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THE GALACTIC CENTER

Take a trip some day to the coastal town of Port Douglas on the northeastern shore of Australia. There, lying on the warm, sandy beach, you will witness the evening splendor of the Milky Way arching from horizon to horizon across the southern cosmic vault (figure 1.1). And as your eyes peer into the starry void, you will marvel at the serene magnificence of this beautiful and overpowering structure that we proudly call *our* galaxy. But succumbing as you do to its hypnotic spell, you will be unaware that its center conceals another universe, shielded from us by a one-way membrane—an event horizon—that eternally forbids the world within it to make contact with the physical reality you will be sensing around you on this night of enchantment.

As a species accustomed to seeking truth and finding beauty in the heart of all things, we find ourselves beckoned by the primacy of the central realm. In Jules Verne’s science fiction classic *A Journey to the Center of the Earth*, Professor Hardwigg and his fellow explorers encounter an assortment of strange, breathtaking wonders as they approach Earth’s core. So it should be, we believe, for other than at the nucleus of this planet, where else ought there be a place more special, more endowed with the qualities that make something unique? Throughout history, it seems, humans have looked to the center of their environment for privilege, wisdom, and comfort. In early Chinese culture, art and invention were to be found only in the “central kingdom,” a

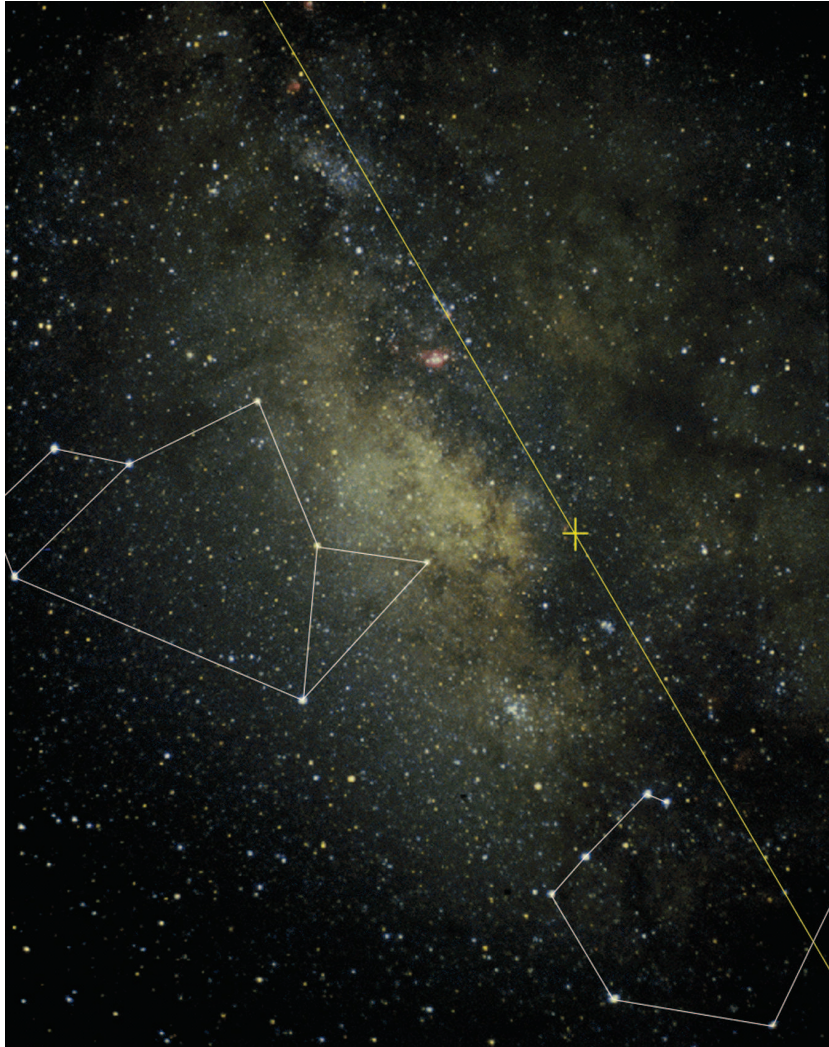


Figure 1.1 Obscured by ragged, dark dust clouds, the galactic center is virtually unobservable even with the largest optical telescopes. This image, made in Cerro Tololo, Chile, shows the region near the border between the constellations of Scorpius and Sagittarius; the former is partially visible at the bottom right, and the latter to the left, in the photograph. North is at the top and West is to the right in this view, which spans an area of about 11,000 by 17,000 light-years. The dynamical center of the galaxy coincides with the cross-mark on the diagonal line that cuts through the galactic plane. (Photograph courtesy of William Keel at the University of Alabama, Tuscaloosa)

sentiment echoed with power by the Romans in defense of their imperial capital city of Rome, the center of anti-barbarism. By extension, the heart of something as majestic as the Milky Way must be special indeed, and we are drawn to it, teased by what it reveals, tormented with the desire to see more.

Our intellectual pilgrimage to the center of the galaxy traces its roots to embryonic attempts in the mid-twentieth century to view the heavens with light much redder and much bluer than the human eye can sense. Yet only in recent years have we been granted the privilege of focusing our attention on the nucleus. And what a journey this is turning out to be. We will begin our trek by embarking on a virtual exploration, navigating through a series of progressively higher-resolution images, reaching a detailed view whose unprecedented clarity challenges the imagination. We will learn about the unique players on this stage, and the nature of the most enigmatic object of them all—the supermassive black hole—caged within a pit of strong gravity in the galaxy’s most mysterious domain.

1.1 THE HIDDEN REALM

The Milky Way is a giant galaxy, encompassing a mass of almost 1 trillion Suns within a diameter of about 100,000 light-years. (A light-year is the distance light travels in a year. By comparison, it takes light 2 seconds to make a round trip to the moon and back, and eight minutes to reach us from the Sun.) The Milky Way belongs to the so-called Local Group of galaxies, a small clustering of over 30 members, and is the second largest, and one of the most massive representatives of this ensemble. The nearest large galaxy, Andromeda (figure 1.2), is 2.4 million light-years away, though several fainter galaxies are much closer. Among them are the conspicuous Large and Small Magellanic Clouds at a distance of 179,000 and 210,000 light-years, respectively.

Our understanding of how the Milky Way came into existence, and of what forces govern its current evolution, began to take shape in the latter half of the twentieth century, when



Figure 1.2 The Andromeda galaxy is a large spiral, comparable in size and appearance to the Milky Way, were the latter to be viewed from outside. Drifting majestically 2.4 million light-years from Earth, we see it today as it appeared that many years ago. Andromeda is the most distant object visible to the unaided eye. (Photograph courtesy of T. A. Rector, B. A. Wolpa, and NOAO/AURA/NSF)

astronomers developed the ability to determine the age of stars and map their concentration with some precision. Our galaxy, we learned, formed from the rapid collapse of a spherical cloud of matter in the primordial expansion of the universe. Most of the elements heavier than helium are the ashes produced by nuclear burning inside stars—much later in the galaxy’s evolution—so the young nursery that spawned the nascent Milky Way was replete

with simple forms of matter, particularly hydrogen. During this collapse, pockets of high gas condensation formed, and these eventually turned into hot stellar balls of plasma. Today, we see these stars orbiting the center of the galaxy predominantly within a flattened pancake, though many near the middle conspire to puff out a central bulge, like the exaggerated hub of an old cartwheel.

By mapping the distribution of its hydrogen clouds, radio astronomers have further concluded that the Milky Way not only contains a flattened disk, but that it is in fact a spiral galaxy whose face-on view projects a highly ordered grand design with graceful arms gilded by glowing star clusters and hot, tenuous gases. Viewed edge-on, its appearance would be noticeably different but just as striking, with a bulging central region and a precariously thin disk tapering off into the darkness of intergalactic space. Our view is actually closer to the latter than the former since our Sun is embedded within the plane. Most striking are the “milky,” sometimes wispy, bands of light produced by the multitude of stars in this swath, cut by the dark, obscuring dust clouds silhouetted against the local spiral arms. It is believed that our galaxy is not unlike Andromeda in appearance, so that alien eyes peering back toward the Milky Way from large distances probably see it very much as we see its sister galaxy in figure 1.2.

Today, the orbits of stars within the galaxy are presumed to reflect the motion of gas from which they formed, locked in harmony to the rotational imprints from the past. The Milky Way rotates gently, though steadily, on an axis whose direction was ordained by the swirling action of the primeval gas. Based on the age of the oldest stars we see, it appears that our galaxy began life as an identifiable separate entity some 10 billion years ago, roughly twice the age of the Sun. Of course, the combination of processes that governed how the initial collapse occurred are not entirely clear, and are still subject to some debate, but our concept of how this sequence of events is ordered does appear to be correct. Some people question whether the contraction to a flattened distribution happened all at once, and whether the thin halo of gas and stars away from the plane might rather have had a different genesis. Several young stars are bucking the trend established by their

milieu, and rotate instead in a direction opposite to that of the rest of the galaxy—an indication that they probably originated from the merger of miniature failed galaxies with the much bigger Milky Way.

