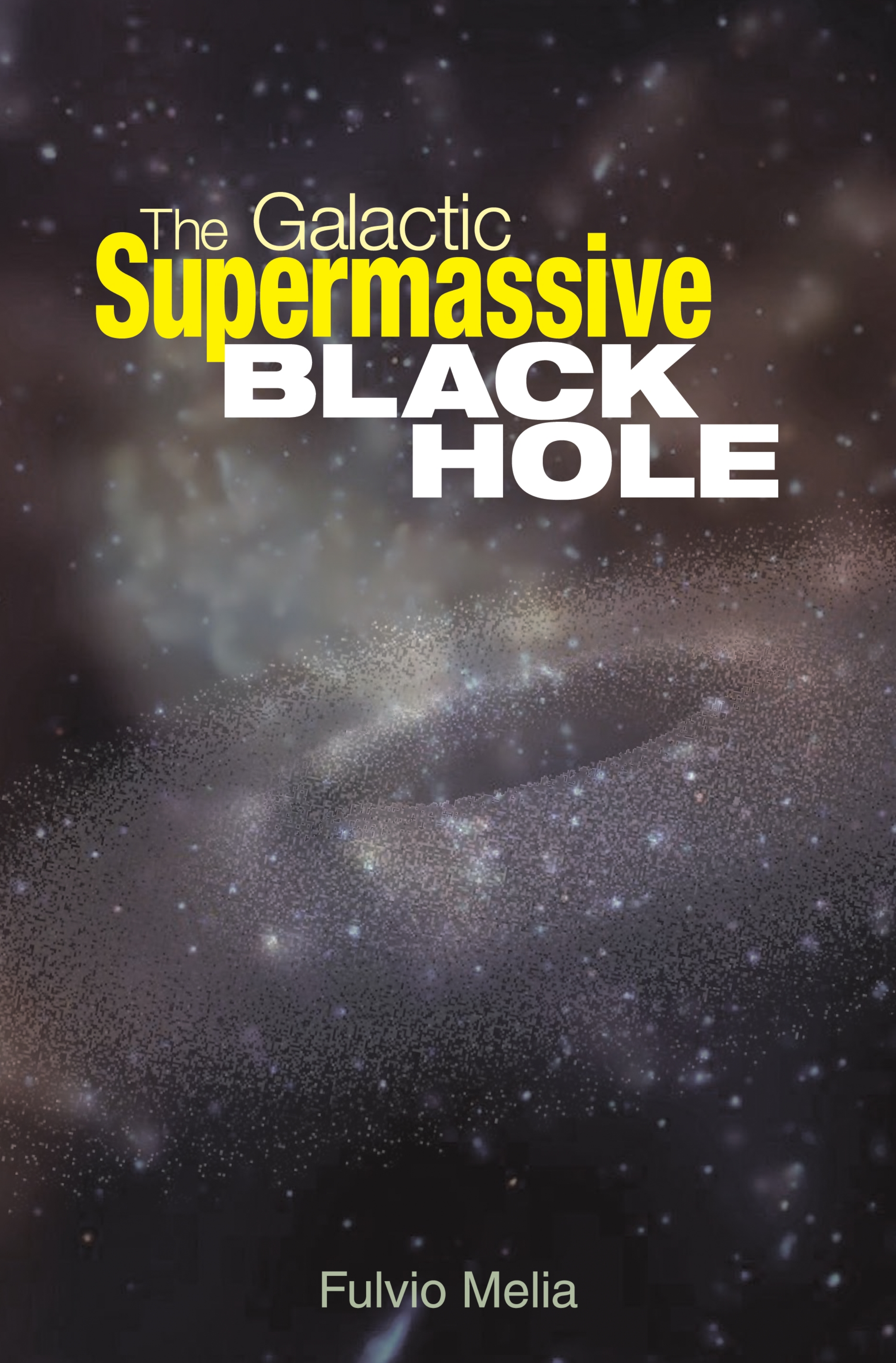
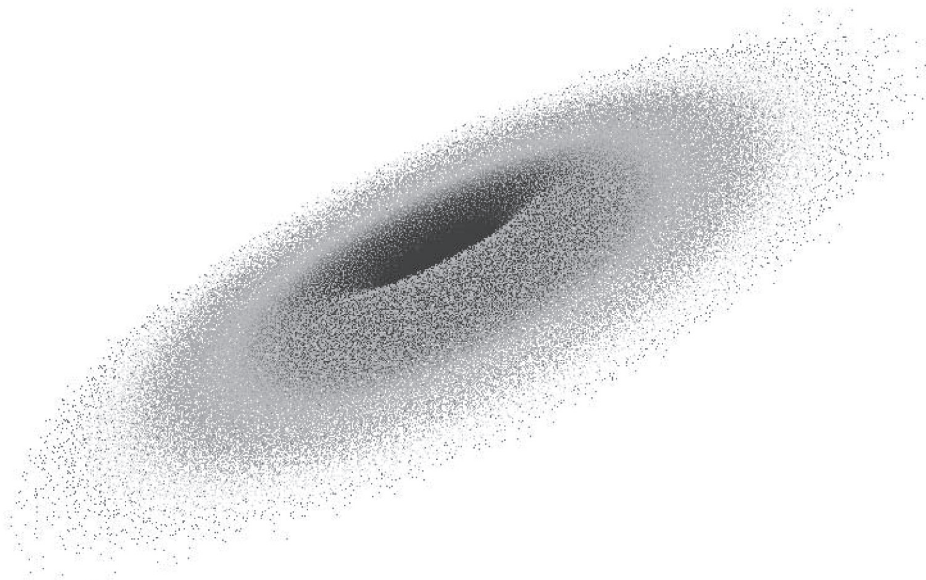


