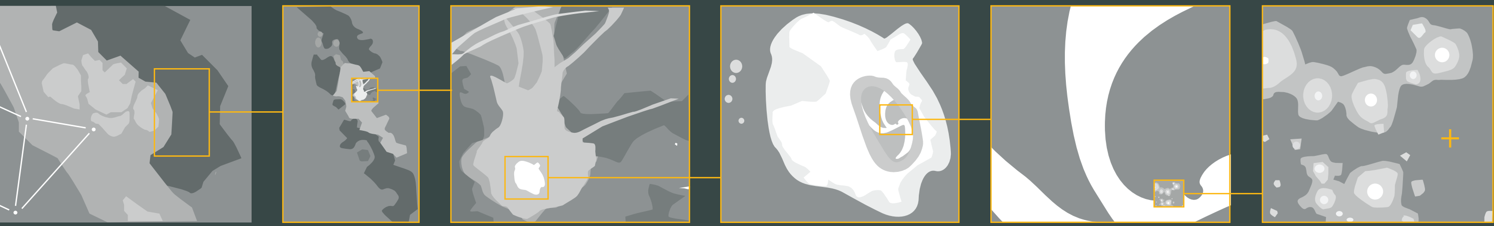


> a trip to the galactic center >

Zoom in from the naked-eye view of Sagittarius to the *unique objects* hidden in the Milky Way's *rich and complicated* core.

By Angelle Tanner

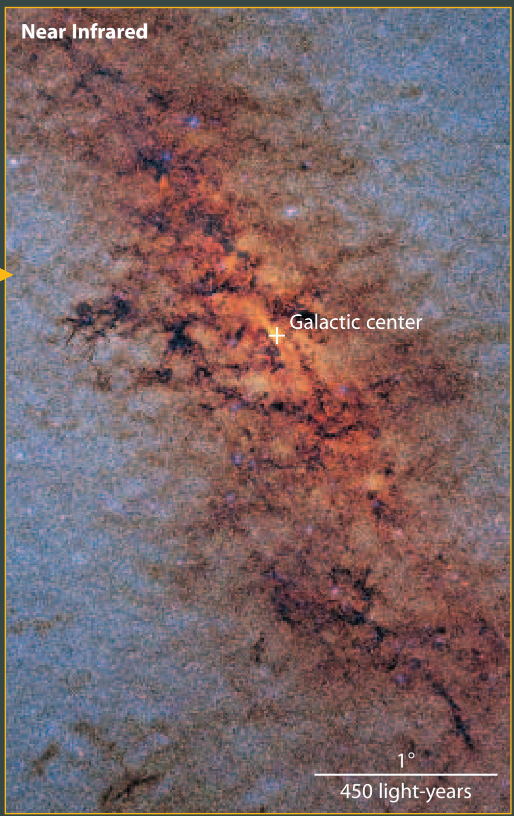
Looking into our galaxy's depths. John Gleason assembled this composite image from pictures he took of the Milky Way, Lassen Volcanic National Park in California, and a star party held by his club at the park's Bumpass Hell parking lot. The small yellow box shows the area covered by the infrared image at right and the radio view at far right.

What's at the heart of the Milky Way? Look toward the galaxy's center on a dark night when Sagittarius is up, and you'll see glowing starclouds that peek tantalizingly out from behind a great, patchy black band of interstellar dust. And that's about all you will see. The dust blocks our view of everything farther than a few thousand light-years from us in the galactic center's direction.