The Milky Way, however, is not an archetype for all the galaxies we can see in the universe. Some are indeed thin pancakes, but lack a central bloated hub of stars. Others are not flattened disks at all; rather, they fill the void with spheroidal aggregates of luminous and nonluminous matter, swirling in space like slowly spinning footballs. Astronomers are now finding that there may be an evolutionary link that governs how and when central bulges form, or under more extreme conditions, how they grow to dominate the entire galaxy. Ellipticals themselves may be produced in catastrophic collisions that lead to the eventual merger of two spiral galaxies.

Indeed, the Milky Way and Andromeda, the two dominant spiral galaxies in our Local Group, are falling toward each other at 300,000 miles per hour. Our descendants eons from now will see Andromeda gradually grow in size until, some 3 billion years hence, the two sister galaxies begin to tear at each other's fringes. Eventually, stars from both doomed spirals will plunge past each other, driven by the gravitational force of the two gargantuan galaxies. The Sun itself, together with our planet, will either spin completely out of our galaxy altogether, traveling on a long, desolate path with very few other stars visible in the night sky, or it may plunge toward the center of the newly formed structure where a cacophony of activity will greet it. Since the Sun is expected to burn and sustain life on Earth for another 5 billion years, intelligent life here will see all of this unfold, albeit at a very slow pace. A billion years later, the two beautiful spiral galaxies will have merged into a giant elliptical spheroidal mass of aging stars. Ironically, though, very few stars will actually collide with each other during this encounter, since most of space is filled with wispy gas. Aside from dramatic changes in the appearance of the night sky, our descendants will continue to live on a planet peacefully orbiting around the Sun.

For now, however, the most intriguing region of the cosmos accessible to us appears to be the centralized hub of our galaxy. Ongoing surveys reveal that this may not be a coincidence; we infer from them that only galaxies with a bulge in the middle, or those that are comprised entirely of a spheroidal distribution of stars, harbor a central pit of mysterious dark matter (see chapter 6). Our target in this book—the heart of the Milky Way—lies in the direction of the constellation Sagittarius, close to the border with the neighboring constellation Scorpius (figure 1.1). These two groups of stars, like the other ten constellations in the Zodiac, are probably the oldest patterns recognized by human civilizations. In Greek mythology, Sagittarius is a centaur, a warlike creature with the torso of a man and the body of a horse. This grouping was also known to earlier civilizations in the Middle East; several of those in the Mesopotamian area associated it with their gods of war, variants of the archer-god Nergal. It appears that the identification of this constellation with an archer was universal. Today, we tend to name celestial objects and features after the constellation in which they are found, so the galactic center is said to lie in the Sagittarius A complex, and gaseous structures within it are called, for example, Sagittarius A East and Sagittarius A West. As we will see, the most unusual object in this region, discovered in 1974, stands out on a radio map as a bright dot.¹ It was given the name *Sagittarius A**, the asterisk meant to convey its uniqueness and importance.

The solar system meanders through the outer reaches of the Milky Way, well within the disk and only about 20 light-years above the equatorial symmetry plane, though about 28,000 light-years from the galactic center. Your view of the night sky from Port Douglas will therefore be that of a luminous band splashed across the “galactic equator.” Orbiting the center on a nearly circular trajectory, the Sun and its planets move at 250 kilometers per second, and take 220 million years to complete one orbit. By

¹The discovery was made by Balick and Brown (1974), following a prediction by Lynden-Bell and Rees (1971) that such an object might exist at the galactic center.

comparison, our human ancestor *Ardipithecus ramidus* began to split from other specialized forms of hominid species that eventually died out only 5 million years ago. In total, the elements that make up our bodies have orbited the center of the galaxy about 20 times since the Sun was formed roughly 4.6 billion years ago.

So why has it taken so long for anyone to recognize the significance of Sagittarius's battlefield? In large part, the answer is "dust." That ubiquitous and relentless vagrant of the household is often just as pesky for astronomers. Dust in space is chemically simpler and typically smaller than its household cousin by a factor of 10 to 100, but if space dust were allowed to settle on your desk, it would likely appear very much the same as the traditional enemy of the varnished. Dust in space occurs wherever any kind of matter exists in concentration. The solar system is filled with it, and its presence is inferred from a triangular glow that appears near the horizon in the evening after sunset. Known as zodiacal light, this faint illumination is produced when sunlight is reflected by tiny dust particles orbiting the Sun.

Dust also appears in the dark space between the stars, but it is not entirely clear where or how it originates. Almost certainly some (perhaps most) of it is produced in the envelopes of very old, puffed-out stars near the end of their lives. As they expand and shed their tenuous envelope, the material within it cools rapidly and molecules are able to crystallize. Eventually, the crystals grow into dust grains composed of carbon and nitrogen ices.

In retrospect it may seem odd that even into the early 1900s people did not recognize that the easily visible dark lanes in the Milky Way (see figure 1.1) were due to absorption, not structure. They were not bothered by the idea that directly toward the center of the galaxy, whose position was by then fairly well known, there weren't as many stars as just off-center. We now realize that if the galactic nucleus were unobscured, its size and brightness would be comparable to that of the full moon, fading away rapidly into the halo and merging gradually with the stellar disk.

The effect of dust on what we see depends rather sensitively on the color of light we are trying to sense. We will learn much more about the nature of light in chapter 3, but for the moment

it suffices to say that in some ways it behaves like waves. Imagine yourself sitting in a gondola on the waters just off Piazza San Marco in Venice. For this analogy, the water is light and the gondola is a dust grain. Water waves that undulate very slowly, so that crests pass by the boat at very long intervals, have little influence; you continue to sit there peacefully, while the waves pass by with virtually no disruption. Waves that have intervals much smaller than the size of the boat—basically ripples—also have little effect; they “bounce” off the gondola with minimal interference. However, waves for which the crests are separated by a distance comparable to the size of the boat will disturb it significantly, and the gondola in turn will disrupt the waves as well.

A very similar effect governs the appearance of the daytime sky. Dust particles in our atmosphere (like those in space) are small, about 0.0001 centimeter across, which happens to be roughly the distance between neighboring crests in visible light. Bluer light has a shorter wavelength (as the crest separation is called) so it behaves more like the ripples on the canal, whereas redder light has a longer wavelength and it passes through the atmosphere virtually unaffected. Sunsets are therefore red, since it is predominantly the red light from the Sun that skims above the horizon through the Earth’s thick atmosphere, while the sky is blue, since the shorter-wavelength blue light is scattered about more readily.

It is ironic that the light for which our eyes are best suited to see also happens to have the wavelength for which space dust is the greatest nuisance. Dust dims our view toward the galactic center by a factor of at least 100 million. And so it happens that the heart of the Milky Way, which would otherwise be the brightest patch of nighttime sky, is in fact so heavily obscured by dust that even the most powerful optical telescopes are useless for observing it.

We are fortunate indeed that the development of tools to detect radio waves, following quickly on the heels of the emergence of radar technology in the mid-twentieth century, has opened up bright new vistas in the heavens. Radio waves have a crest separation of a centimeter or more, far greater than the size of dust

grains in space. Like the slowly undulating water waves flowing past the gondola in Venice, they bypass the dust with no discernible effect, so the experience of looking at the galactic center using a radio telescope is similar in many ways to the feeling of liberation one gets when the fog lifts and the visibility increases. We will see that the gloomy appearance of the galactic center on an optical photograph (see figure 1.1) contrasts sharply with the fountain of brilliance animating radio images of the same region.

1.2 REMOVING THE DUSTY VEILS

The role of every telescope is to gather as much light as possible and to focus it onto a detector. Before the advent of electronic automation, the detector was often a human eye, squinting at images fed through an array of glass lenses. These days, the detector for such a telescope could very well be a photographic film (which produced figures 1.1 and 1.2) or a charge-coupled device (CCD), which works in much the same way as a digital camera. Radio telescopes operate in a fashion similar to that of optical devices, though with several notable differences having to do with the wavelength of the radiation. Visible light has a wavelength of only about 0.0001 centimeter, so even a modest telescope with a diameter of 1 meter can create images with eye-pleasing sharpness given that one can fit a million crests of this light within a mirror of that size. But light with a wavelength of 1 centimeter would fill such a device with only 100 crests, producing a much poorer resolution and an unsatisfying image.

