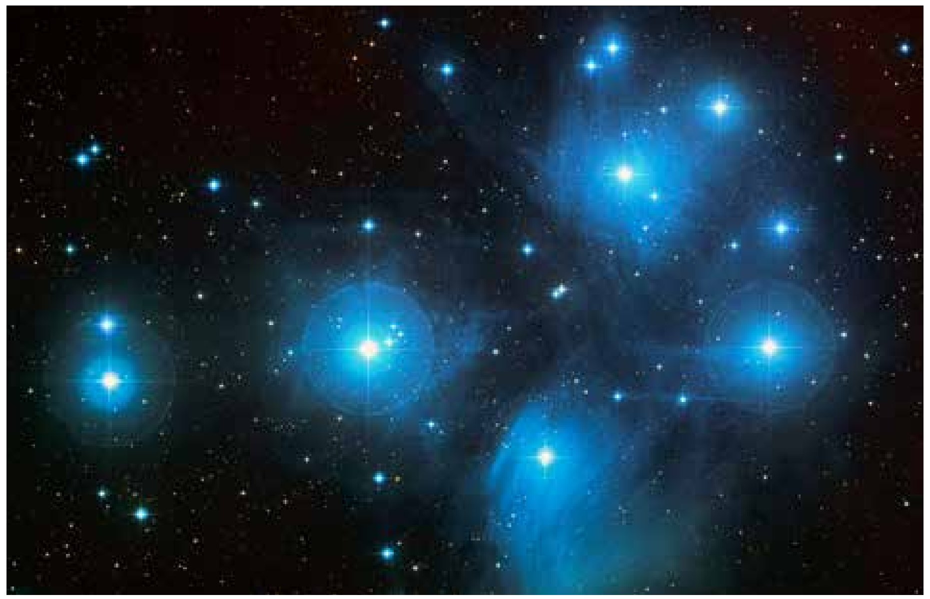
**FAST FACT**
**27,200**
LIGHT-YEARS
The Sun's distance from the galaxy's center

**Pandora's Cluster**
3.52 billion light-years

ESO/D. COE (STScI)/J. MERTEN (HEIDELBERG/BOLOGNA) (PANDORA'S CLUSTER)

*billion light-years*
2.75 | 3 | 3.25 | 3.5

The Carina Nebula (NGC 3372) ranks among the Milky Way's biggest stellar nurseries. 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. NASA/ESA/N. SMITH (UCB)/THE HUBBLE HERITAGE TEAM (STScI/AURA)



**The Pleiades star cluster (M45) resides 440 light-years from Earth in the constellation Taurus. A prototypical open cluster, it spans about 15 light-years and holds some 500 stars. These luminaries will disperse over the next few hundred million years.** NASA/ESA AND AURA/CALTECH

dust-obscured regions of the disk, and reveal that the central component of our galaxy, called its "bulge," is really a vast football-shaped star cloud seen nearly end on. This discovery resulted in a classification change for the Milky Way from spiral galaxy to barred spiral galaxy.

Several ambitious and complementary projects now aim to provide a true 3-D portrait of our galactic home. The European Space Agency's Gaia spacecraft, which was launched in 2013, should return position and motion information of unprecedented accuracy for roughly a billion stars.

But Gaia largely covers optical wavelengths, which means that intervening dust clouds limit how deeply it can probe into the galaxy's disk. Dust doesn't affect radio wavelengths, and a facility called the Very Long Baseline Array (VLBA) can measure distances and motions to a small number of sources more accurately than Gaia. By linking 10 radio dishes located from Hawaii to St. Croix so they function as a single telescope, the VLBA has the greatest resolving power available to astronomy. Two projects, the Bar and Spiral Structure Legacy (BESSEL) survey and the VLBI 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 the nearest star today is Proxima Centauri, 4.22 light-years away, other stars played this role in the past and will do so in the future.

All stars orbit the center of the galaxy, but these orbits are more elliptical and more tilted than planetary orbits in the solar system. The Sun now lies about 27,200 light-years from the Milky Way's center — more than one-third of the way into the disk — and roughly 90 light-years above the galaxy's midplane. During each orbit, which takes about 240 million years to complete, the Sun's position oscillates above and below the galactic plane. Other stars in our vicinity follow slightly different paths, which means that the distribution and composition of our stellar neighborhood gradually changes. Stars routinely pass much closer to the Sun than Proxima Centauri is now.

For example, in 2014, astronomer Ralf-Dieter Scholz of the Leibniz Institute for Astrophysics in Potsdam, Germany, discovered that a faint M dwarf star detected by WISE was about 20 light-years away, making it a previously unknown close neighbor. A team led by Eric Mamajek at the University of Rochester in New York noticed that "Scholz's Star," which is actually a binary, shows little motion across the sky but rapid motion directly away from us, suggesting it might have grazed the solar system.

The study reveals that the binary passed well inside the Oort Cloud, coming within 52,000 AU about 70,000 years ago, and now holds the record for the closest flyby of any known star. It will take about 2 million years for any comets dislodged by this passage to reach planetary orbits, but the system's low mass — just one-sixth the Sun's — and its path through the outer Oort Cloud argue against any significant comet enhancement.

Dim, low-mass M dwarfs like Scholz's Star and Proxima Centauri actually typify the Milky Way's stellar population. Most of the galaxy's roughly 400 billion stars are likely M dwarfs, but because they emit little visible light, we're still finding those close to the solar system through infrared surveys like WISE. For stars, mass is destiny. M dwarfs may be dim, but their low masses mean they burn their nuclear fuel sparingly and will keep shining billions of years after the Sun dies.

Some stars barely shine at all. They never generate energy in their cores though 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 within 16 light-years of the Sun, but only 10 of them are visible to the naked eye.

The night sky distorts our picture of the galaxy's stars in another way, too. Of the 100 brightest stars in the sky, a third lie within 100 light-years. These include Sirius, the night sky's brightest, 8.6 light-years away; Procyon, 11 light-years away; Vega and Fomalhaut, both 25 light-years off; Castor (52); Aldebaran (65); and Regulus (77). But another third lie more than 400 light-years away, including Polaris (430), Antares (600), Betelgeuse (640), Rigel (860), and Deneb (2,600). All these stars have masses more than seven times the Sun's and are tens of thousands of times more luminous. Consequently, they burn through their hydrogen fuel at a faster clip. Long before our Sun's fires quench, these stars will end their days in spectacular supernova explosions.