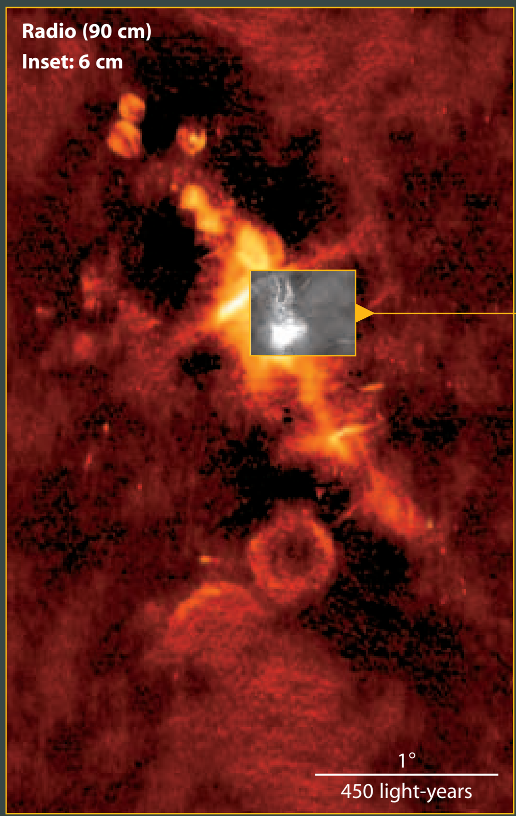
In the last few decades, however, astronomers have been able to peer through this obscuring dust by observing at infrared, radio, and X-ray wavelengths with ever-increasing sensitivity and resolution. In this way, we can now see clear to the Milky Way's center — and we've found a lot going on there. Our galaxy's core swarms with exotic phenomena and objects large and small. Many of these have been described in this magazine over the years, but it can be hard to picture how they all fit together. So join us on a journey as we traverse 26,000 light-years to take a tour of the galactic center.

We begin by stepping outdoors to look up at the familiar Milky Way toward Sagittarius *(facing page)*. Our eyes are drawn to a particularly bright patch just off the spout of the Sagittarius Teapot star pattern. This is the Large Sagittarius Starcloud, rising from the Teapot's spout like a puff of steam. It does not mark the direction to the galactic center. Rather, the center lies a few degrees west and is hidden behind opaque clouds. Nothing at all marks it in visible light.

Look at this spot with infrared eyes, however, and the view becomes more transparent. The zoomed-in view at lower left is from the