To achieve the same effect with a radio telescope (see figure 1.3), the mirror—or dish—should therefore be about 10,000 times bigger (roughly 10 kilometers in diameter!). Fortunately, there are ways around this hurdle, about which we will learn more, and at any rate, spectacular imagery is feasible even with smaller radio telescopes (see figure 1.4). This is the reason why the lexicon of radio astronomy includes terms such as “radio dish,” rather than lens or mirror, given the immensity of the structure needed to



Figure 1.3 The Very Large Array (VLA) in Socorro, New Mexico, is one of the world's premier astronomical radio observatories. Arranged in a large Y pattern, the 27 antennas span a region up to 36 kilometers (22 miles) across, roughly one and a half times the size of Washington, D.C. Each of the antennas is 25 meters in diameter. However, the signal from all 27 can be combined electronically to yield a resolution of an antenna 36 kilometers across, with the sensitivity of an equivalent dish 130 meters wide. (Image courtesy of NRAO/AUI)

conduct any meaningful observation. You'll know how impressive a radio telescope can be if you've ever stood beneath one—the biggest among them are bigger than a football field. For a radio telescope, the receiver is a combination of a feed antenna at the focus, an amplifier (since the signal is often very weak) and a power detector. It works by measuring the intensity of the radio waves at every point in the patch of sky being studied, and then converting this level of radiation into a color that the human eye can recognize. So figure 1.4, for example, is a map of 90-centimeter

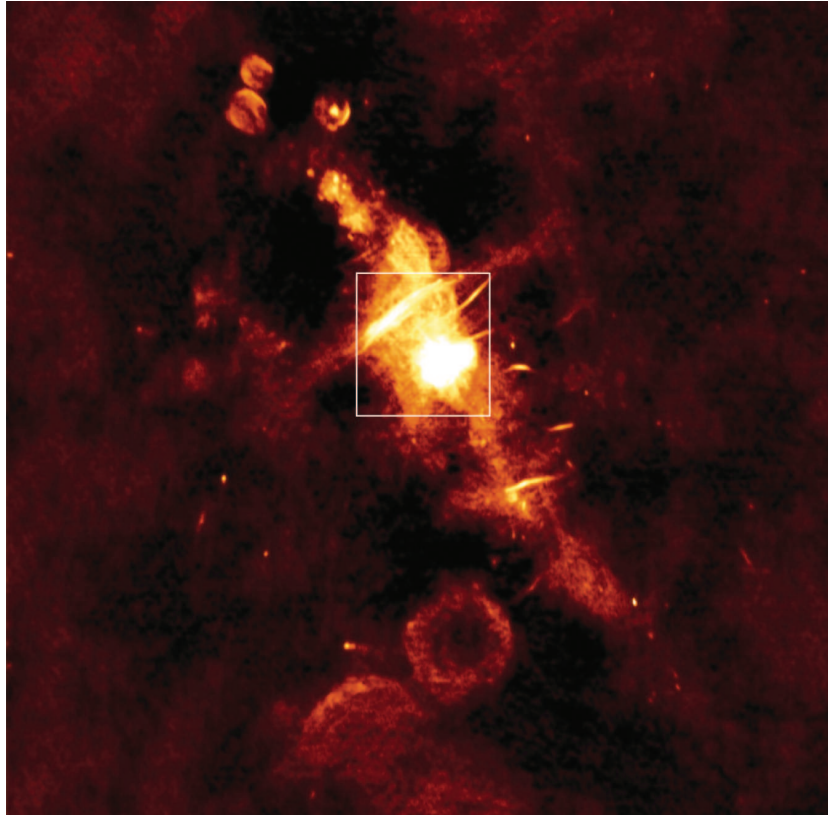


Figure 1.4 Radiation with a wavelength significantly larger than the size of dust particles (which are typically 0.0001 centimeters) in the interstellar medium can pass through the dust clouds without any noticeable attenuation. Thus, if our eyes were sensitive to light with a wavelength of 90 centimeters, the galactic center would reveal itself to us as one of the brightest and most intricate regions of the sky. Fortunately, the Very Large Array (VLA) can do that. This radio image, which spans an area of about 1,000 light-years on each side, i.e., about 1/10 the size of figure 1.1, shows a rich morphology that contrasts with the mostly obscured central region of that earlier optical image. There are no stars visible here because their radiation peaks in the infrared to ultraviolet portion of the spectrum. The radio emission seen here is instead produced by supernova remnants (the circular structures), wispy, snakelike synchrotron filaments, and highly ionized hydrogen gas. The central box shows the bright region magnified in figure 1.5. (Image courtesy of N. E. Kassim and collaborators, Naval Research Laboratory, Washington, D.C.)

radio intensity from the galactic center, though converted into a pre-selected sliding scale of colors that our eyes can interpret. The proper choice of colors preserves our intuition about which regions are bright and which are not.

Jules Verne and Professor Hardwigg would be thrilled with this image, which confirms what our deep-rooted expectations would lead us to believe—a hitherto unexplorable region opens up to reveal a glorious panorama of activity, culminating in a crescendo of light toward (where else?) the middle. This spectacular 1,000 light-year view is the largest and most sensitive radio image ever made of the Milky Way's center at a uniformly high resolution. The concentration of objects and features along the diagonal from the upper left to the lower right reveals the disklike shape of the Milky Way viewed edge-on, and presents a harvest of beauty and complexity to excite the imagination of experts and nonexperts alike. The most prominent feature in this image is the bright central concentration, known as Sagittarius A, within which sits a cauldron of hot, swirling gas, imploding stars and exploding shells, all identifiable in images taken with progressively higher magnification.

Radio astronomers can magnify a patch of the sky, while preserving the eye-pleasing clarity, by looking for light with a smaller separation between the crests, that is, with a shorter wavelength, because for a given radio dish-size, the number of captured crests increases when more of them are squeezed into the array. Often, however, a magnified view displays new complexities in structure that may not always be apparent with the sliding scale of colors employed for the larger image. The number of chosen hues may simply be too small to adequately separate out the many new details that emerge. As such, the color coding is not always the same from figure to figure, even though some of the features may be in common.

Take the narrow blue filaments launched from the central splash of light in figure 1.5. These traverse the galactic plane, which runs from the upper left to the lower right. They trace the configuration of intense magnetic field activity in this region, and are

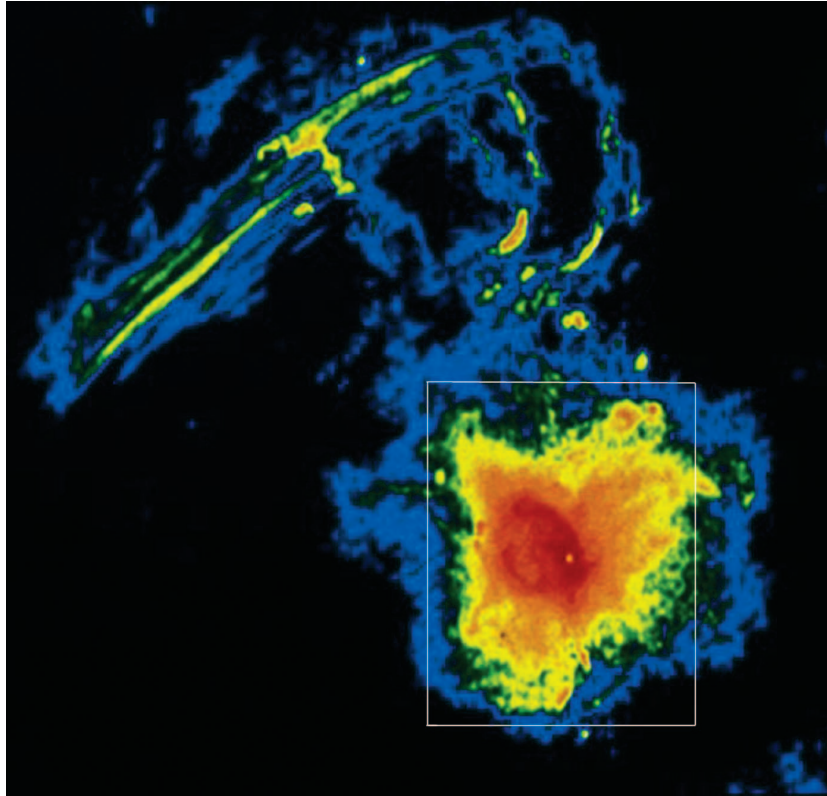


Figure 1.5 Magnified view of the central, bright region in figure 1.4. This image, produced by the Very Large Array, N.M., shows the intensity of radiation with a wavelength of 20 centimeters, produced mostly by magnetized, hot gas between the stars. The size of this magnified region is about 1/5 of that shown in figure 1.4, spanning a couple of hundred light-years in either direction. Again, the galactic plane runs from the top left in this image to the bottom right (as in figure 1.1). One of the most interesting features appearing here is the system of narrow filaments (some wrapped around each other) with a width of about 3 light-years. These radio filaments are oriented perpendicular to the galactic plane. The bright Rosetta-like region surrounds the center of our galaxy, which is magnified further in the following images. The spot in the middle of the red spiral identifies the radio source known as Sagittarius A*, believed to be the supermassive black hole at the center of our galaxy. The box to the lower right in this image shows the central 25 light-year region magnified in figure 1.6. (Image courtesy of F. Yusef-Zadeh, and the National Radio Astronomy Observatory/Associated Universities, Inc.)

evident also in the lower-magnification image of figure 1.4, identified by the yellowish-white streaks smudged across the middle of the photograph. These filaments, it turns out, are produced by very energetic particles flung around tight magnetic field lines, not unlike what happens when a penny is thrown into the strings of a harp. Others have suggested that these filaments may be the relics of galactic nucleation seeded by cosmic strings. Though intriguing, this hypothesis does not appear to be tenable since there is no natural way to link the properties of these speculative entities to the actual morphology of the observed threads. Any alternative theory that tries to explain them, however, must contend with the daunting task of accounting for their highly ordered structure over uncharacteristically long distances.