## From stars to clusters

Going further up the mass scale results in an ever-dwindling number of stars, and not just because the most massive ones are so short-lived. Stars are born in dense, cold molecular clouds. Once a massive star forms, its intense ultraviolet light and a powerful outflow called a stellar wind start to disperse the birth cloud, limiting the number of other massive stars able to form nearby. Only a few dozen stars in the Milky Way have energy outputs exceeding a million times the Sun's. Topping the list are WR 25 and Eta Carinae, two massive

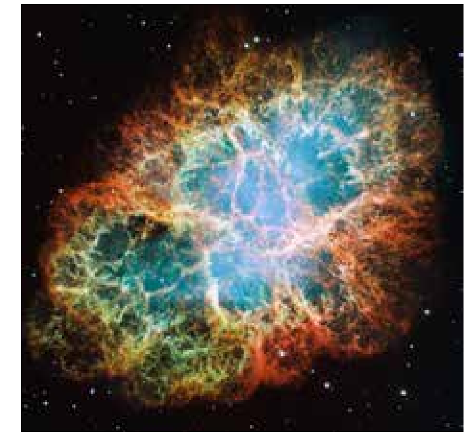
### HOW THE MILKY WAY GALAXY GOT ITS NAME

Spend some time under the stars any clear night far from city lights, and a ghostly band called the Milky Way eventually will come into view. Flecked with some of the brightest stars in our galaxy and cleaved by intervening dust clouds for about a third of its extent, the Milky Way has been recognized since antiquity. In mythology, it was frequently associated with a cosmic pathway or heavenly stream.

The ancient Greeks called it *galaxías kýklos*, the "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 lactea*, the "milky way." Galileo Galilei took the first step in understanding what it actually represented in 1610, when his new and improved spyglass revealed that the pale light came from individual faint stars "so numerous as almost to surpass belief."

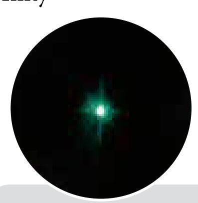
Over the next two centuries, as astronomers began to understand that the Milky Way was part of an "island universe" that included the Sun and other visible stars, the name for a mythical cosmic pathway was transferred to our galactic home. — *F. R.*

**At a distance of 1,350 light-years, the Orion Nebula (M42) 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.** NASA/ESA/M. ROBBERTO (STScI/ESA)/THE HST ORION TREASURY PROJECT TEAM



**Massive stars live fast and die young, exploding as supernovae and leaving behind remnants like the Crab Nebula (M1). Such star death often triggers future star formation as shock waves compress surrounding gas.** NASA/ESA/J. HESTER AND A. LOLL (ASU)

**FAST FACT**
**150,000**
LIGHT-YEARS
Diameter of the galaxy's disk



**3C 48 (quasar)**
4.05 billion light-years

NASA/ESA/NICMOS (3C 48)

*billion light-years*
3.75 | 4 | 4.25 | 4.5

Sagittarius A*, the bright spot at the heart of the luminous cloud at center, glows strongly in X-rays as matter swirls into the maw of a 4-million-solar-mass black hole. This supermassive object lies 27,200 light-years from Earth and is the gravitational hub of our galaxy. NASA/CXC/UNIVERSITY OF WISCONSIN/Y. BAI, ET AL.

## FROM AU TO LIGHT-YEAR

Where the solar system ends, interstellar space and the galactic frontier begin. At the fringe of the Oort Cloud, perhaps 100,000 astronomical units (AU; the average Earth-Sun distance) away, comets are about as likely to be dislodged from the solar system as to continue in their slow orbits. From here on out, expressing 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 closest large star-forming region, is about 1,350 light-years 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 galaxies like our own developed and evolved over billions of years. — *F. R.*

binary systems located about 7,500 light-years away and shining with 6.3 million and 5 million solar luminosities, respectively. Another eight stars in the Carina Nebula make the cut as well, and seven more occur in a stellar grouping called the Cygnus OB2 association.

Massive stars play a powerful role in mapping out our galaxy's spiral arms. They can be seen across great distances, they explode before wandering too far from their stellar nurseries, and they can light up their dissolving birth clouds and excite molecules within them, like water and methanol. Under the right conditions, which are common in star-forming regions, these molecules can become masers — the microwave equivalent of lasers — and beam amplified radio waves our way, creating beacons that cut through starlight-blocking dust clouds.

Star groupings of various types also help trace galactic structure. OB associations are loose collections of between 10 and several hundred hot, young, and massive O- and B-type stars spanning up to a few hundred light-years. The nearest is the Scorpius-Centaurus OB2 association, which lies about 470 light-years away and boasts the red supergiant Antares among its members. Its oldest subgroup was born roughly 15 million years ago, and shock waves from a supernova helped trigger star formation in a neighboring cloud about 5 million years ago.

Open star clusters, such as the Hyades and Pleiades in Taurus (150 and 440 light-years away, respectively) and the Beehive in Cancer (about 580 light-years distant), are relatively compact collections of stars that formed together within the same molecular cloud. These clusters contain anywhere from dozens to hundreds of stars in a region less than about 50 light-years wide, and they will gradually disperse over a few hundred million years. Astronomers have cataloged about 1,200, though the Milky Way may contain as many as 100,000.

In places like the Orion Nebula and the Eagle Nebula (1,350 and 7,000 light-years away, respectively), where young stars have emerged from their birth clouds and set them aglow, scientists are seeing the creation of new open clusters less than 2 million years old. Young clusters can be detected in the infrared even before they break out of their natal cloud. Using data from WISE, a team led by Denilso Camargo at the Federal University of Rio Grande do Sul in Brazil reported in 2015 the discovery of hundreds of dust-shrouded clusters embedded deeply in their host molecular clouds.

OB associations, open clusters, and embedded clusters all reside in the Milky Way's disk. But globular clusters form a radically different kind of galactic tracer. Essentially giant star balls, these clusters pack tens of thousands to perhaps a million stellar siblings into spheres less than 300 light-years across. Our galaxy has fewer than 200, and all are more than 10 billion years old. Globular clusters orbit the galaxy's center, but they follow wildly inclined paths that take them far above and below the disk. Researchers now know that the Milky Way has pilfered at least some globular clusters, but more on that later.