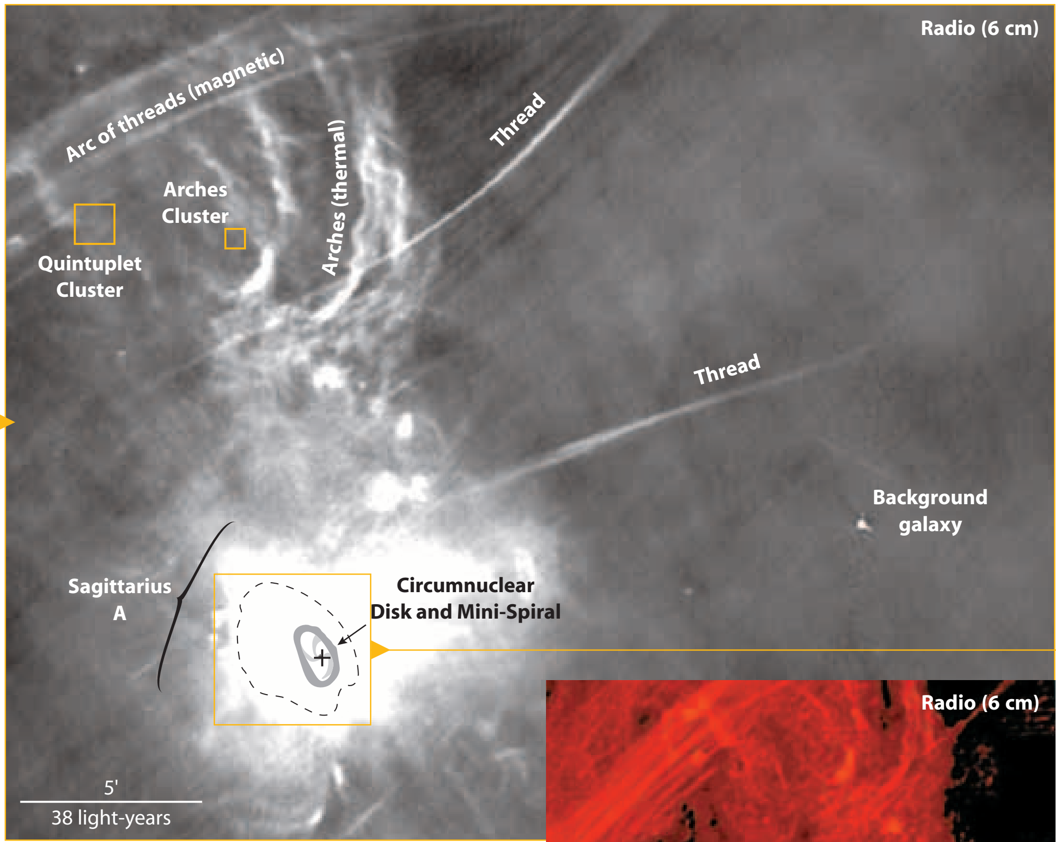


2MASS / IPAC

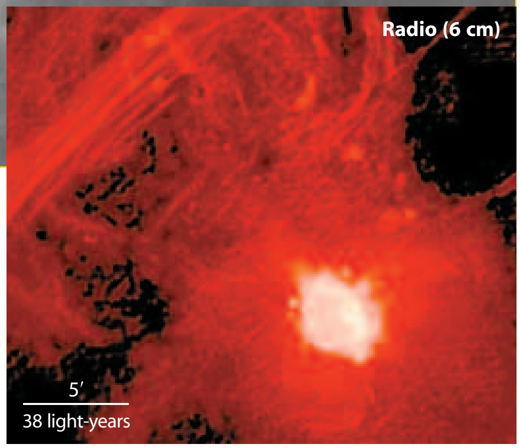


W. M. GOSS / C. LANG / VLA / NRAO

Above, left: **Peering through the dust: an infrared view toward the galactic center. This image only hints at the tens of millions of stars filling this 2.8°-wide view. As in all near-infrared color images with this article, blue represents a waveband centered on 1.2 microns, green 1.6 microns, and red 2.2 microns — shifting our normal color vision toward longer wavelengths by a factor of 3.** ***Above, right:*** **The same field as at left, imaged at the radio wavelengths of 90 centimeters and** ***(inset)*** **6 cm by the Very Large Array in New Mexico.**



The most prominent gas features in the galaxy's central half degree, imaged here in radio, include the turbulent Arches, many thin magnetic threads, and large, powerful Sagittarius A, one of the first radio sources discovered in the early days of radio astronomy.



A false-color rendering of the 6-cm radio image, bringing out the 4-arcminute (30-light-year) bright oval inside Sagittarius A.

Two Micron All Sky Survey (2MASS). Dense masses of stars around the galactic center now show through, though they are still considerably dimmed and reddened by dust. The large reddened region glowing behind the patchy foreground is the inner part of the galactic bulge, roughly 500 light-years wide. The dark patches are the cores of especially dense dust clouds. One of them partly hides a small, very bright spot: the galaxy's dense central star mass, roughly 30 light-years wide, where many millions of stars crowd together toward the center.

What radio reveals is interstellar gas, shaped here into a unique collection of overlapping structures.

Radio astronomy gives a clearer view — though most stars themselves are invisible at radio wavelengths. What radio reveals is interstellar gas, shaped here into a unique collection of overlapping structures.

Among the most striking of these features are the thin "threads" that crisscross the images roughly east-west (horizontally) at right angles to the galactic plane. These structures, observed only at the galactic center, glow in radio by means of synchrotron radiation: emission from charged particles spiraling at relativistic speeds around magnetic-field lines. The threads highlight a smooth magnetic field that pervades the galactic-center region.

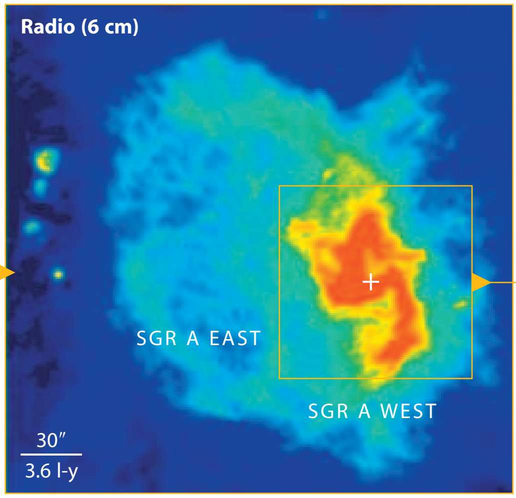
The radio image on the previous page also reveals ring-shaped supernova remnants small and large, spawned from the abundance of high-mass, short-lived stars that form in the galaxy's central region. These blast waves plow into surrounding interstellar material, compressing it enough to trigger ongoing cycles of massive-star formation, which in turn yield new supernovae.