Figure 1.5 shows what the inner few hundred light-years of our galaxy would look like if our eyes were attuned to radio light with a wavelength of 20 centimeters. The central Rosetta-like structure reveals itself to be a composite of several individual elements, including the large, expanding shell from a powerful explosion that occurred at the galactic center sometime within the past 100,000 years. Although this hot bubble of gas looks in many ways like the remnant of a catastrophic collapse of a dying star after it has spent all of its nuclear fuel (i.e., a supernova), it is difficult to reconcile this interpretation with the energy required to produce this structure. It appears that as many as 50 to 100 supernovas would need to go off virtually simultaneously in order to create such a grand design. This special remnant, known as Sagittarius A East, is unique in our galaxy, and may instead have been produced by the explosive reaction of a star that ventured too close to the supermassive black hole, about which we will have much more to say later. Calculations show that these explosions ought to occur about once every 100,000 years or so. Like a comet approaching the Sun, rounding behind it and then receding to the far reaches of the solar system, the doomed star plummets toward the center and attempts to escape around the other side. Unlike the comet, however, it is compressed by the inexorable and unimaginably strong gravitational field of the black hole and explodes with

the power of 50 supernovas to create the fireworks on display near the lower-right portion of this image.

The red source within the yellow remnant of the explosion is known as Sagittarius A West. We will have a clearer view of what it represents in the highly magnified images that follow (see, for example, figure 1.6). But here we acknowledge for the first time the appearance of a mysterious, pointlike object in the middle of the red and yellow fireball. Apparently, it defines the exact location of the Milky Way's center, and its radiative properties are unlike those of any other source in the galaxy. Its name is Sagittarius A*, and for reasons that will become clearer as we progress through this book, it is the deceptively unpretentious face of a 2.6 million solar-mass behemoth lurking in the middle of this inferno.

The exploding shell region of figure 1.5 is magnified further in figure 1.6, constructed from radio measurements at 6 centimeters. Using this shorter wavelength, we are now able to see features as small as a fraction of a light-year. The central red structure—Sagittarius A West—is barely 10 light-years across. We don't see the pointlike Sagittarius A* here since the chosen color scale saturates the radiative intensity in the middle in order to give us a vivid impression of the three-arm spiral. This hot gas is moving so rapidly in a counterclockwise rotation that photographs taken five to 10 years apart can actually reveal displacements of some features relative to each other, even at the 28,000 light-year distance to the galactic center (see figure 2.3). The velocity is as high as 1,000 kilometers per second in some places, indicating that a very strong gravitational force must be present to keep this gas from escaping the galaxy. In the late 1980s, the Nobel Laureate Charles Townes and his coworkers identified this motion, which was at that time inferred from the wavelength-shift of certain spectral lines, as an early piece of evidence for the presence of a large concentration of dark matter in the nucleus, which presumably provides the strong pull that keeps the gas motion in check.² We will return to this important discussion in chapter 2.

²Read a detailed report on this work by Serabyn et al. (1988).

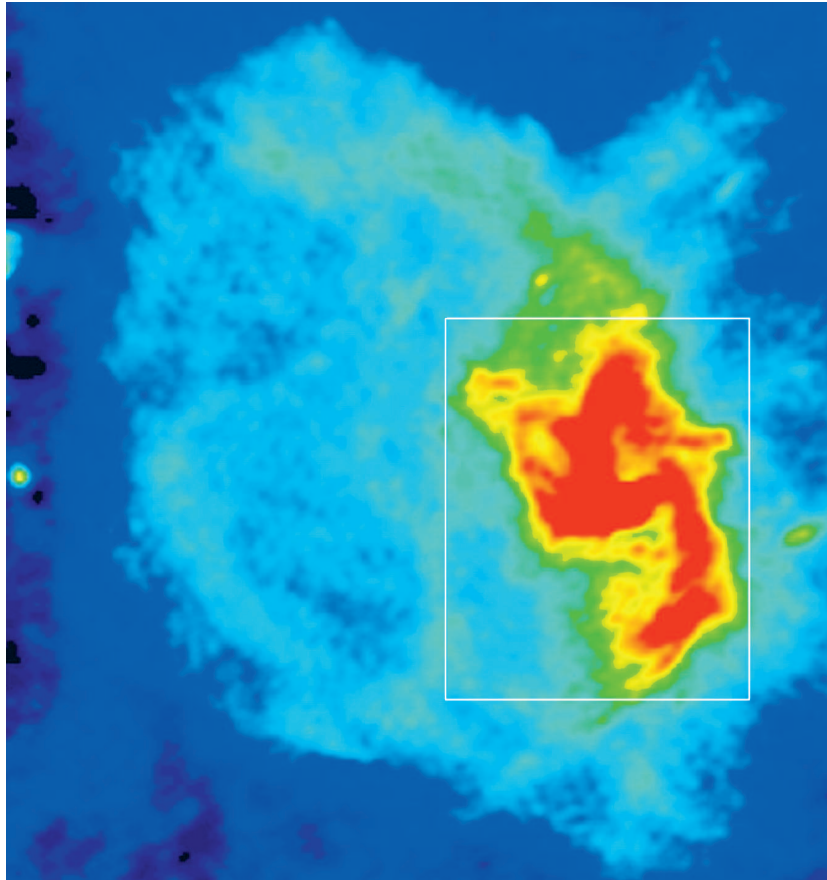


Figure 1.6 On a scale of about 25 light-years, the bright central region of figure 1.5 comprises two main components in this VLA radio continuum image (here rendered at a wavelength of 6 centimeters). The yellow shell-like structure (known as Sagittarius A East) is due primarily to particles radiating their energy as they spiral in a magnetic field. Its characteristics suggest an explosive origin, some 10,000 to 100,000 years ago, perhaps from the disruption of a star that ventured too close to the massive pointlike object in the nucleus. At the center of this shell, we see a spiral-shaped structure (mostly in red) of hot plasma radiating as it cools. The red feature, which orbits within 10 light-years of the central source of gravity, is known as Sagittarius A West. The weak extended blue region is a halo of thin gas surrounding this peculiar remnant. The box to the right in this image shows the central 10 light-year region magnified in figure 1.7. (Image courtesy of F. Yusef-Zadeh at Northwestern University, and the National Radio Astronomy Observatory)

1.3 THE PRINCIPAL CONSTITUENTS

We are now poised to plunge deeper into the center, to a distance as small as one-twentieth of a light-year from the location of our massive target. Compare this with the typical distance—a couple of light-years—between stars in the solar neighborhood, and you can begin to sense that we are in a territory where the physical conditions become exotic, if not extreme.

Shimmering and ethereal, the Sagittarius A West spiral (figure 1.7) turns harmoniously with the grandeur of a galactic whirlpool. Why three arms, we wonder? Are they really all connected? A peek ahead to figure 1.9 on page 22 reveals that at least one of these limbs—the one at lower right—is scraping the inner edge of a doughnut-shaped torus of molecular gas. We don't see it here because the radio telescope was tuned to the specific wavelength of the radiation produced by the spiral itself. We do have some evidence based on the velocity measurements of the gas shown in figure 2.3 that the vertical arm is actually a tongue of gas cascading downward toward the nucleus. These individual peculiarities notwithstanding, all three limbs are engaged in a beautiful ballet that sweeps the hot, ionized gas around Sagittarius A* like dancers encircling the royal throne.

As we magnify the view further (figure 1.8), we begin to see evidence for a dynamic interaction between the principal players on this stage. To the north of Sagittarius A*, one can just make out a cometary-like feature with a tail pointing away from the nucleus. This object is the envelope of a red giant star that is being stripped and blown away by a powerful wind originating somewhere near the center of the image. Infrared photographs of this region (see figure 1.12) reveal the presence of strong wind-emitting stars whose combined mass expulsion reaches levels of one solar mass every couple of centuries, which is sufficient to evaporate this gentle red giant and drive the efflux upward to high galactic latitudes.