The Galactic Supermassive BLACK HOLE

Fulvio Melia

The Galactic

Supermassive Black Hole



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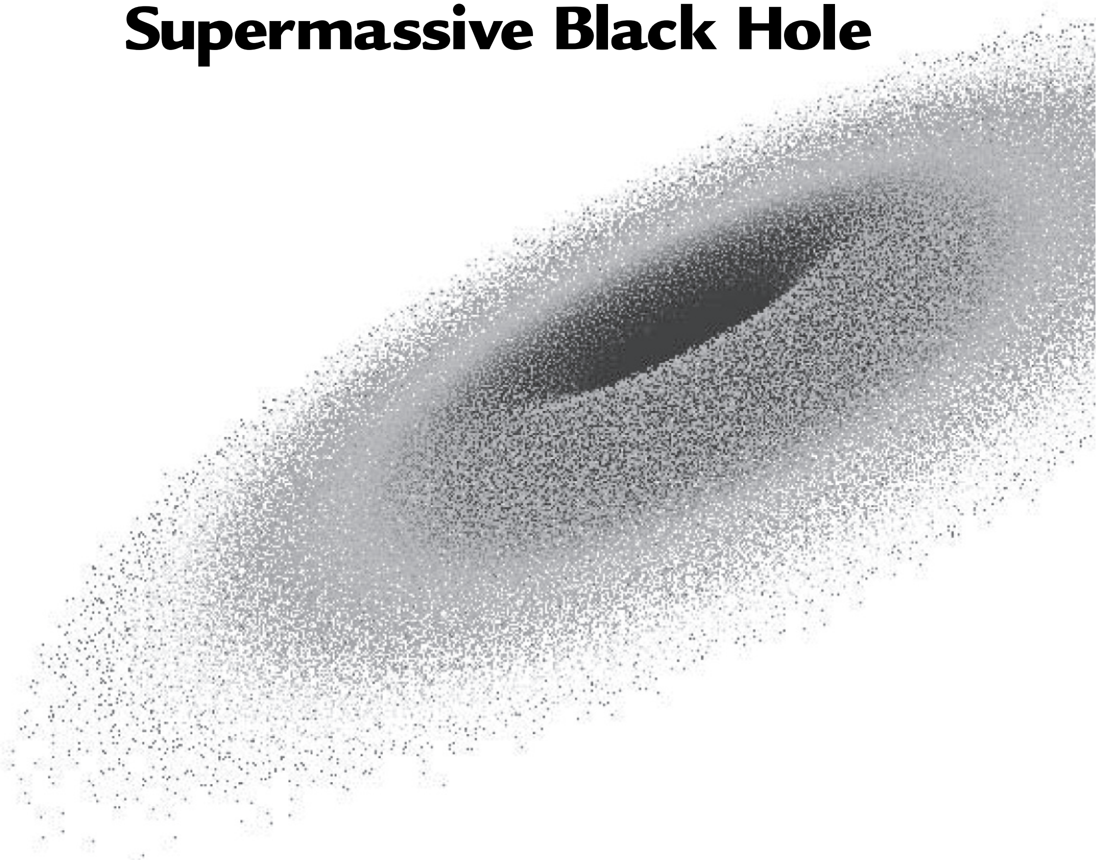

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Foreword

On March 26, 2004, at the end of an international meeting in Green Bank, West Virginia, a plaque commemorating the discovery of Sagittarius A* was fastened to the leg of a 14-meter radio telescope. One hundred scientists from around the world, and employees of the National Radio Astronomy Observatory (NRAO), stood in the unusually warm March sunshine to celebrate the occasion.

The 14-meter telescope had been the key instrument enabling the detection of what we now believe to be the Galaxy's central black hole. In the winter of 1972, the disk had been installed on top of a mountain near Huntersville, 35 kilometers south of Green Bank, where a line-of-sight radio link carried signals and operating commands between the telescope and the campus of the NRAO. The mountain is not high. Once spring arrived, the signals from the radio transmitter near the 14-meter antenna would be so badly attenuated by the intervening tree leaves that NRAO wouldn't operate it during the warm months. But in its short 1.5-year lifetime, the 14-meter telescope completed its task of unlocking the door to a treasure trove of exciting new science associated with the central source of strong gravity.