### 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, the seed for new stars. 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 mainly 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 not too far from end on. Until recently, astronomers regarded the bulge as sort of a senior center for aging stars, a population that formed rapidly as the galaxy assembled through mergers with smaller galaxies some 10 billion years ago. Predominantly older stars do occupy parts of the bulge well above and below the disk, but recent studies show a wide range of stellar ages, from 3 to 12 billion years, closer to the midplane. Various lines of evidence suggest the bulge population formed largely as a result of natural instabilities in the evolving disk.

At the center of the bulge is the galaxy's anchor, the object everything else orbits — a supermassive black hole weighing about 4 million solar masses. Regular monitoring of the galactic center shows that it often flares in X-rays — the signature of matter falling toward its doom — but this pales in comparison to what we know a monster black hole can do, and there is evidence it has been more active in the past. In 2010, data from NASA's Fermi Gamma-ray Space Telescope revealed ginormous gamma-ray-emitting bubbles reaching 25,000 light-years above and below the galactic center, likely the smoking gun of a powerful outburst millions of years ago.

The precise structure of the disk remains poorly known, including the number and position of its spiral arms. Recent radio studies of thousands of sources — stars in embedded clusters detected in the infrared, nebulae set aglow by young stars, giant molecular clouds, and water and methanol masers — seem to show that the Milky Way has four major spiral arms that originate near the galactic center and wind outward. In order from the center moving toward the Sun, they are the Norma-Outer Arm, the Scutum-Centaurus Arm, and the Carina-Sagittarius Arm. Farther out, we encounter the Perseus Arm, and farther still, the outer arc of the Norma-Outer Arm.

**FAST FACT**

**1.5 to 2**

**TRILLION SUNS**

**Galaxy's total mass (including dark matter)**

Astronomers long thought that the solar system resided in a starry spur located near the inner edge of the Perseus Arm. Yet one of the first surprising results from the BESSEL and VERA projects is that our "spur" is a significant structure, sporting as much massive star formation as the adjacent major arms. At this point, astronomers aren't sure whether to classify our local patch of the galaxy as a branch of the Perseus Arm or an independent segment.

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 extended its size by about 50 percent over previous values. The number of stars in the disk had seemed to drop off around 50,000 light-years from the center, but then 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 up a few hundred light-years, then down, then up, 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 galaxies orbiting our own may have produced the ripples. One in particular, known as the Sagittarius Dwarf Spheroidal, has passed through the disk multiple times and is gradually dissolving into streams of stars as it orbits the Milky Way. Like a stone tossed into still water, the gravitational effect of a satellite galaxy plunging through the disk could produce ripples. Simulations suggest 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 disk sits within a spherical volume called the galactic halo, a place ruled by globular clusters and satellite galaxies, as well as strewn with stars stripped from 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 largest and brightest globular 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 — called dark matter — reaching 900,000 light-years across, or about six times the disk's diameter. This stuff makes up 27 percent of the cosmos and created the gravitational infrastructure that coaxed ordinary matter into structures that eventually built galaxies like our own.

The current phase of galactic exploration already has provided major new insights, but many questions remain. As astronomers consolidate 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.

Two million stars glow in the core of Omega Centauri, though this is just 20 percent of the globular cluster's total. Omega lies 17,000 light-years away and likely is the bulge of a disrupted dwarf galaxy. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

What does the Milky Way look like from afar? From what we know, it resembles this barred spiral galaxy, UGC 12158. This island universe spans about 140,000 light-years and lies some 400 million light-years away. ESA/HUBBLE AND NASA

*billion light-years*

4.75 5 5.25

# What's blowing BUBBLES IN THE MILKY WAY?

Strange hourglass lobes extend for 25,000 light-years on either side of our galaxy's center. by Liz Kruesi

The Milky Way's gamma-ray bubbles stretch some 50,000 light-years. ASTRONOMY: ROEN KELLY

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.

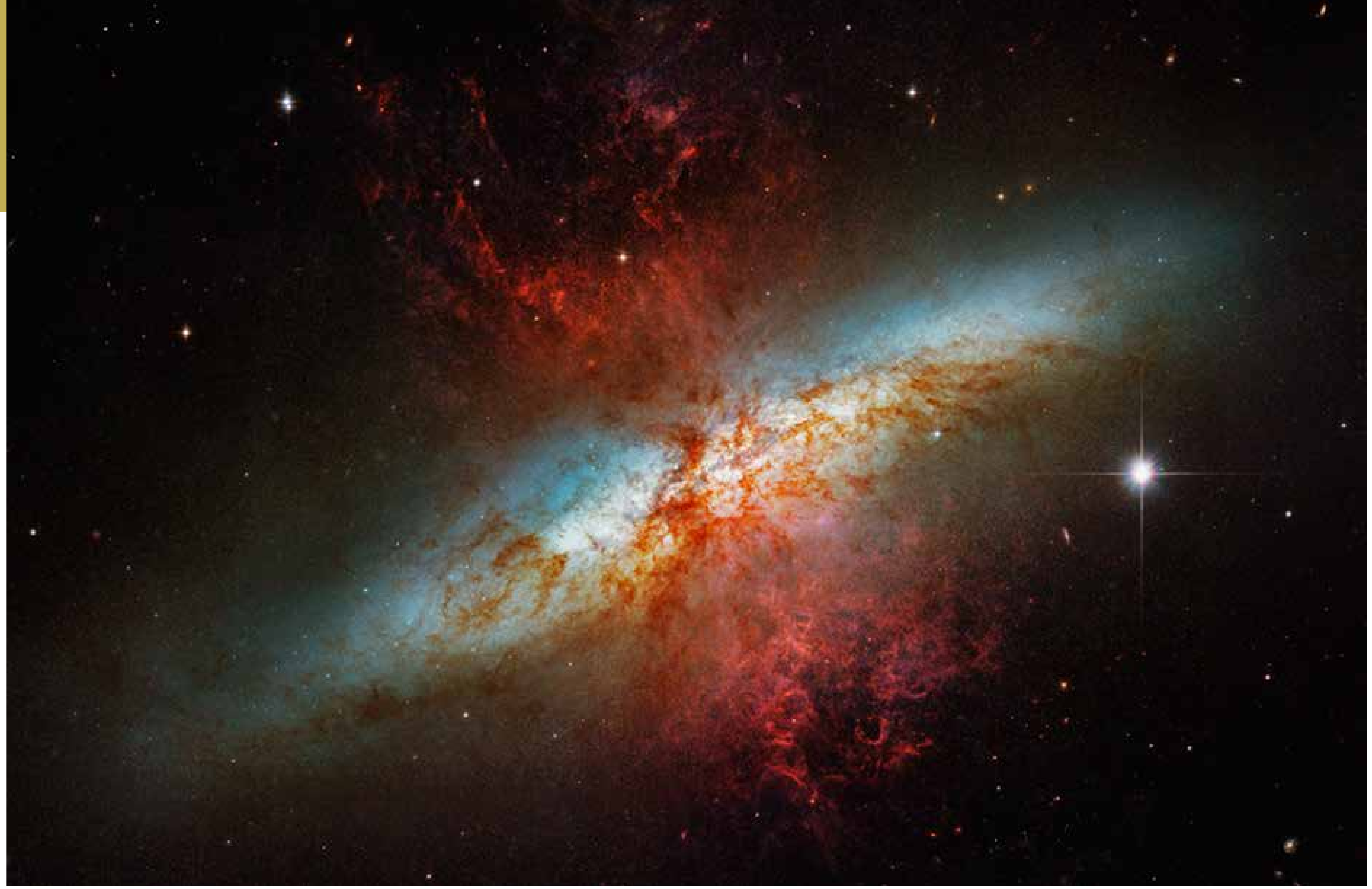
Astrophysicists cannot say what created them. They have narrowed down how long ago these bubbles formed, and they are beginning to sort through their composition. And soon, researchers will have another observatory that should reveal even more.