The prominent character in this play, Sagittarius A*, is unmoved by the surrounding commotion. An inspection of its

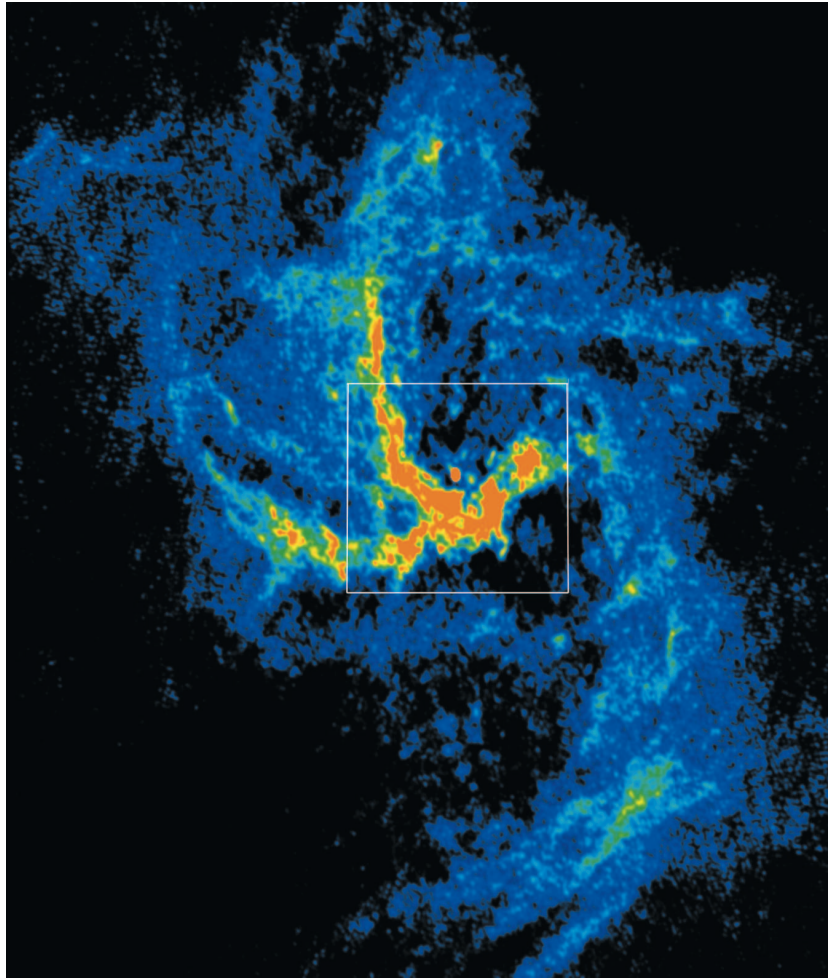


Figure 1.7 This false color image, representing a magnified view of the (red) spiral structure in figure 1.6, shows the 6-centimeter radio emission of highly ionized gas in orbit about the galactic center. Each of the “arms” is about 3 light-years in length, though it is not clear whether we are witnessing a real spiral pattern or merely a superposition of independent gas flows into the center. Nonetheless, astronomers have now determined that this gas is moving about the center with a velocity as high as 1,000 kilometers per second. The box in the middle of this image shows the central 2 light-year region magnified in figure 1.8. (Image courtesy of F. Yusef-Zadeh at Northwestern University, and the National Radio Astronomy Observatory)

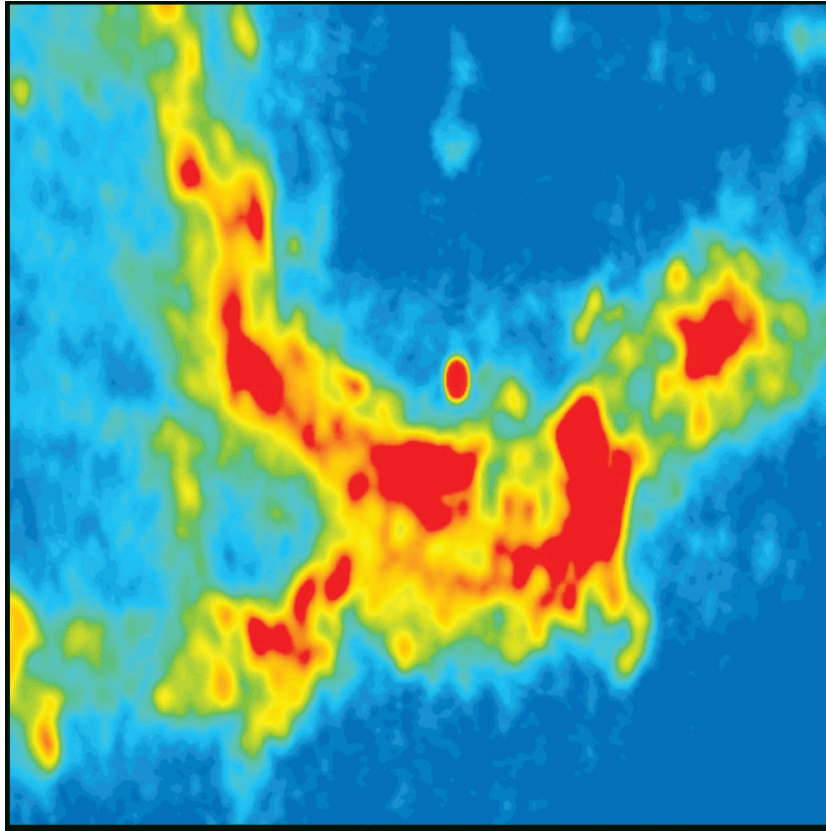


Figure 1.8 As we magnify the central (boxed) region of figure 1.7 further, we begin to see the structure of plasma radiating at a wavelength of 2 centimeters. The prominent features are the central portion of the spiral pattern of Sagittarius A West, and a bright pointlike source known as Sagittarius A*, near the middle of the photograph. We will learn that this object is associated with a mass of several million Suns and that it resides right at the center of our galaxy. We first noticed this spot of emission near the middle of the “Rosetta” in figure 1.5. To the north of Sagittarius A*, the cometary-like feature (in light blue against the dark blue background) is associated with a luminous red giant star that stands out near the top of figure 1.12. The gas blown upward from its envelope provides evidence of a strong wind emanating from the region near the supermassive black hole. The distance between Sagittarius A* and the red giant is approximately 3/4 of a light-year. (Image courtesy of F. Yusef-Zadeh at Northwestern University, and the National Radio Astronomy Observatory)

position shows that it has not budged relative to the projected location of distant quasars over several decades of continuous radio monitoring.³ These bright beacons are so distant that for all intents and purposes their position is fixed to the firmament, providing us with a virtual grid to track the motion of nearby objects. And on this grid, Sagittarius A* has sat measurably still while the stars in its proximity (see figure 2.2) and the surrounding hot gas have swirled around it.

Sagittarius A* simply does not respond to its environment; it truly is the big gorilla that remains unfazed while all around it flail in frenzy. One can estimate how massive an object must be for it to respond—or, more accurately, to not respond—in this fashion, given the overall hustle and bustle at the galactic center. The most up-to-date calculations endow it with a mass of at least 1,000 Suns, which already rules out any known stellar object as the possible culprit underlying its behavior. As we will see in chapter 2, its mass is in fact significantly greater than this, though the argument based on its perceived lack of motion is an independent and important confirmation that its nature is nonstellar.

The now familiar spiral structure of Sagittarius A West provides a useful backdrop for the montage shown in figure 1.9. This image is unusual in that it demonstrates the interplay between two components that choose to reveal themselves with a light of very different color. By now we know about the three-arm spiral, whose gentle sweeping motion is anchored to Sagittarius A*. But when we look at the galactic center with sensors that detect far infrared radiation, we also see the manifestation of a molecular torus (rendered here in violet) orbiting the nucleus in a counterclockwise rotation. Its frail appearance belies how much mass it contains—at least 10,000 Suns' worth of molecular gas fills this ring. We see it at infrared wavelengths due to the warm dust trapped within it. Near Sagittarius A*, about a dozen very bright, blue stars (see

³This work can be rather challenging for radio astronomers, but the precision of their measurements improves with time. For a technical discussion on this topic, see the papers by Backer & Sramek (1999) and Reid et al. (1999).

figures 1.10 and 1.11) pump out 10 million Suns' worth of optical and ultraviolet radiation that is heavily absorbed by this dust, recalling the analogy with the water waves lapping against the gondola, producing a situation in which the heated particles glow with the infrared warmth of embers in a well-stoked camp fire.