The 14-meter antenna became operational towards the end of 1972. Its signal was combined with those from three older 26-meter antennas at NRAO's campus to form a huge but very sparsely filled "aperture" 35 kilometers in diameter fixed to the Earth. As the Earth rotated, the four antennas strung out in a line turned with it, enabling the array to sweep out a large, odd wedge-shaped aperture and to form the sharpest—though certainly not the cleanest—images in radio astronomy at that time.

This strangely shaped telescope configuration did not produce pretty images. Even a single point source, such as a distant star, was smeared, elongated, and surrounded by a series of ripples like those produced by a rock falling into a still pond. This Huntersville–Green Bank interferometer would distort the image of a haystack beyond recognition.

But for the first time, it was uniquely capable of finding tiny bright needles lurking within that haystack.

Though the hot gas swirling around the central black hole emits light across the entire spectrum, very little of it reaches Earth. Estimates indicate that only one in a trillion visible photons radiated in our direction survives to reach us through the dense, dark clouds within the disk of the Galaxy. The discovery of the black hole had to await detection either in the radio spectrum, where small dust particles are highly ineffective absorbers, or in X-ray light. Radio astronomers were ready first.

Hiding within the messy haystack of radio emission—known as Sagittarius A—at the galactic center, was a bright golden needle that had never been recognized before. The hot gas orbiting the black hole, now known as Sagittarius A*, is the cause of intense radio emission emitted from a region smaller than our solar system, something like the light from a hot, intense welder's arc at night in a city full of streetlights. Cameras built prior to 1973 produced poorly focused images, so Sagittarius A* appeared as just one of many luminescent smears on an image that was lost in the glare of the other surrounding lights. The 35-kilometer baseline of the Huntersville–Green Bank interferometer, however, was ideally suited to produce images of small, intense points of light; the others were resolved out and did not register in the image that the interferometer produced. As we now know, Sagittarius A* would be easily detected the first time that the 35-km array interferometer looked in its direction.

By 1973, two proposals had been submitted to use the 35-kilometer aperture to look for bright structures buried deep within Sagittarius A. In December 1970, before anyone imagined that a huge black hole might be lurking at the center of the Milky Way, Bruce Balick, then a graduate student from Cornell working on his PhD thesis at Green Bank, proposed to NRAO to use the Huntersville–Green Bank interferometer to probe HII Regions for particularly bright sources that might reveal very hot young stars. Thirteen months later, he amended the proposal to add his close colleague Robert Brown of NRAO and asked to include in the proposal additional HII Regions seen in the southern sky. He didn't mention Sagittarius A by name, but it was high on his list of propitious targets. The amended request was approved.

A second proposal arrived at NRAO in June 1972 from Dennis Downes and Miller Goss, both Americans working at the Max-Planck-Institut in Germany at the time. The idea that a black hole ought to reside in the center of most large galaxies, such as the Milky Way, had been receiving a great deal of attention since late 1970, especially in Europe where Downes and Goss were working. They specifically mentioned the search for a huge black hole as their motivation and Sagittarius A as the target in their NRAO proposal. As it turns out, their proposal was far more prescient than that of Balick and Brown.

Two proposals to observe the same object at the same time constitute a proposal conflict—a situation that public observatories find very uncomfortable. Unless there are special circumstances, a target common to several proposals is observed just once. An adjudication process determines which proposing team is awarded time on the telescope: the team that proposes first, the team with the best scientific case, or a merger of individuals from both teams. However, these strategies are invoked only when the target conflict is recognized. Balick and Brown had not mentioned Sagittarius A by name, whereas Downes and Goss did. So to no one's surprise, NRAO missed the conflict entirely.

In the end, it was the team that was fortunate enough to get the observing time first that would discover the black hole in Sagittarius A. The other team was likely to be disappointed, frustrated, and perhaps angry. This is a telescope scheduler's worst nightmare.

Work on the interferometer's electronics ran late, so Downes and Goss were scheduled to go first, late in 1973. But as it turned out, they could not in that year abandon the responsibility of brand-new jobs and urgent projects. NRAO agreed to postpone their observation. Meanwhile, Balick and Brown were scheduled for their observation on February 13 and 15, 1974. Balick, by then a postdoctoral fellow at the University of California at Santa Cruz, flew to Green Bank, while Brown, a scientist at NRAO in Charlottesville, Virginia, remained at home to assist with the processing of the data on the large computers available there.