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."



**Glowing hydrogen erupts from the center of the starburst galaxy Messier 82. Astronomers think the Milky Way's Fermi Bubbles could be something similar.** NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

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 also can encourage gamma-ray radiation through a process called the Inverse Compton Effect. When ambient 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."

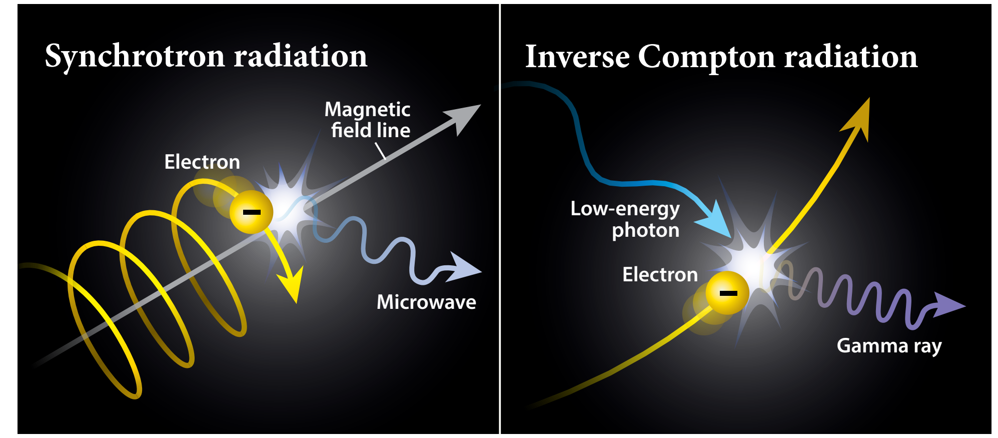
It paid off — they uncovered a haze of gamma rays.

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," says Dobler. "It had this sharp edge, and it had this hourglass shape."

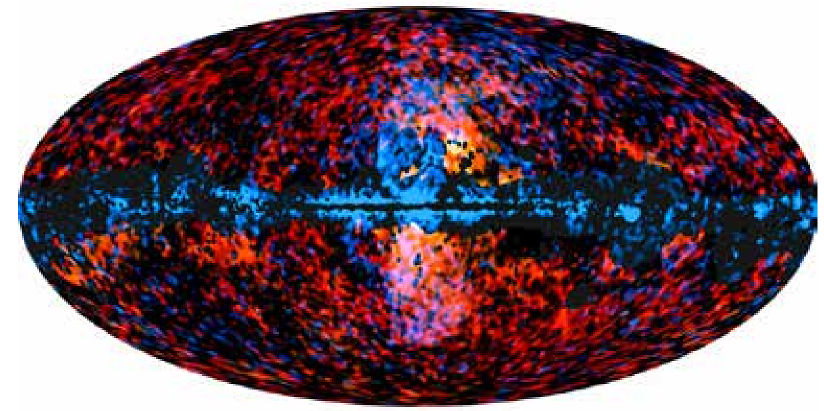
If the emission really had defined structure, it was a much bigger discovery. But many scientists, including members of the Fermi science team, doubted that the haze existed.

**"It wasn't just this diffuse, fuzzy blob ...," says Gregory Dobler. "It had this SHARP EDGE, and it had this HOURGLASS SHAPE."**

*Contributing Editor* ***Liz Kruesi*** *writes about pieces of the cosmic puzzle from her home in Austin, Texas.*




**(Above) Synchrotron radiation happens when electrons traveling along the Milky Way's magnetic field lines change directions. When a high-energy electron smacks a photon, it creates a gamma ray through inverse Compton radiation.** *ASTRONOMY*: ROEN KELLY



**(Left) ESA's Planck spacecraft gathered this all-sky map of the galactic haze in microwaves, which was placed over Fermi Gamma-ray Space Telescope data (blue). Fermi's observations clearly show two hourglass lobes.** ESA/PLANCK COLLABORATION (MICROWAVE); NASA/DOE/FERMI LAT/DOBLER ET AL./SU ET AL. (GAMMA RAYS)

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. Because these 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.