Like cogs in the inner workings of an elaborate clock, the cartwheel and ring separately perform their exquisite movement on rigid axes linked to the common hub centered on Sagittarius A*. In the galactic center, this becomes a recurring theme. As we uncover each new dynamic entity, invariably we also discern its direct connection to this massive anchor, be it a fleeting wisp of thin gas, an orbiting star, or a large ordered structure threaded by magnetic fields.

At this point, we are not yet even close to our final destination, but let us pause briefly to collect our thoughts and consolidate our discoveries. We have explored the galactic center almost exclusively using radio waves, uncovering structure and activity for which not even the best optical images of the Sagittarius region could provide a precedent. The radiation spectrum is far more extensive than this, however, and it would be foolish for us to believe that we have exhausted our means of exploration. Space dust is a serious detriment to our imaging capabilities only for visible light, and we have not yet tapped into the possibility of looking at Sagittarius with an infrared telescope (other than our brief far-infrared view of the molecular torus in figure 1.9), or—which could prove equally fascinating—searched for the ripples of light at much shorter wavelengths, X-rays and gamma rays. Observations of these rays, which may bounce off the dust particles but are not otherwise seriously disrupted, are best made from the relative vacuum of space, and we will continue with our journey in the next section. For now, our travel log may be summarized schematically, as shown in figures 1.10 and 1.11.

These figures illustrate, in proper juxtaposition, the principal elements at play near the galactic center, especially the manner in which they relate to Sagittarius A*. The cluster of bright, blue stars to the left is not really isolated, but represents a concentration of such objects rendered more fully in an actual photograph

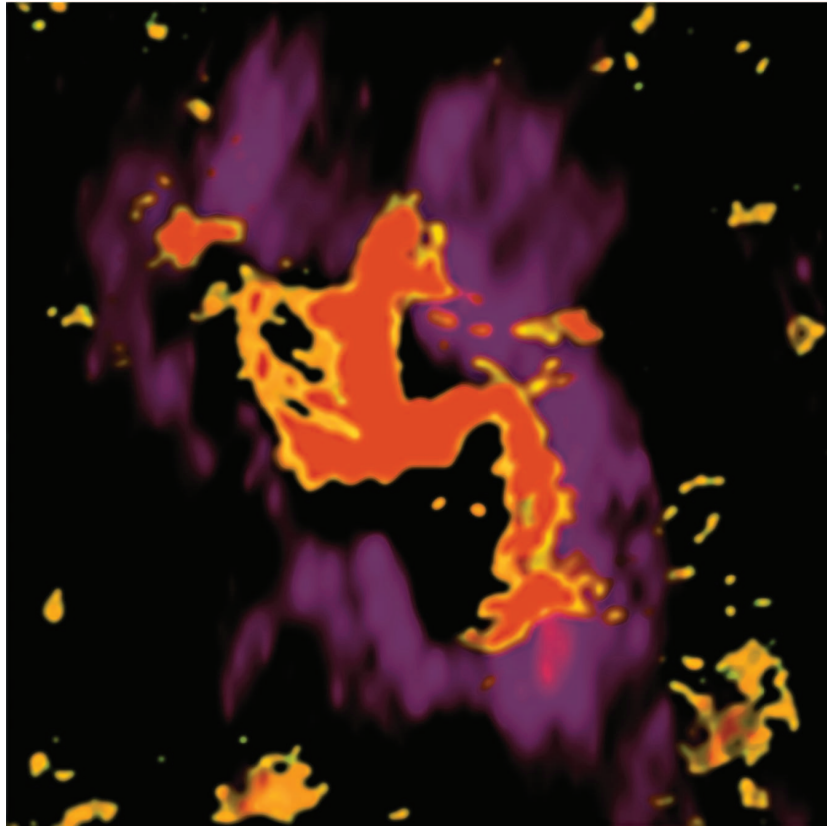


Figure 1.9 The images we have seen so far of the galactic center were taken at radio wavelengths. At optical wavelengths (see figure 1.1), the central region of our galaxy is mostly obscured. There is also some obscuration at infrared wavelengths, but not as severe as in the optical. This image, produced by superposing the radio photograph of the spiral in figure 1.7 with the view provided by millimeter cameras (shown in violet), provides evidence for the presence of a torus of dusty gas in orbit about the central source of gravity, Sagittarius A*. The dust in this ring shines by converting ultraviolet light into an infrared glow. The hot gas within it, however, radiates most of its energy at radio wavelengths, which are then converted into the optical colors recognized by the human eye. A more detailed description of the features seen here is provided in the schematic diagrams shown in figures 1.10 and 1.11. (Image courtesy of F. Yusef-Zadeh at Northwestern University, M. Wright at the Radio Astronomy Laboratory, UC Berkeley, and the National Radio Astronomy Observatory)

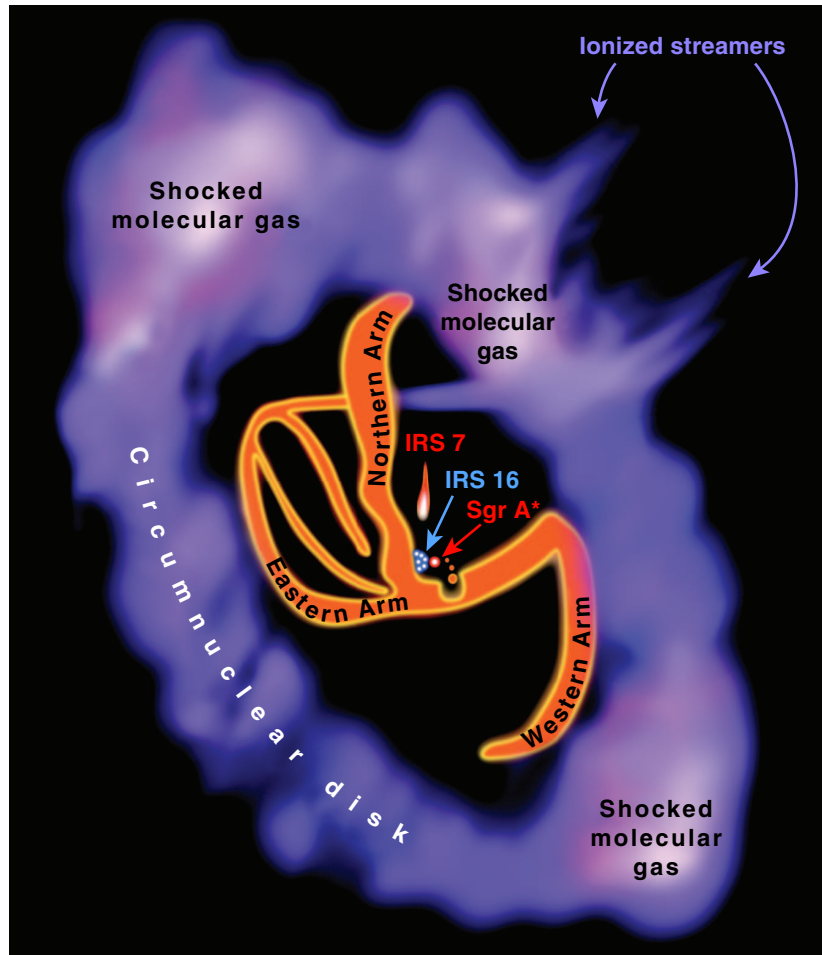


Figure 1.10 This cartoon of the inner 15 light-year region of our galaxy shows the exotic collection of astrophysical phenomena existing within the cavity of the circumnuclear disk (seen in figure 1.9). The dominant source of gravity is the strong radio source Sagittarius A*, which gives all indications of being a supermassive black hole. The nearby cluster of at least two dozen hot blue stars (known as IRS 16), bathes the entire cavity with ionizing radiation, and seems to be the source of a powerful wind that sweeps out from the central region with a velocity exceeding 700 kilometers per second. This wind is the apparent cause of the cometary tail associated with the red giant star IRS 7 in figure 1.8. The region surrounding Sagittarius A* is magnified in the view shown in figure 1.11. (Illustration by Linda K. Huff, reprinted by permission of the artist)