The weather was ideal for the observing run: the sky was sunny and the air stable, which meant that the radio signals coming through the atmosphere were only minimally distorted. (In stormy weather, radio sources can be badly distorted by atmospheric effects, making the detection of small objects very difficult.) The observation was flawless, and the detection of a small, bright object in Sagittarius A was obvious from the moment the telescopes were aimed in the right direction. Balick continued to observe it for almost six hours, letting the Earth rotate the aperture so that a better image of the region around Sagittarius A could be built up over time.

And thus began decades of intriguing research on the nature and characteristics of the massive black hole right here at the heart of the Milky Way. The plaque dedicated in 2004 enshrined Balick and Brown's radio observations in February 1974, the people who built the hardware, and the years of fascinating subsequent discoveries. Today Sagittarius A is being observed across the spectrum, except, of course, in the optical and ultraviolet, where the attenuation by the intervening dust forever blocks our view of the galactic center.

As you can imagine, however, the discovery of Sagittarius A* ignited the issue of the conflicting proposals. The NRAO scientist Dave Hogg, who was responsible for scheduling the interferometer, was informed by Balick of the stunning new results. Hogg was simultaneously elated and aghast. Downes and Goss were informed immediately. They were obviously disappointed that another group had been given time to perform the very same experiment that they had expected to conduct a few months later. Meanwhile, Balick and Brown exerted pressure on Hogg to permit them to rush their exciting results into print.

Hogg knew that the situation was delicate. With the passage of time, he no longer clearly remembers the sequence of events that ensued. Brown, whose office was near Hogg's, recalls that Hogg contacted Downes and Goss right away and, for lack of a more satisfactory resolution, offered them their time on the 35-kilometer Huntersville–Green Bank interferometer. Goss later recalled: "With [the pressure of our new jobs], the urgency to complete the Downes-Goss proposal decreased. Dave Hogg became aware of the proposal conflict in early 1974 and wrote a letter on February 15, 1974 (note the precise discovery date), proposing several ways to resolve the conflict. However, Goss and Downes seemed to have lost interest at this point."[1] In any event, Goss very kindly withdrew the Downes-Goss proposal.

From March through May, Balick and Brown pondered over their results. It was clear that the substantial intensity of the source and its small size showed conclusively that the radiating object was hotter and more intense than any other radio source then known in the Milky Way. The flux of radio emission in the beam of the synthesized telescope divided by the area of the beam, or the measured "surface brightness", was at least 1,000 times that of the Sun's. That pointed immediately to the significance of the discovery since no star and no hot gas then known had a surface brightness greater than ten times that of the Sun's.

[1] See Goss, Brown, and Lo (2003).

Sagittarius A* was recognized to be clearly something special at the time of its discovery. Subsequent radio measurements with far more sophisticated instruments have shown that the actual surface brightness of this source is even higher than the initial determination. This fact, its unique location at the center of the Milky Way, and its copious emission of radio waves underscore its uniqueness and importance. Sagittarius A* remains unchallenged as the most intriguing radio source in the Galaxy.

By June 3, 1974, Balick and Brown had completed the analysis of their data, reached a cautious conclusion about their significance, and written and submitted a short announcement for publication. The paper received expedited processing by the editor of *The Astrophysical Journal Letters*. It appeared in the December 1, 1974, issue.

At least a hundred papers reporting new data and interpretive ideas about Sagittarius A* have been written since 1974. The meeting in 2004 was a grand occasion for scientists to meet at Green Bank, to share their latest results and ideas, and to develop a strategy for coordinating their observing campaigns in the years ahead. It was also a time to look back circumspectly to see how far and how fast the research on Sagittarius A* had come. One thing is clear: Sagittarius A* is both an object and, as the 2004 Green Bank meeting demonstrated, a subject as well—a scientific subject in its own right.

Bruce Balick
Green Bank, West Virginia

Preface

A sustained period of discovery over the past two decades has fostered a growing interest in the galactic center. This region of the sky is now the focus of many observational campaigns and an ever-growing theoretical investigation, the former because it is by far the closest (active) galactic nucleus, the latter because Sagittarius A*—the supermassive black hole lurking there—offers us the most viable opportunity of studying the physics of strong fields.

One ought to approach the task of writing a book on this subject with some trepidation, knowing that what drives the excitement of new findings at the same time guarantees a rapid evolution in content. We have come far in understanding the behavior of Sagittarius A*, yet we all know that there is still much to be learned.

Unfortunately, the primary literature on this subject is now at such a mature level that young astronomers and physicists wishing to pursue its study and scientists in other disciplines find it daunting to bring themselves up to speed with current developments. My hope is that this book will assist them in their exploration.

With the many entry points created by investigators over the years, research on Sagittarius A* may at first appear to be a complex pattern of interwoven threads. I have tried to synthesize this extensive work into a crucible of essential ideas, while providing a coherent story overall. But for completeness, I have also compiled an extensive set of references to the original literature for the benefit of those wishing to study the various topics at greater depth.