## Jets vs. stars

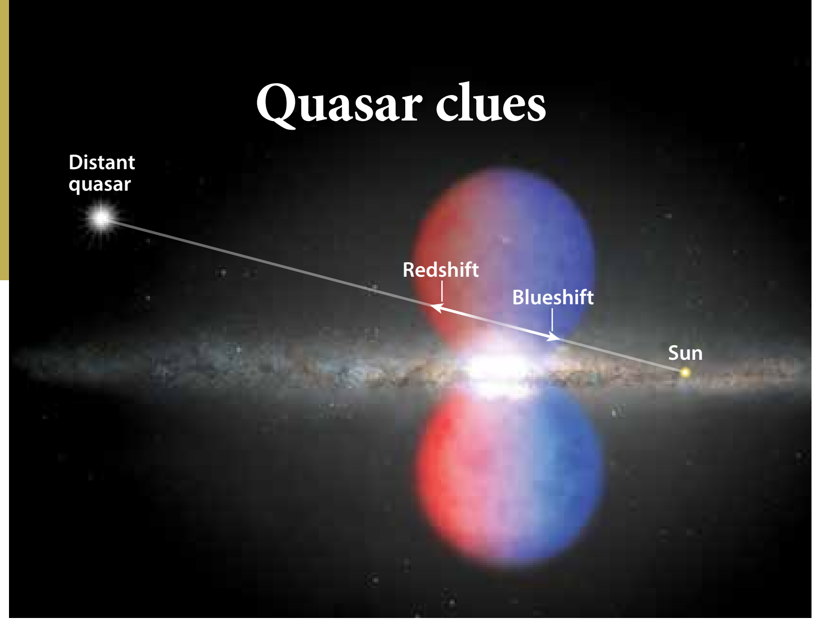
Those distinct edges aren't just for looks, though. This characteristic gives clues to what's causing the bubbles. "When you leave particles to themselves, then generally they sort of smoothly diffuse outward," says Slatyer, who's now an assistant professor at MIT. "If there's a sharp edge, then that suggests that whatever is making the gamma rays cuts off pretty abruptly at that edge."

Some scientists suspect the bubbles' edges are caused by shock fronts, like the bow-shaped feature of air created by a supersonic jet. Others theorize magnetic fields trap charged particles.

The most convincing source of these shock fronts or magnetic fields are 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




**(Right) 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.** NASA/ESA/A. FEILD (STScI)

**(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.** NASA/SONOMA STATE UNIVERSITY/AURORE SIMONNET

the bubbles: first, during those stars' lives as they emit stellar winds, and second, when they explode as supernovae at their deaths.

Astronomers in the field are split, though, about which explanation they prefer. As for Finkbeiner, he has preferred the jet scenario ever since finding the bubble structures. But, he adds, "As the years go by, all of us are kind of sticking with our original idea, and that tells us we don't have enough data to convince anyone either way."

## Into the ultraviolet

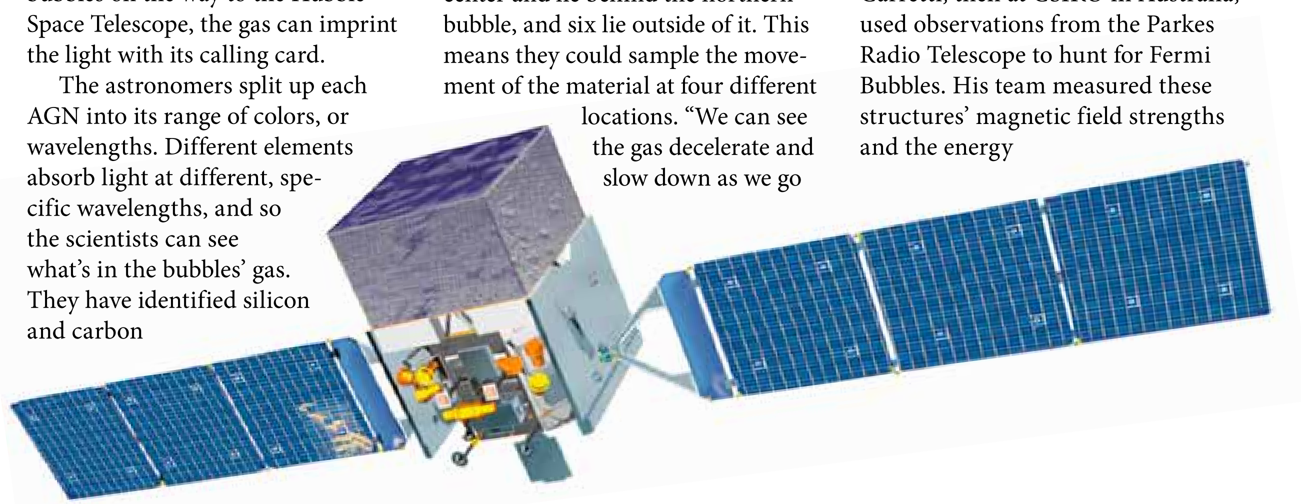
To break the stalemate, astronomers have turned to ultraviolet light. The Space Telescope Science Institute's Andrew Fox and colleagues are using the brilliant centers of active galaxies, called active galactic nuclei (AGNs), as spotlights behind the Fermi Bubbles to sample small sections. When light 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 range of colors, 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 atoms — 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," says Fox. "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 signpost'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.

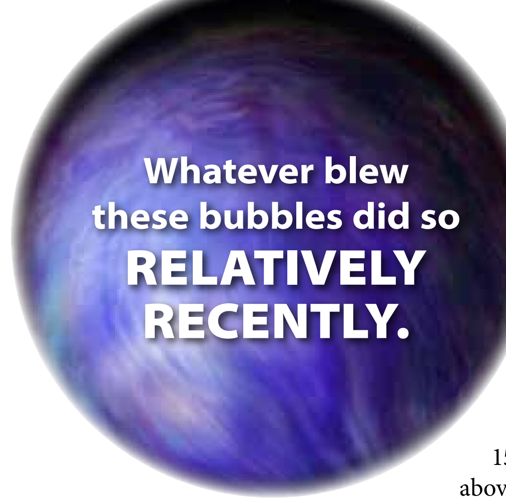
The next step in their research is to study the southern bubble, which is much more difficult. That's because more matter — for example, the Magellanic Stream of material being pulled from the Magellanic Clouds into the Milky Way — lies in the way and contaminates the data. Separating the two bubbles' 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 Joss Bland-Hawthorn and Martin Cohen that focused on X-ray data from the ROentgen SATellite (ROSAT), 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," Slatyer says, but astronomers don't yet have enough X-ray data about the bubbles to help further narrow the structures' source.

These 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 Parkes 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.




The idea is that as massive stars explode as supernovae, 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 Fermi Bubbles, 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 unexpected 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?

H.-Y. 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 our 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.

"Our 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 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 ROentgen 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 ramming 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.

"Now, 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 more crucial information to solve the puzzle. "We're just hoping it's a much better image of what's going on."