The large bright area at the center is the powerful radio source Sagittarius A, more than 50 light-years wide in the large image above. It's one of the brightest radio sources in the sky after the Sun.

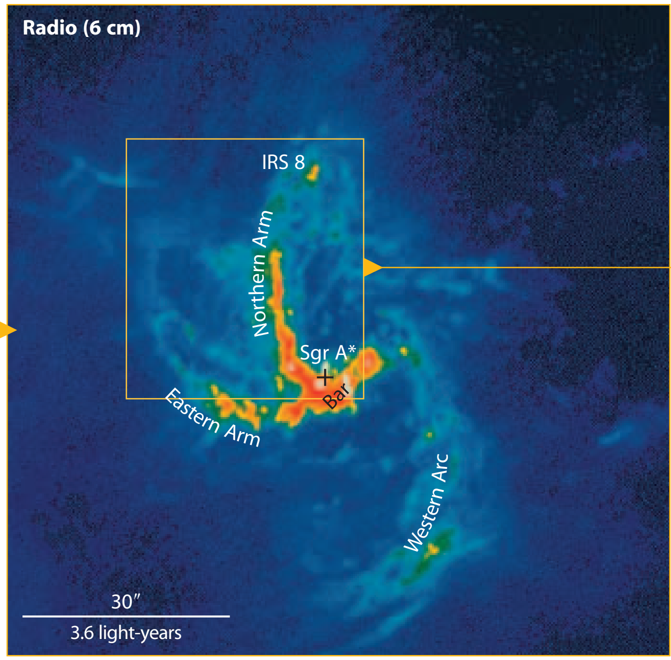
The next few images zoom in on the prominent bright oval forming much of Sagittarius A. The oval's eastern side, Sagittarius A East, appears to be a hypernova remnant — the aftermath of an especially massive star's sudden death. In the oval's western side we discover a feature called the Mini-Spiral, only about an arcminute (7 light-years) wide. A strong, point-like radio source offset from the Mini-Spiral's center is named Sagittarius A* ("A-star"). This source marks the true dynamical center of our Milky Way: a black hole containing the mass of 3 million Suns.

The first sign that Sgr A* is something very special came from studies of velocities in the Mini-Spiral's different components. These include the Northern Arm, the Western Arc, the Eastern Arm, and the Bar. The clue was the Doppler shifts of emission lines from the gas along these structures. The motion of the Northern Arm, for instance, suggested material flowing toward or orbiting around something having many millions of solar masses at the position of Sgr A*. The Mini-Spiral was once believed to be shaped by spiral density waves similar to those that create the big spiral arms in galaxies. However, the velocity data suggest that its material is falling inward from a ring of dense molecular gas just outside the Mini-Spiral called the Circumnuclear Disk. This disk (or ring) orbits the Mini-Spiral at a speed of 100 kilometers per second. Collisions between dense clouds within it dissipate orbital angular momentum, thereby causing

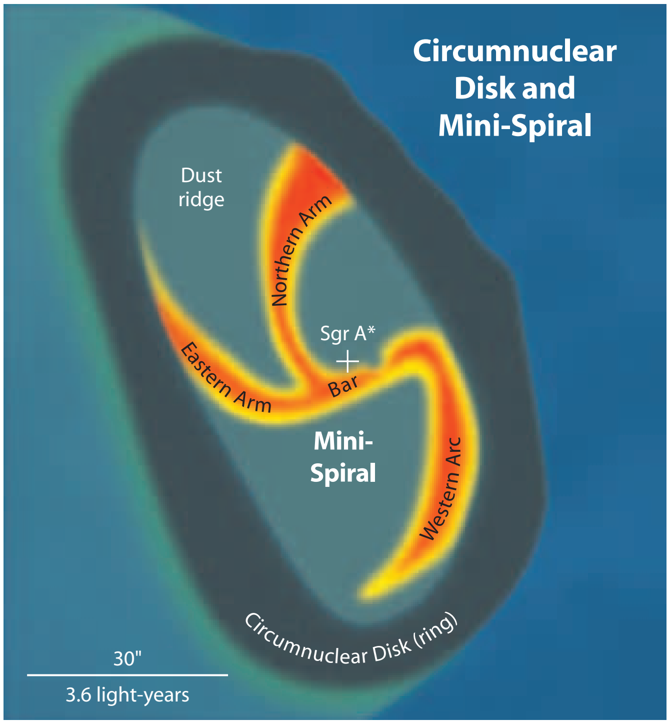
The Mini-Spiral consists of gas streams falling inward toward the central black hole.