I have had the good fortune over the years of being directly involved in galactic-center research, and in these endeavors I am very grateful to my students and collaborators for the pleasure of our joint efforts. They include Peter Tamblyn, Jack Hollywood, Laird Close, Sera Markoff, Alexei Khokhlov, Marco Fatuzzo, Robert Coker, Mike Fromerth, Siming Liu, Gabe Rockefeller, Brandon Wolfe, Chris Fryer, Susan Stolovy, Heino Falcke, Victor Kowalenko, Ray Volkas, Roland Crocker, Pasquale

Blasi, Don MacCarthy, George Rieke, Benjamin Bromley, Randy Jokipii, Vahé Petrosian, Martin Pessah, Martin Prescher, Andrea Goldwurm, Guillaume Bélanger, Eric Agol, Max Ruffert, Fred Baganoff, Joe Haller, and Daniel Wang.

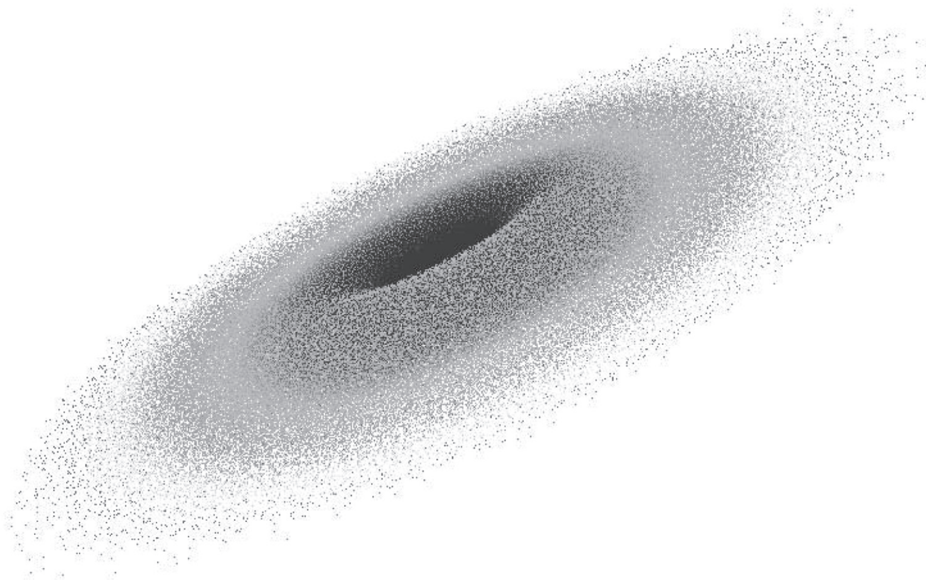
I am particularly grateful to my close friend and longtime collaborator Farhad Yusef-Zadeh, whose early radio images of the galactic center inspired my interest in this field and whose ongoing drive and groundbreaking observations continue to be a fountain of enthusiasm and new ideas. And for generously supporting my research in this area for more than a decade and a half, I gratefully acknowledge the National Science Foundation, the National Aeronautics and Space Administration, and the Alfred P. Sloan Foundation.

Finally, to Patricia, Marcus, Eliana, and Adrian and to my parents, whose guidance has been priceless, I extend my enduring love and gratitude.

Fulvio Melia
Tucson, Arizona

The Galactic

Supermassive Black Hole



Chapter 1

The Galactic Center

Stellar radial velocity measurements, sensing the gravitational potential at the nucleus of our Galaxy,[1] and remarkable proper motion data acquired over eight years of observation have now allowed us to probe the central distribution of mass down to a field as small as 5 light-days. The heart of the Milky Way is evidently ensconced within two clusters of massive and evolved stellar systems orbiting with increasing velocity dispersion toward the middle, where $2.6–3.6 \times 10^6\ M_\odot$ of nonluminous matter is concentrated within a region no bigger than 0.015 pc—a mere 800 AU.[2]

The stellar kinematics in the central region is consistent with Keplerian motion—pointing to a supermassive black hole as the likely manifestation of this dark matter. Its inferred mass is arguably the most accurately known for such an object, with the possible exception of NGC 4258.[3]

But this condensation of matter is not alone at the galactic center; within a distance of only 20 light-years or so, several other principal components function in a mutually interactive coexistence, creating a rich tapestry of complexity in this unique portion of the sky. This assortment of players includes an enshrouding cluster of evolved stars, an assembly of young stars, molecular and gas clouds, and a powerful

[1] See McGinn et al. (1989), Rieke and Rieke (1989), Sellgren et al. (1990), and Haller et al. (1996).

[2] These results are based on measurements of the stellar velocity dispersion within the inner 0.1 pc of the Galaxy (reported by Genzel et al. 1996; Eckart and Genzel 1996, 1997; and Ghez et al. 1998) and, more recently, on the determination of specific stellar orbits, discussed extensively in chapter 5. See Schödel et al. (2002) and Ghez et al. (2003b).