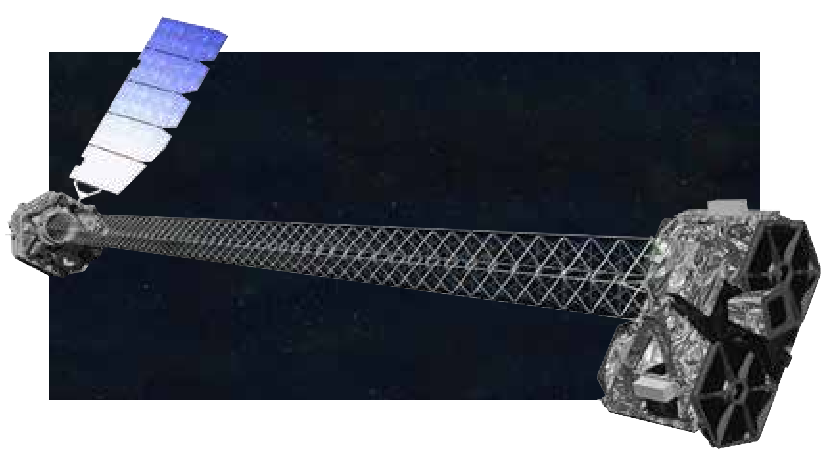
And of course, a bit of luck wouldn't hurt, either.

**Without NASA's Fermi Gamma-ray Space Telescope, which launched in 2008, astronomers were blind to the Milky Way's giant bubbles. They couldn't see the high-energy radiation.** NASA/KIM SHIFLETT

# What lurks in the MONSTROUS HEART of the Milky Way?

Dust normally obscures the Milky Way's galactic center. This view stacks images from NASA's Great Observatories — Hubble, Chandra, and Spitzer — to pierce the veil by combining visible, X-ray, and infrared light. NASA/JPL-CALTECH/ESA/CXC/STScI; NASA/JPL-CALTECH (NUSTAR)

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**



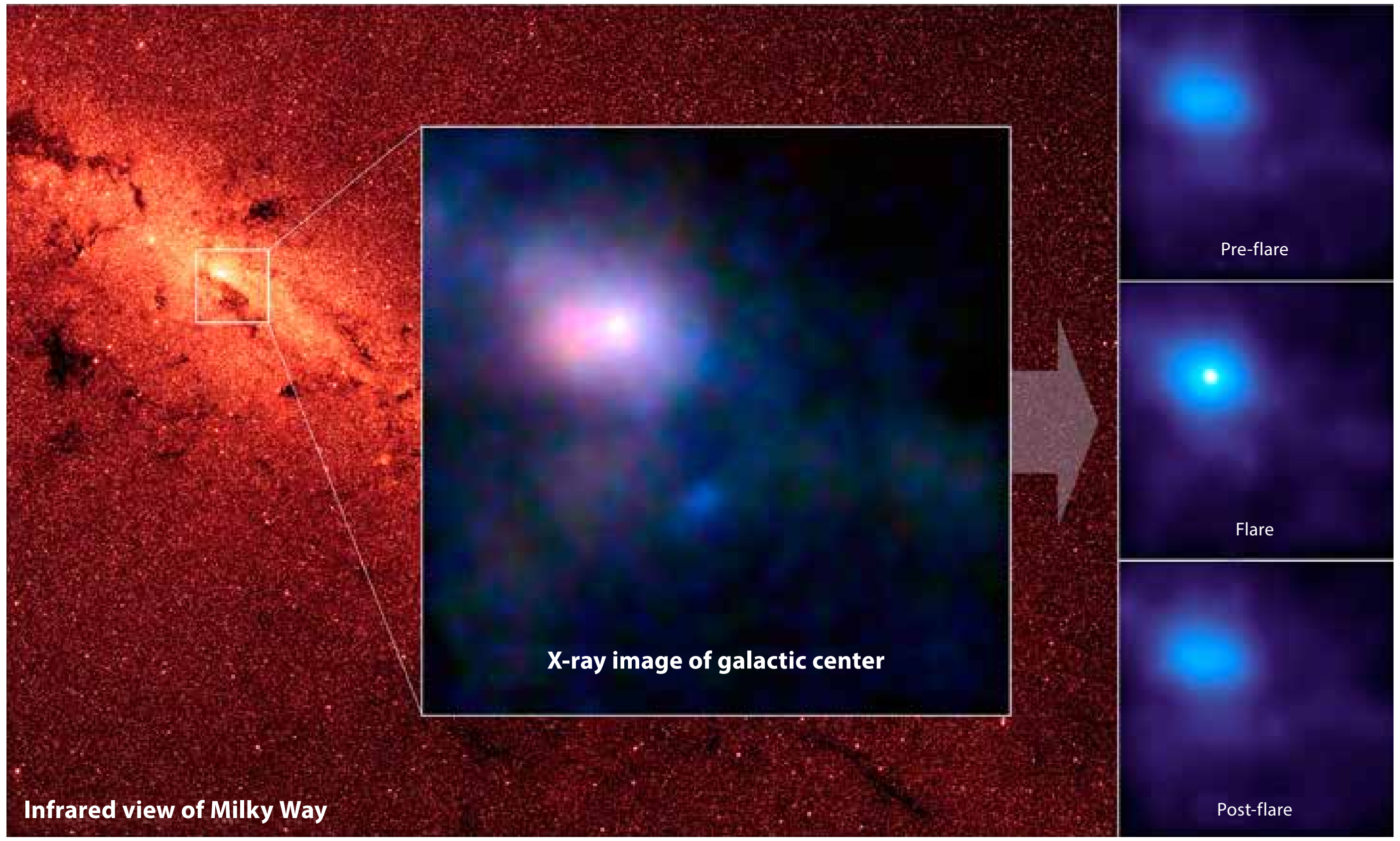
For 24 terrifying minutes, Fiona Harrison and her team watched the spikes in electric current. Each burst indicated that another one of their space telescope's tinker-toy-like sections had exited its holding cell and locked into place. With the 57 sections fully deployed, a school-bus-sized mast now 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




**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.** NASA/JPL-CALTECH

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 ½° by ½° 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.

"This 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 Joey 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 quiescent, or sleeping, state of the supermassive black hole is what we want" for a thorough analysis, Hailey adds.