The Sagittarius A bright oval processed to bring out the Mini-Spiral: streams of gas falling the last few light-years toward the central black hole. Courtesy Farhad Yusef-Zadeh, VLA, and NRAO.



A higher-resolution radio view showing the main components of the Mini-Spiral. Courtesy W. M. Goss, VLA, and NRAO.



The Circumnuclear Disk, just a few light-years across, encloses and feeds the Mini-Spiral. Gas clouds that collide in the disk should lose orbital momentum, allowing parts of them to fall inward.

enough material to peel off and fall inward to form a 1,000-solar-mass stream racing toward the massive object lurking at Sagittarius A*.

Some interesting objects in and around the Mini-Spiral have been seen by giant telescopes working at infrared wavelengths. These include a collection of hot, windy stars embedded in the Northern Arm and interacting with its gas and dust; a low-density bubble in the Bar called the Mini-Cavity, which was blown by one or more hot stars; and a type-*M* supergiant star known as Infrared Source (IRS) 7. Further inspection of the emission around IRS 7 reveals an unexpected surprise — a tail! The wisp of dust trailing this bloated star is thought to be matter ablated from its outer atmosphere by the windy, hot stars in the cluster IRS 16, the rich swarm in the central light-year around Sagittarius A*.

Millions of stars of all masses and spectral types crowd the field around the core, but only the most luminous ones are directly visible in the infrared. These include other cool *M* giants and supergiants as well as hot, massive *O* and *B* stars, especially in the IRS 16 cluster. The presence of young, blue supergiants and older red giants indicates multiple epochs of star formation in the galactic center, such as might be spawned by sporadic cloud collisions. The forces created by the large central mass, turbulent stellar winds, and the magnetic field act to inhibit the normal process of star formation by gravitational collapse seen elsewhere in the galaxy. For clouds to collapse here, they must be much more massive and dense than elsewhere, and the process may need help from external forces such as supernovae and cloud collisions. With such unusual star-forming conditions, it's not surprising that the galactic center contains an unusual abundance of especially massive stars among its newborns.

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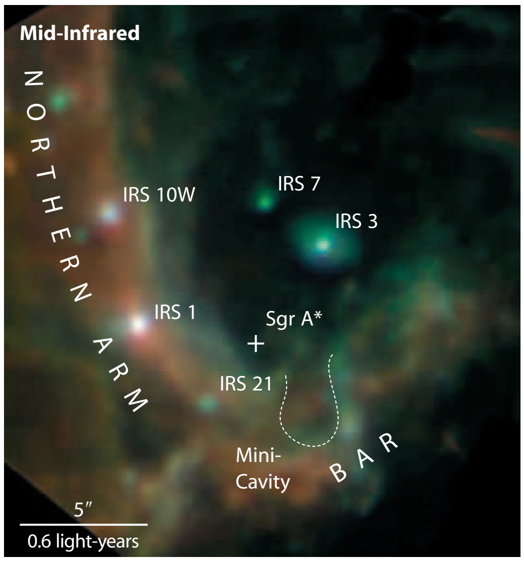
Some of the brightest stars, including IRS 8, have clearly visible diffuse nebulae surrounding them. The horseshoelike structure around this star is created by the star's wind interacting with dust flowing in along the Northern Arm. This interaction forms a bow shock; Northern Arm material traveling at around 100 km per second piles up against the strong stellar wind (gusting at 1,000 km per second) the same way water in a stream flows around an obstructing boulder.