[3] The spiral galaxy NGC 4258, in the constellation Canes Venatici, sits not too far from the Big Dipper, some 23 million lt-yr from Earth. Using Very Long Baseline Interferometry (VLBI), Miyoshi et al. (1995) identified microwave water maser emission from molecular material orbiting within the galaxy's nucleus at velocities of up to 650 miles per second. The disk within which these water molecules are trapped is tiny compared to the galaxy itself, but it is oriented fortuitously so that Doppler shifts can provide an unambiguous measure of the orbit's velocity and hence the enclosed mass. The black hole at the nucleus of NGC 4258 is thereby known to have a mass of $3.6 \times 10^7\ M_\odot$.

supernova-like remnant, known as Sagittarius A East.[4] Some view this assortment of objects as an indication that the galactic center may be linked to the broader class of active galactic nuclei (AGN), in which a supermassive black hole is thought to be a key participant in the dynamics and energetics of the Galaxy's core. Thus, developing a consistent picture of the primary interactions between the various constituents at the galactic center not only enhances our appreciation for the majesty of our nearby environment but also improves our understanding of AGN machinery in a broader context.

In this chapter, we shall describe the principal components residing within the Galaxy's inner core and account for the overall morphology of this region, revealed primarily through the power of modern X-ray and radio telescopes. The dark matter, it turns out, may not be so dark after all, particularly if its inferred association with a point emitter of radio waves proves to be correct.

1.1 Discovery of Sagittarius A*

The radio source that would later be viewed as the most unusual object in the Galaxy was discovered on February 13 and 15, 1974, under excellent weather conditions and with virtually problem-free instrumental performance. Balick and Brown (1974) reported this "detection of strong radio emission in the direction of the inner 1 pc core of the galactic nucleus" later that year, adding that the structure had a brightness temperature in excess of 10^7 K, that it was unresolved at the level of $\sim 0.''1$, and that it was clearly distributed within just a few arcseconds of the brightest radio and infrared emission seen previously from this region. (At the 8 kpc distance to the galactic center, $1'' \approx 0.04$ pc.) The novelty that permitted them to distinguish pointlike objects from the overall radio emission in the inner $20''$ was the newly commissioned 35-kilometer baseline interferometer of the National Radio Astronomy Observatory (NRAO), consisting of three

[4]The heart of the Milky Way lies in the direction of the constellation Sagittarius, close to the border with the neighboring constellation Scorpius. 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 structure within it is called, for example, Sagittarius A East (or Sgr A East for short) and Sagittarius A West (Sgr A West). As we shall see, the most unusual object in this region, discovered in 1974, stands out on a radio map as a bright dot. Its name is Sagittarius A* (Sgr A*).

26-meter telescopes separable by up to 2.7 kilometers and a new 14-meter telescope located on a mountaintop about 35 kilometers southwest of the other dishes.

Balick and Brown had included the central infrared (IR)/radio complex as part of a program to identify "super-bright radio knots" in HII Regions, though in principle the motivation for establishing that the galactic center is active in ways similar to more powerful galactic nuclei had been discussed and developed over the previous three or four years. For example, Sanders and Prendergast (1974) had hypothesized earlier that year that, although now quiescent, the galactic center may once have housed energetic processes like those seen in BL Lac. And in 1971, Lynden-Bell and Rees used a prescient application of the then very speculative black hole model for quasars to point out that the galactic center also should contain a supermassive black hole, perhaps detectable with radio interferometry. Proposing that a central black hole may be currently emitting $\sim 1.5 \times 10^8\, L_\odot$ of ultraviolet light and that it is blowing away a hot nuclear wind, they invoked a process first suggested by Salpeter (1964)—that gas circulating about the central object eventually flows viscously through the event horizon—to postulate a source for the required energy.

The argument made by Lynden-Bell and Rees was based on the implausibility of starlight alone ionizing the extended thermal source surrounding the central region, not to mention the difficulty of producing a "nuclear wind" with both ionized and neutral material moving at speeds exceeding $200\,\mathrm{km\,s^{-1}}$. They proposed instead an ultraviolet nonstellar continuum produced by the hypothesized black hole, which presumably also created the observed efflux of mass. We shall see below that the actual picture is not quite as straightforward as this, but Lynden-Bell and Rees's proposal functioned as an influential catalyst in the early attempts to characterize the new radio source as a black hole phenomenon.