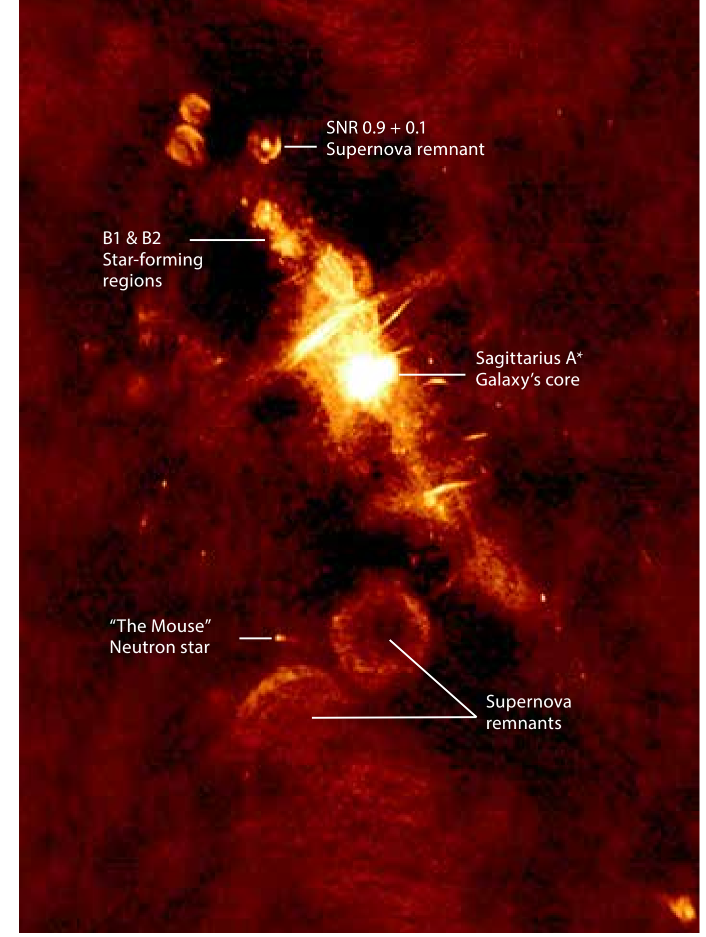
And astrophysicists were lucky, at least at first. In NuSTAR's first four months, the telescope spied two brilliant flares about 50 times brighter than the black hole's baseline and two fainter ones closer to about 20 times the intensity. But they've pointed the telescope at Sagittarius A* several more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




**The Milky Way's center, invisible to our eyes, is home to some of the most exotic objects in the universe.** NRAO/AUI AND N.E. KASSIM, NAVAL RESEARCH LABORATORY

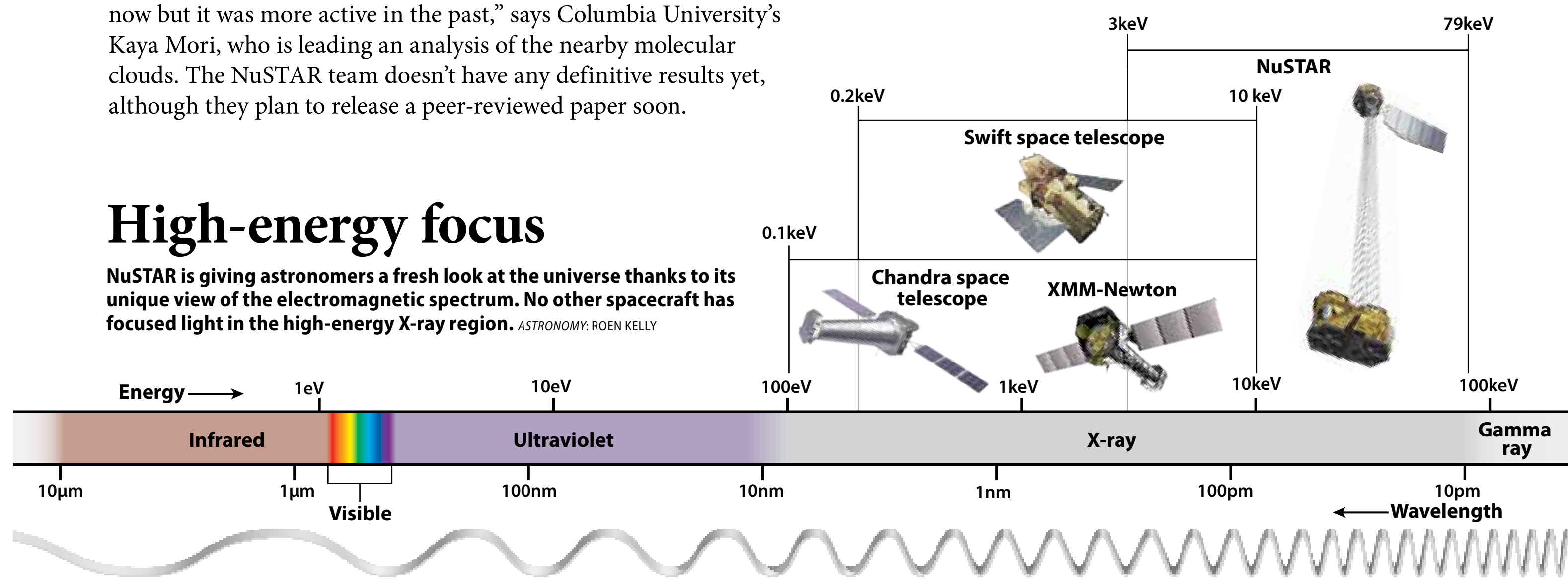
## Found: magnetic monster

These screams aren't the only excitement NuSTAR has seen at the galactic center. On April 24, 2013, another NASA telescope, Swift, which scours the sky for bursts of hard X-rays and gamma rays, detected a brilliant X-ray flare at the same site.

High-energy astrophysicists hoped this signal indicated the dusty gas cloud called G2 had begun interacting with the supermassive black hole. This object, discovered in late 2011, has had a case of conflicting personalities. Some scientists believe it's a gas cloud harboring a star while others think it's just a cloud.

# High-energy focus

**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.** *ASTRONOMY:* ROEN KELLY




*Contributing Editor* ***Liz Kruesi****'s coverage of black holes in* Astronomy *magazine won her the 2013 David N. Schramm award for high-energy astrophysics science journalism.*

**Principal Investigator Fiona Harrison of the California Institute of Technology was awarded this year's Rossi Prize, the highest award in high-energy astrophysics, for assembling and leading the NuSTAR team, which has "opened a new window on the universe."** LANCE HAYASHIDA/CALTECH MARCOMM

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 3.76 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 slowly, completing each rotation in about two to 12 seconds.