As we zoom in to the galaxy's innermost nucleus, our field of view on the facing page shrinks to a mere 1 arcsecond, or 0.13 light-year, square. For the last eight years the research group of which I am a member, headed by Andrea Ghez at the University of California, Los Angeles, has tracked the proper motions of stars in the 1-arcsecond-wide Central Cluster. Several of these stars are clearly orbiting the position of Sgr A*. We have followed one star, S0-16, through about half of a very tight, eccentric ellipse. We find that at its closest, it swung just 60 astronomical units from the black hole (only 1½

Left: **Great numbers of stars come back into view when we switch to near infrared. This high-resolution image was taken with the 8-meter Gemini North telescope. Courtesy F. Rigaut, Gemini Observatory, and NOAO.**

Below: **Zooming in on the Mini-Spiral's central portion at the mid-infrared wavelength of 12.5 microns, which reveals room-temperature dust. The pointlike infrared sources (IRS) in this false-color image are supergiant stars. The galactic-center black hole at Sagittarius A* is completely invisible.**



A. GHEZ/M. MORRIS/KECK OBSERVATORY

times Pluto's average distance from the Sun) at more than 9,000 km per second! Kepler's laws of motion tell us that the mass contained within this small separation amounts to at least 3 million solar masses, providing the most compelling evidence for a supermassive black hole.

Our group was also the first to measure absorption lines in the spectrum of one of the orbiting stars, S0-2, not only identifying it as a late *O* or early *B* main-sequence star but also finding a radial velocity for it.

Another group, led by Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics, Germany) has also been tracking the orbits of stars in the central cluster. Last October the group announced results for S0-2's orbital motion, which match ours (January issue, page 18). Taking other orbits into account as well, Genzel's team finds a black-hole mass of 2.6 million Suns.

Further confirmation of the compact nature of Sgr A* comes from the object's rapid X-ray variations. Drastic changes in as little as 10 minutes prove that the X-ray source can be no bigger than about 10 light-minutes (about 1 a.u.) wide, or the variations would be smeared out (*S&T:* January 2002, page 18). The X-ray source is presumably hot material on the verge of spiraling into the black hole itself. The laws of physics say that such a large mass in such a small volume cannot avoid ending up as a black hole. The hole's mass dictates that it is 16 million km across, yawning about 0.1 a.u (just under 1 light-minute) wide.

However, Sgr A* is remarkably quiet and dim as galaxy-center black holes go. Normally we see no infrared and only very weak, fitful X-ray emission at its position. Apparently, the hole is being "starved" of infalling matter. Geoffrey Bower (University of California, Berkeley) and several colleagues recently determined the hole's intake to be less than a ten-millionth of a solar mass per year, a factor of 1,000 less than previous studies suggested. Perhaps the many hot stars in the hole's vicinity blow away almost all infalling gas before it can get near the hole. Or maybe past eruptions from major accretion events at the hole did the job.

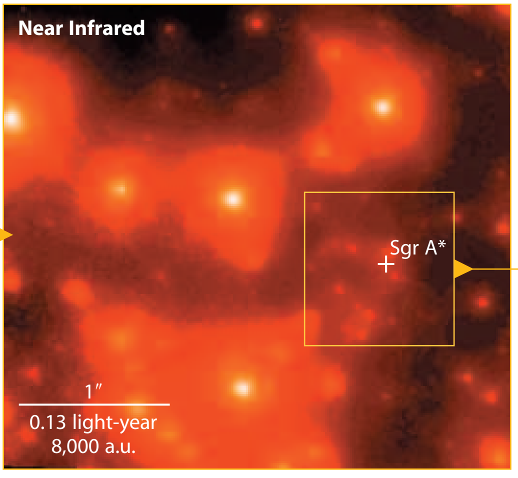
In fact, observations made last year with the Chandra X-ray Observatory revealed, for the first time, at least two lobes of 20-million-degree gas extending dozens of light-years from the center. Frederick Baganoff (MIT) and colleagues announced in January that these may be the remnants of powerful eruptions from a time when the Milky Way's black hole was far more active than it is now.