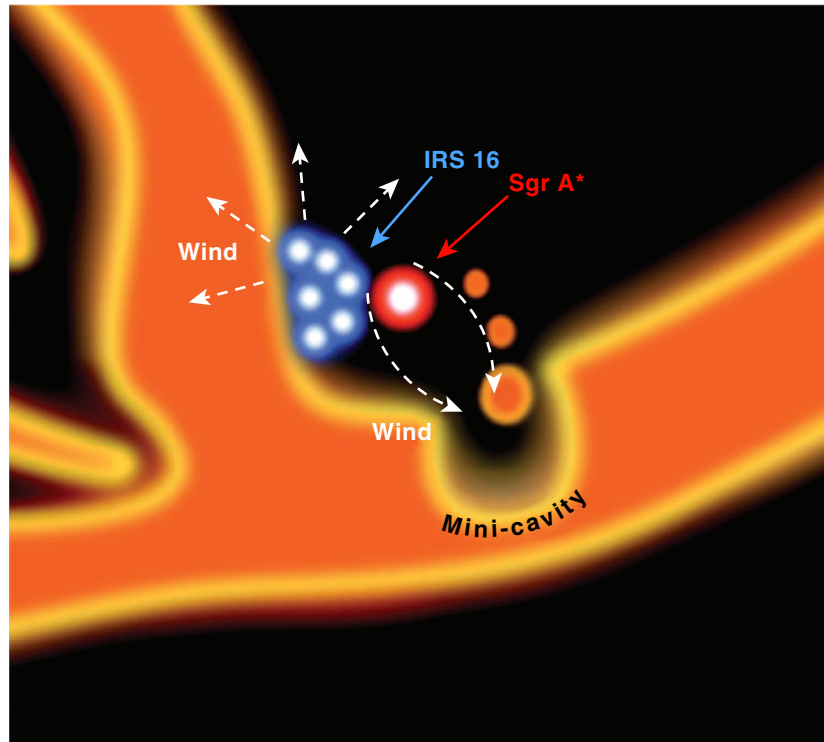


Figure 1.11 The existence of a peculiar hole (known as the “mini-cavity”) in the radio-emitting gas surrounding Sagittarius A* may be due in part to the effects of winds emanating from the bright, blue stars to the left and focused gravitationally by the supermassive black hole, Sagittarius A*. (Illustration by Linda K. Huff, reprinted by permission of the artist)

of this region (figure 1.12). And to the right of our main character, there appears to be a mini-cavity in one of the spiral arms, which may have been produced in part by the impact of a concentrated wind flowing from the direction of Sagittarius A*. It is thought that the powerful wind from the bright, blue stars is focused gravitationally by the central massive object, producing a train of plasma blobs that help to carve out the hot, ionized gas as they plow into the orbiting material. There is no doubt that the galactic center is an intricate region, with a personality forged from

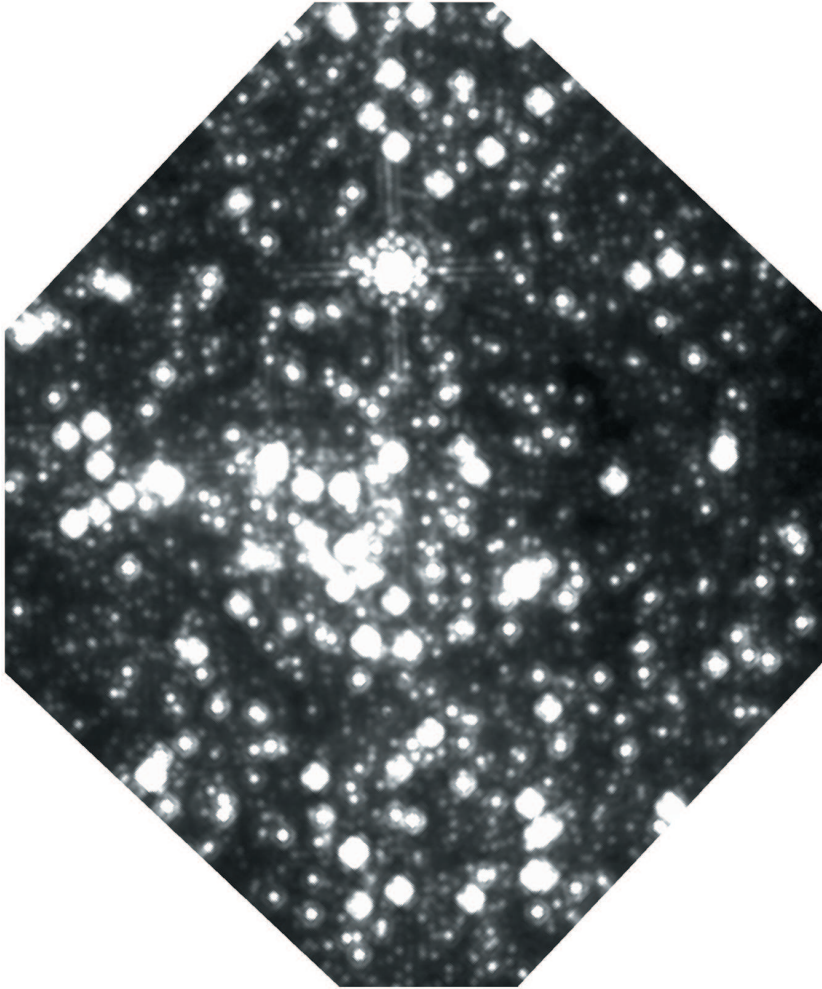


Figure 1.12 A near infrared photograph of the inner 2 light-year region of our galaxy, taken with the NICMOS 1.6-micron detector aboard the Hubble Space Telescope, shows the presence of a dense stellar cluster surrounding the nucleus. This field is the same as that shown in figure 1.7. The difference is that at this particular wavelength, most of the emission is from stars, whereas in the previous images we were witnessing the radiation produced by diffuse gas between the stars. Interestingly, the central source Sagittarius A* emits very little at this wavelength, so it does not even show up here. We will see a magnified view of the region surrounding Sagittarius A* in figure 2.1. (Image courtesy of M. Rieke and the NICMOS team at the University of Arizona)

the traits of its characters and their relative interactions. And yet, other than the bright, blue objects to the left of Sagittarius A*, we have hardly mentioned the role played by stars in the overall ensemble. Surely they must figure in somehow, given that much of what we know about the Milky Way is based on the light we see from them. Indeed they do, and in a rather surprising way. In the next section we will introduce these new cast members, and devote most of chapter 2 to a description of the breakthrough measurements that they have allowed us to make in recent years.

1.4 EXPLORATION FROM SPACE

In all the radio images we have examined thus far, other than the enigmatic, immovable object at the heart of the Milky Way, there are no points of light to be seen anywhere. There is a very simple reason for this—stars emit very little radiation at radio wavelengths. Evolution has served us well with our eyes, fine-tuning them to sense light with a wavelength corresponding to the Sun’s dominant output, which we call “visible light” for obvious reasons. To survive optimally in our environment, we must have senses tuned to the medium conveying the most detailed information, and since Earth’s atmosphere is bathed with the Sun’s rays, it is sensible for us to be able to “see” this light. Most of the stars in the galactic center, like the Sun, should therefore be readily visible to our naked eye, though not to a radio telescope. Unfortunately the presence of space dust makes this otherwise simple task virtually impossible.

All is not lost, however, because it turns out that dust’s deleterious effects weaken quickly as the separation of the light crests increases. In the canals of Venice, a water wave with a wavelength four times the size of the gondola is significantly less intrusive on the boat’s stability than one with two. Well then, what if we could photograph the galactic center using an infrared camera, sampling the light produced with a wavelength longer than that to which our eyes are attuned, but short enough that the stars are still visible to that device?

Attaining this goal has been one of the greatest achievements in our relentless campaign to uncover what is happening at the galactic center, though not without its challenges. Stars twinkle for the same reason that airplanes experience turbulence. Earth's atmosphere is simply not static—it moves—and the light passing through it is deflected, causing the star's intensity and apparent position to fluctuate. Neighboring stars, particularly those huddled close to Sagittarius A*, are therefore not separable on a photographic plate unless something is done to stop the twinkling. The advent of the space age toward the end of the twentieth century has made it possible for us to avoid this problem altogether by moving our platform above the atmosphere. In this regard, the deployment of the Hubble Space Telescope in orbit around the Earth will be remembered as one of the most notable scientific advances ever. Its array of instruments included a 1.6-micron camera with the capability of taking infrared photographs of the heavens with a clarity never before approached in human history.

Peering toward the galactic center, the Hubble Space Telescope recorded the image shown in figure 1.12, which finally reveals to us the dense stellar cluster compressed within the inner 2 light-years of our galaxy, the same region we viewed at radio wavelengths in figure 1.8. Recall that in the solar neighborhood, there would be just a single star within this same volume! Sagittarius A* lurks specter-like in the very middle of this picture, but it does not emit infrared light so we have no way of studying it *directly* with the Hubble Space Telescope. However, its overpowering influence on the stars around it is enormous, and much of chapter 2 will be dedicated to this phenomenon, because it is currently the best means we have of measuring Sagittarius A*'s mass. We recognize in this photograph the concentration of bright stars to the left of where Sagittarius A* would appear, constituting the blue stellar cluster we identified earlier in figures 1.10 and 1.11. We also note to the north the appearance of the very bright, red giant, whose envelope is evaporating to form the cometary blaze we saw in figure 1.8.