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 a trillion times that of Earth. These extreme magnetic fields are unstable and can initiate cracks and shifting of the magnetar's surface, which releases a big burst of energy. Each time that cracked spot on the surface spins into view, telescopes detect the energy.

**NuSTAR was launched from a Pegasus rocket strapped to the belly of Orbital Science's Stargazer aircraft in 2012.** ORBITAL SCIENCES CORPORATION

So far, astronomers have found 28 of these magnetic monsters, typically right after a major outburst.

Armed with the 3.76-second spin period discovered by NuSTAR, radio astronomers looked toward the galactic center and also detected the magnetar, called SGR J1745–2900. This observation came as a huge surprise because scientists had looked for radio-pulsing neutron stars in orbit around Sagittarius A* for years, says Kaspi. Such an object would be the ultimate tool to test the general theory of relativity and measure the black hole's mass precisely. "But people were doubtful you could ever do it because the intervening material, particularly in the galactic center region, is so great that those radio waves would be totally scattered away," she says.

The radio pulses from the magnetar imply there was much less scattering than models predicted. "It shows us there's potentially a much clearer window to the galactic center in radio waves," Kaspi adds. "And it reopens the hope that we can detect radio pulsars there and maybe one day do these amazing dynamical relativistic tests."

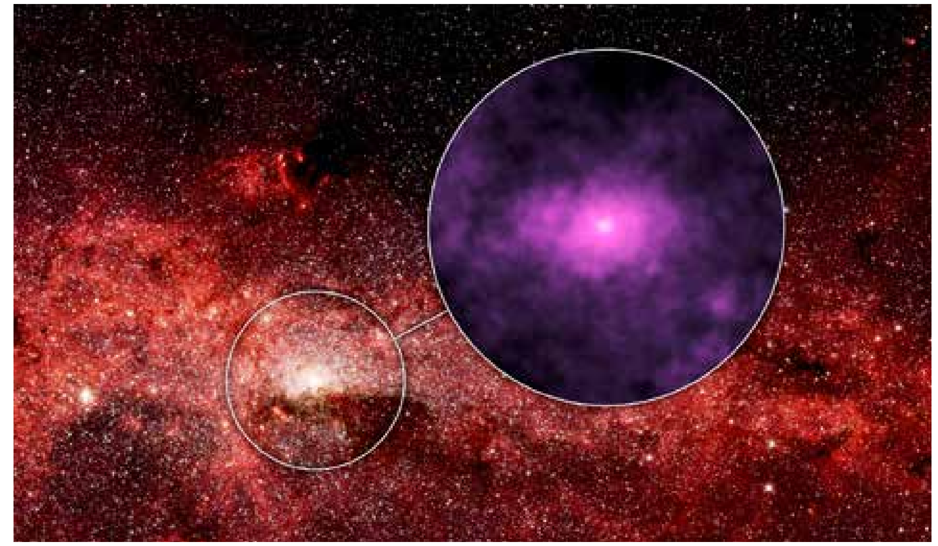
## A stellar graveyard?

One of the best gifts a new telescope can give astronomers is an unexpected discovery. And that's precisely what NuSTAR has done.

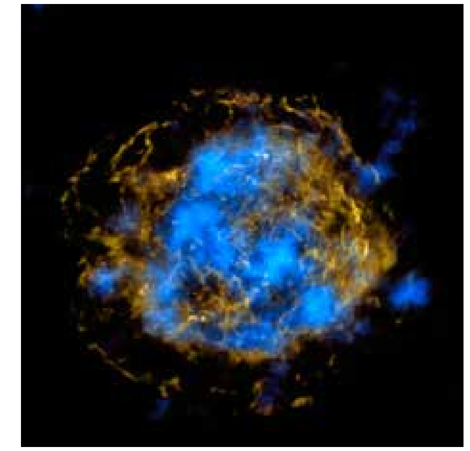
Most of the X-ray-emitting objects in the galactic center throw out only soft X-rays. For example, Chandra and Europe's XMM-Newton had detected a haze of soft X-rays in the Milky Way's central region. The light from this soft X-ray haze fades out at higher energies. While astronomers aren't positive yet what this haze is, the most likely source is the combined blaze of thousands 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, Kerstin Perez was studying one of the rare galactic center objects that doesn't disappear at higher-energy X-rays. To concentrate only on this nebula, called G359.95–0.04, 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.



**It might not look like much, but this magenta dot holds the Milky Way's heart of darkness — a supermassive black hole. NuSTAR's high-energy X-ray view of the galactic center is among the most detailed ever and shows a spinning dead star, or pulsar, as well as an unexpected X-ray haze.** NASA/JPL-CALTECH



**NuSTAR imaged the radioactive guts of a supernova remnant — Cassiopeia A — for the first time ever, shedding light on how stars die. Here, NuSTAR data of radioactive material (titanium) is blue and low-energy X-rays from the Chandra spacecraft are yellow.**
NASA/JPL-CALTECH/CXC/SAO

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 hole binaries in the region?

In the meantime, scientists are using NuSTAR data to tally the point sources — like individual stars — that lie just about ¼° 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 resolve it out into objects 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 entered its extended 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 crammed with exciting celestial objects, all within a few fields of view of today's best instruments — it's the perfect astrophysical laboratory.

### MAPPING A STAR'S SCATTERED REMAINS

NuSTAR's primary mission — which ran from August 2012 until fall 2014 — addressed four main science goals. While one was to study black holes like the one at the center of the Milky Way, another was to understand how a massive star explodes as a supernova at the end of its life. Astronomers try to simulate these stellar explosions on supercomputers, but they've long had a problem: Their stars don't explode. They had assumed supernova blasts were symmetric. But perhaps they're not.

To find out if such explosions are in fact symmetric, NuSTAR scientists looked for the distribution of an element produced in the high temperatures and pressures of supernova blasts: titanium-44 (Ti-44). This element is radioactive, meaning it releases electron antiparticles along with energy in the form of light photons as it decays to a different element. Those photons have specific energies, or colors; two of them are in NuSTAR's detection range.

NuSTAR stared at the young supernova remnant Cassiopeia A for about 1.2 million seconds in 2012 and 2013. When Brian Grefenstette of the California Institute of Technology and his colleagues analyzed the locations of Ti-44, they saw the material was spread asymmetrically throughout the blast's remnant. — *L. K.*