From the time of its discovery, the unusual nature of the sub-arcsecond structure and its positional coincidence with the inner 0.04 pc core of the Galaxy provided compelling evidence that it should be physically associated with the galactic center—perhaps even defining its location. Its high brightness temperature, small angular size, and nearby association with strong IR and radio continuum sources made it unique in the Galaxy. Other sources, such as pulsars, resemble the central compact radio structure in a few of its characteristics but not all. Its unusual properties were later confirmed by Westerbork[5] and Very Long Baseline Interferometry (VLBI) observations.[6]

Several years later, maps of 12.8 μm NeII fine-structure line emission from the galactic center[7] revealed that the ionized gas within the central parsec of the Galaxy is not only moving supersonically, but that it is also highly ordered. Regions of blueshifted NeII emission could be separated cleanly from preferentially redshifted streamers, and more precise high-resolution Very Large Array (VLA) observations by Brown, Johnston, and Lo (1981) placed the unresolved radio emitter very near the dynamical center of this implied circular motion. It was around this time that Brown (1982) named the unusual radio source Sagittarius A* (or Sgr A* for short) to distinguish it from the extended emission of the Sagittarius A complex and to emphasize its uniqueness and importance.[8]

Studies of the infrared fine-structure line emission of NeII were followed soon afterwards with mapping observations of the $^3P_1$–$^3P_2$ fine-structure line emission from neutral atomic oxygen at 63 μm.[9] It soon became apparent that the clouds producing the NeII emission and the gas containing the neutral oxygen were rotating about the galactic center with velocities corresponding to a Keplerian mass of $\sim 3 \times 10^6\ M_\odot$ within the central parsec. Though not accepted immediately, these were early indications that Sagittarius A* might be a concentrated source of gravity, with an estimated mass remarkably close to the value inferred much later from the motion of stars in this region.

Sagittarius A*'s unusual character and possible association with quasar activity—albeit on a significantly smaller scale—were cemented soon thereafter with dual-frequency radio observations made on 25 epochs over a period of three years.[10] Sagittarius A*'s lightcurve clearly demonstrated a variability of 20%–40% in its centimeter-flux density on all timescales, from days to years. As we shall see in the remainder of this

[5]See "A Full Synthesis Map of Sgr A at 5GHz" by Ekers et al. (1975).

[6]These were presented by Lo et al. (1975) in a paper entitled "VLBI Observations of the Compact Radio Source in the Center of the Galaxy."

[7]These observations were first reported by Lacy et al. (1979) and Lacy et al. (1980).

[8]Ten years later, this nomenclature was also used to denote the central radio point source, now known as M31*, in the nucleus of M31 (Melia 1992b) and has since been generalized to identify all such sources in the nuclei of nearby galaxies.

[9]Both the NeII and OI observations and the early evidence they provided for a central massive object were reported in a series of papers by Townes and his collaborators, including Lacy, Townes, and Hollenbach (1982), Townes et al. (1983), and Genzel et al. (1984).

[10]See Brown and Lo (1982).

book, these temporal fluctuations and a wealth of evidence accumulated since the early 1980s have rendered Sagittarius A* the prime suspect in the radiative uncloaking of the putative supermassive black hole at the center of our Galaxy.

1.2 Radio Morphology of the Central Region

Before we focus our attention exclusively on Sagittarius A*, however, let us first widen the field of view and examine its position among the other key components of the galactic nucleus. Color plate 1 shows a wide-field, high-resolution 90 cm image centered on Sagittarius A, covering an area of $4^\circ \times 5^\circ$ with an angular resolution of $43''$. This map of the galactic center is based on archival data originally acquired and presented by Pedlar et al. (1989) and Anantharamaiah et al. (1991), who observed the galactic center with the VLA 333 MHz system in all four array configurations between 1986 and 1989. But it was only the use of a wide-field algorithm that properly compensates for the nonplanar baseline effects seen at long wavelengths that permitted LaRosa, Kassim, and Lazio (2000) to properly image such a large field of view and obtain increased image fidelity and sensitivity. A schematic diagram in galactic coordinates of the extended sources seen in the 90 cm image is shown in figure 1.1.

With the exception of the Sagittarius A complex centered on Sagittarius A*, nearly all of the sources in color plate 1 are detected in emission, providing for the first time a view of the large-scale radio structure in the galactic center. However, of the seventy-eight small-diameter ($<1'$) sources concentrated toward the galactic plane, about half have steep spectra ($\alpha \approx -0.8$) and are therefore probably extragalactic, though a small population of radio pulsars and young supernova remnants cannot be excluded. The other half are concentrated even more toward the galactic plane and are thus probably HII Regions.

Within the central $15'$ (or roughly 37 pc for an assumed galactic-center distance of 8 kpc), the most notable structure is the Sagittarius A complex, consisting of the compact nonthermal source Sagittarius A*, surrounded by an orbiting spiral of thermal gas known as Sagittarius A West.[11] Along the same line of sight lies the nonthermal shell source known as Sagittarius A East, which appears to be the remnant of an energetic explosion. In their initial analysis, Pedlar et al. (1989) found

[11] A description of this structure may be found in Ekers et al. (1983) and Lo and Claussen (1983).