In chapter 2 we will see a magnified view of the central region of this infrared photograph, and learn that some of these stars

dart across the sky with the highest velocities in the galaxy (some as fast as several thousand kilometers per second), venturing recklessly to within a mere twentieth of a light-year from Sagittarius A*, before engaging in a hasty retreat. It is possible that even smaller stars, too faint to be seen in this photograph, though far more numerous than the bright ones captured in this image, may steal even closer and, occasionally, fall in. One of them may have produced the huge explosion whose remnant signature is evident in the glorious fireworks on display in figure 1.5.

The advent of the space age has also given us the means to view the heavens at very high radiation energies, where the effects of space dust are equally insignificant. X-rays and gamma rays traversing Earth's atmosphere are readily absorbed by the atoms within it, which is fortunate for us as organic beings since these high-energy rays would otherwise quickly kill living cells and render Earth incapable of supporting life. But out in space, where the density of gas and dust are much lower, X-rays and gamma rays flow freely over very long distances. During its time in orbit, the Compton Gamma-ray Observatory did for gamma-ray astronomy what the Hubble Space Telescope has been doing at infrared and optical wavelengths. Before its fiery descent, plunging into the Pacific Ocean during the summer of 2000, this bus-sized detector enabled us to answer the question: "What would the sky look like if we could see gamma rays?"

The answer is figure 1.13, in which the firmament seems to be filled with a shimmering high-energy glow diffusing throughout the galactic plane. In the last decade of the twentieth century, Compton produced several spectacular images of the sky, sensing radiation with more than 40 million times the energy of visible light. Like many of the other images shown in this chapter, the colors we see in this figure are coded to represent a range of intensities our eyes would detect if they could see that particular type of radiation (in this case, gamma rays). Some of this light is produced by the most exotic and mysterious objects in the universe. Within the galactic plane, much of the high-energy radiation is produced by pulsars—rapidly spinning, magnetized neutron stars barely as

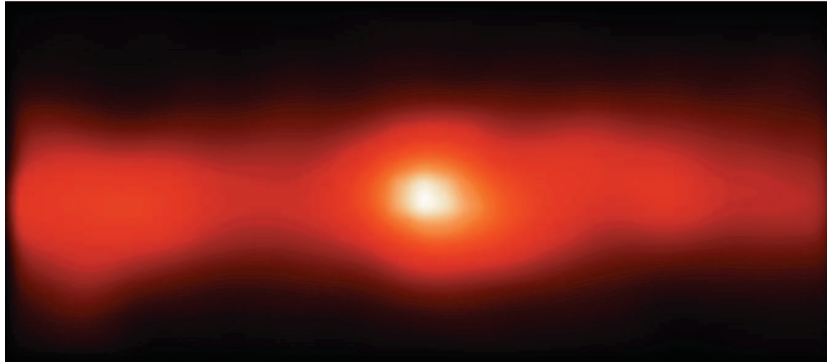


Figure 1.13 High-energy-sensing instruments have difficulty resolving features as small as those seen in the previous radio images, since each photon entering the detector carries a greater punch, and is therefore more difficult to corral. Nonetheless, in the course of a full-sky survey, the EGRET instrument aboard the Compton Gamma-Ray Observatory detected a very-high-energy source that is coincident with the galactic center. This false-color image, showing the gamma-ray intensity within a field of 10 degrees by 30 degrees (so roughly half of the image-size seen in figure 1.1) is color-coded such that white represents a count rate 300 times higher than that of black. In this view (for which one degree corresponds roughly to 430 light-years) the galactic plane (shown as a yellow line in figure 1.1) lies in the horizontal direction. The photon energy sampled in this image is greater than 1 billion electron volts. (By comparison, the electron in a hydrogen atom is stripped away from the nucleus with an energy of only 13.6 electron volts.) Given that the angular resolution of the gamma-ray detector is relatively poor, it is not clear from just this particular observation alone whether the gamma-ray source at the galactic center is associated with a pointlike object, or whether it is diffuse over a region of up to 300 light-years in extent. But recent theoretical work suggests that the gamma rays are produced by the remnant of a hyper-explosion (shown in figure 1.6) that occurred at the galactic center sometime within the past 100,000 years. (Image courtesy of J. R. Mattox in the Department of Physics and Astronomy, Francis Marion University, and NASA)

big as a city, though formed in the violent crucibles of stellar explosions—stellar-sized black holes, such as the well-known Cygnus X-1, and hyper-energetic hydrogen nuclei, known as cosmic rays, which can easily puncture the exterior walls of a spacecraft. Above and below the plane, quasars beyond our galaxy are pow-

ered by supermassive black holes like the one at the galactic center, and produce gamma-ray beacons out to the edge of the visible universe. However, the most prominent source for the high-energy radiation is clearly the galactic center, which illuminates the inner 2,000 light-years of the Milky Way. Curiously, the centroid of this intensity is not Sagittarius A*, as many may have expected, given that black holes can be prodigious sources of power, but rather the explosive remnant Sagittarius A East (figure 1.5). In retrospect, that should not surprise us since the process that created this fiery corona appears to have been the most energetic event of the past 100,000 years.

The Compton Gamma-Ray Observatory was also designed to have the remarkable capability of detecting the radiation produced when matter, in the form of electrons, annihilates with antimatter, in the form of positrons. Given that the mass of these particles is always rigidly fixed, the light they produce when they collide escapes with the finely tuned energy of 511,000 electron volts, which can be distinguished from the rest of the radiation field. The fruits of this engineering and scientific feat produced one of the most memorable images ever seen of the sky, shown with the galactic plane oriented horizontally in figure 1.14. We are witnessing here the annihilation of matter and antimatter on a grand scale, stretched across a 20,000 light-year portion of the galactic plane.

Jules Verne's Professor Hardwigg would quickly point out that notwithstanding the immensity of this panorama, the action is clearly focused on the nucleus. Indeed, to produce such an eerie specter, some 10 million billion billion billion billion (10^{43}) positrons must be sacrificed each and every second at that location. What we do not yet know for sure is whether this antimatter is produced by Sagittarius A*, or one or more members of its entourage. This uncertainty arises because high-energy gamma rays pack an abnormally strong punch and are difficult to corral, so although the Compton Gamma-Ray Observatory could easily count how many were reaching it from a given direction, it could not with precision determine their exact origin. In addition, the glow we

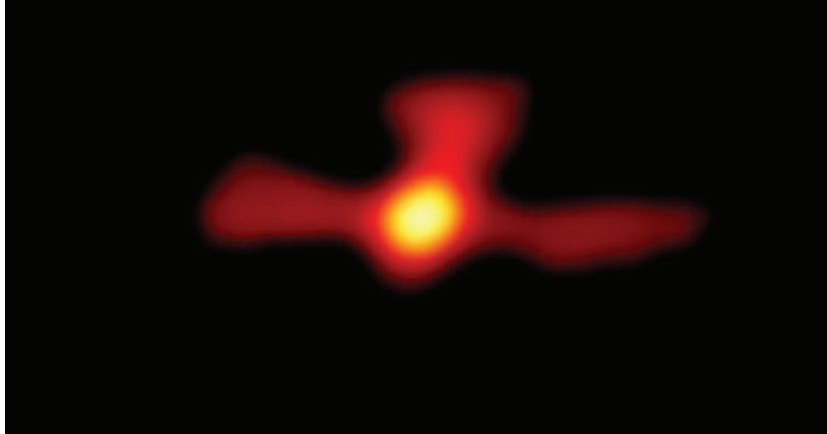


Figure 1.14 This map, spanning a region approximately 20,000 by 10,000 light-years, was produced by the OSSE instrument aboard the Compton Gamma-Ray Observatory. It reveals where antimatter (in the form of positrons) is being annihilated near the galactic center. When positrons annihilate with electrons, they produce characteristic photons with an energy of 511,000 electron volts, whose intensity is shown as a function of position in this color-coded map. The map shows evidence for three distinct features: (1) a central bulge, (2) emission in the galactic plane (which lies in the horizontal direction in this image), and (3) an enhancement or extension of emission above the plane. (Image courtesy of J. Kurfess at the Naval Research Laboratory, and W. Purcell in the Department of Physics and Astronomy, Northwestern University, and NASA)

see in figure 1.14 is definitely diffuse, rather than pointlike, so the positrons live a long time before they meet their partner and perish, which allows them to wander far from their originating site. Future high-energy space missions will have a significantly better spatial resolution, which will allow us to complete our investigation of this phenomenon and finally point to the true source of antimatter in the galaxy.

And so we have begun developing a case for the unusual character of Sagittarius A*. In the next chapter, we will complete our inward trek and assemble the evidence that compels us to accept as real its supermassive black hole status. The implications for our view of how the universe functions are profound, touching on

the most enigmatic prediction of general relativity—the existence of separate worlds largely disconnected from the one in which we live. In chapter 3, we will develop this theory from first principles and reach an understanding that will facilitate our interpretation of the observational vistas we are uncovering during this journey to the center of our galaxy.