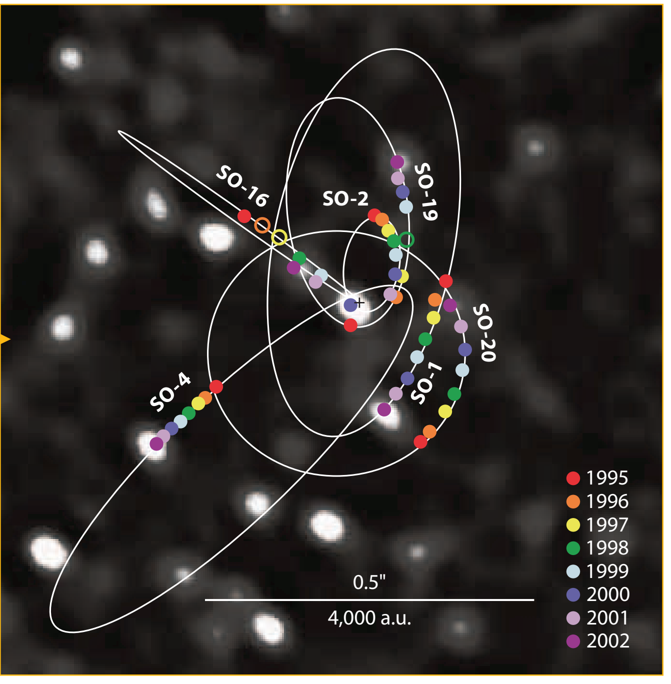
The laws of physics say that such a large mass in such a small volume cannot avoid ending up as a black hole.

The weak emission we currently see from Sgr A* is probably produced by a small accretion disk and jets right around the hole itself. Detection of an infrared flare in May 2000 opened the door for many intriguing interpretations — ranging from a discrete accretion event, to an unrelated variable star in the vicinity, to magnification of a background source by gravitational lensing.

Orbits of six stars around Sagittarius A*. This 2.2-micron adaptive-optics image, a mere 1 arcsecond square, was taken in 2002; symbols show the positions of the six stars for each of the previous 7 years as well. The white orbits are best fits to these positions. Four of the orbits have only short arcs of data and thus are very tentative, but the stars S0-2 and S0-16 have swung through half or more of their ellipses, allowing their orbits to be specified well. S0-16 swung a mere 60 astronomical units from the black hole. Courtesy A. Tanner, S. Hornstein, A. Ghez, and Keck Observatory.

***Below:* Zooming deep into the central star cluster IRS 16 at a wavelength of 2.2 microns. This image was taken a few years before the one at right; note that several stars moved slightly during the intervening time. Courtesy A. Ghez and Keck Observatory.**





Super Clusters

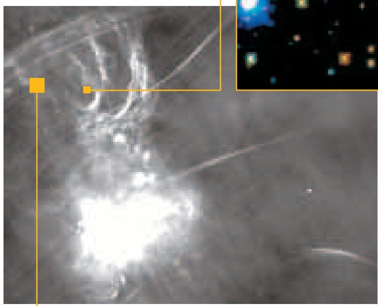
We've journeyed right to the Milky Way's very heart. Before ending our tour, however, let's back off a bit and look at a few other noteworthy sights in the area.

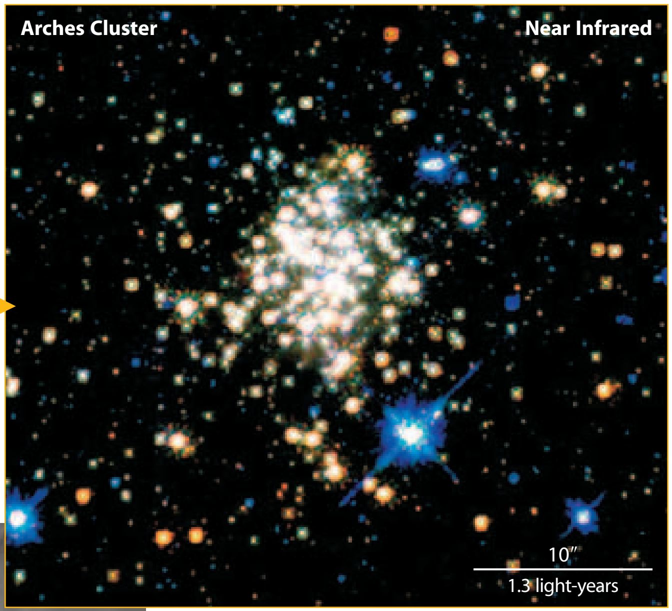
North-northeast of the galactic center by at least 100 light-years, amid the uncountable swarms of ordinary stars, lies a collection of intriguing and record-holding objects. These include the Arches and Quintuplet massive-star clusters, the Pistol Star, and the Pistol Nebula.

The Pistol Star is a strong candidate for the title of the most massive star known, apparently weighing in at as much as 200 to 250 Suns. Such a massive star is hard to explain theoretically. Some astronomers suspect that the Pistol Star is actually a binary or multiple system rather than a single behemoth, much as R136a, a supposed supermassive star in the Large Magellanic Cloud, proved to be (*S&T:* March 1998, page 40). The Pistol Nebula is lit up by the intense ultraviolet radiation from the nearby Quintuplet Cluster, which gets its name from the five enshrouded infrared stars that were originally seen here. They show up orange in the color infrared image at left.

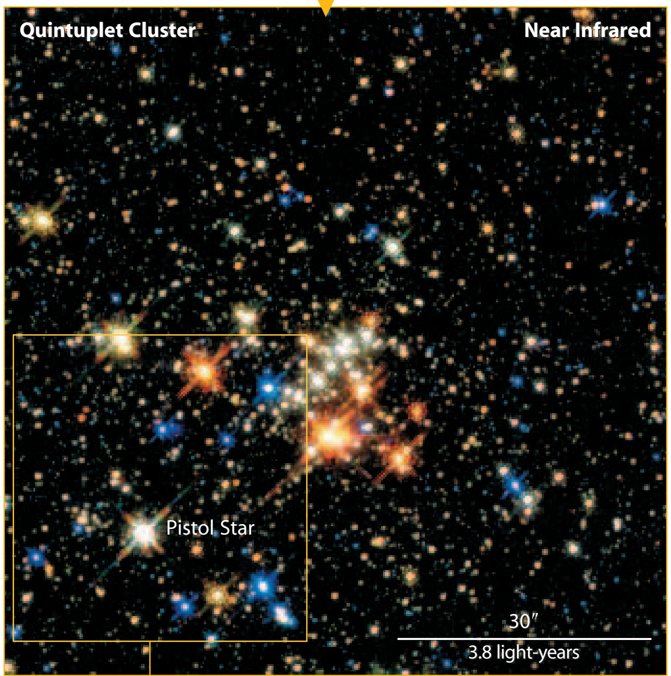
West of the Quintuplet Cluster is another record holder, the Arches Cluster, named for the nearby Arches filaments prominent at radio wavelengths. This cluster has the greatest density of massive *O* stars observed in our galaxy, along with an overabundance of the similarly hot but more evolved massive stars known as Wolf-Rayets (spectral type *W*). Finding such big star clusters so near the gravitational pull of the galactic center is surprising; tidal forces should rip them apart. If they are even slightly in the center's foreground or background, however, they would be a greater distance from it than they appear. These are the only two star clusters known in the region, not counting the galactic-center cluster (IRS 16) itself.

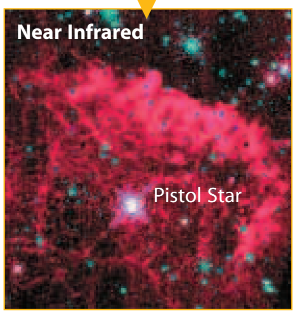
During our trip to the galactic center we have zoomed in from the naked-eye view by a factor of 120,000. At every stop along the way lie objects that probably exist in other galactic nuclei to one degree or another, waiting for more powerful telescopes to find them. At the same time, future studies of other galaxy centers will, we hope, allow us to better understand the many amazing phenomena in our own.





The Arches Cluster, located 100 light-years or more from the galactic nucleus, has the highest density of hot, massive type-*O* stars known in our galaxy. The three infrared images on this page were made with the NICMOS camera on the Hubble Space Telescope. Courtesy Don Figer, STScI, and NASA.





The Quintuplet Cluster, named for the five reddened infrared sources that were originally seen here (orange in this image), is another dense collection of massive hot stars located at least 100 light-years from the galactic center. Off its edge is the supermassive Pistol Star, named for the faint, pistol-shaped nebula around it.

Angelle Tanner *studies the galactic center as a graduate student at the University of California, Los Angeles. Her thesis analyzes a collection of sources along the Mini-Spiral's Northern Arm.*