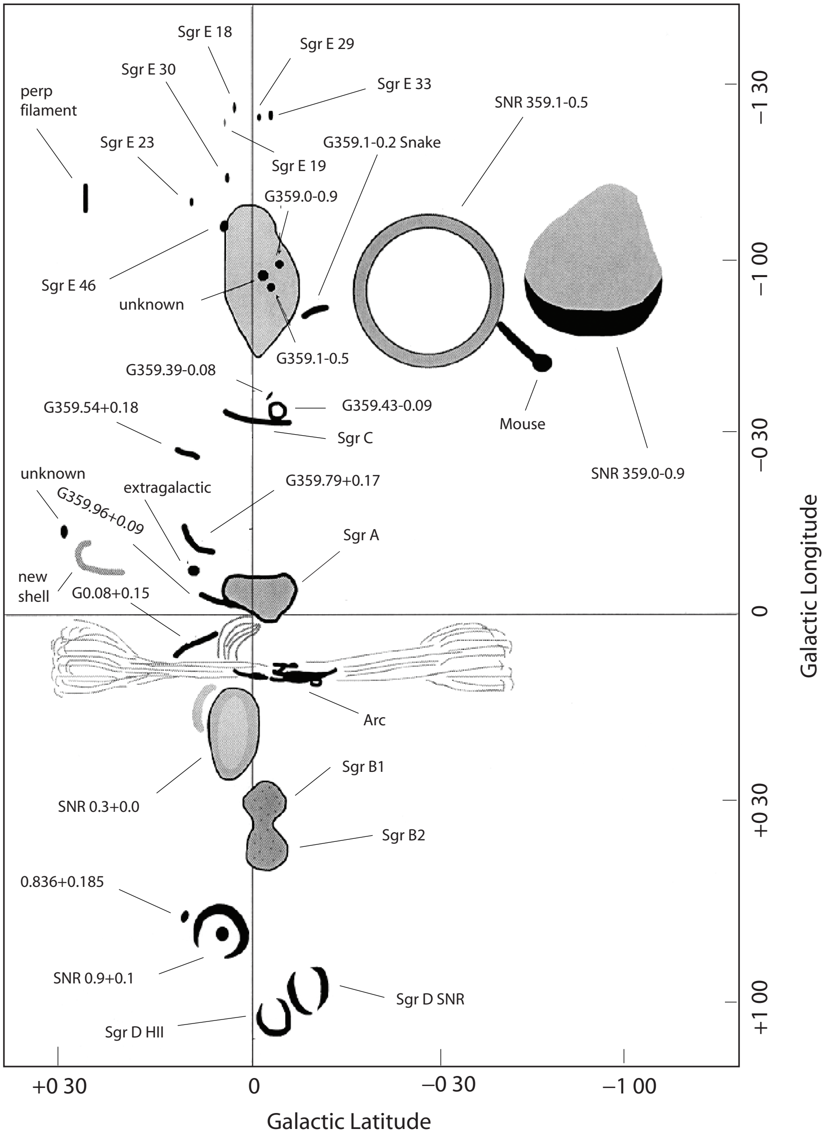


Figure 1.1 This is a schematic diagram of the extended sources shown in the 90 cm image of the galactic center in color plate 1. The perspective has been rotated so that the galactic plane is vertical in this representation. (From LaRosa, Kassim, and Lazio 2000)

that Sagittarius A West is seen in absorption against the background of Sagittarius A East, indicating that the latter must lie behind the former. Sagittarius A clearly contains detail within that is not evident in color plate 1; magnified views of the principal subcomponent sources are shown at higher frequency in color plates 2 and 3.

Some $15'$ to $20'$ (or 50 pc in projection) north of Sagittarius A is located the galactic-center arc. First resolved into a large number of narrow filaments by Yusef-Zadeh, Morris, and Chance (1984), they show strong polarization with no line emission and are therefore nonthermal synchrotron sources, probably magnetic flux tubes flushed with relativistic electrons. The fact that several HII Regions appear to be interacting with the filaments in this arc suggests that particles are being accelerated in situ via magnetic reconnection. Several other (isolated) filaments within the central half degree also contribute to the nonthermal magnetic structure, and most are oriented perpendicular to the galactic plane.

Other features of note in this image are supernova remnants (such as Sgr D and SNR $0.9 + 0.1$) and giant molecular clouds (such as Sgr B1 and Sgr B2). Although stars are not visible, the drama of their collective births and deaths is manifest throughout the galactic center. These clouds are in fact regions of star formation and become discernible when newborn stars heat the surrounding gas and make it shine in the radio. All in all, this radio continuum view, together with observations at mm, infrared, and X-ray wavelengths (see below), points to the galactic center as constituting a weak, Seyfert-like nucleus that sometimes also displays mild outbursts of active star formation, as we shall see.

The bright central source in color plate 1 may be magnified further by tuning the receivers to a higher frequency and therefore a better resolution. The region bounded by a box in color plate 1 is shown at 20 cm in color plate 2, a radio continuum image spanning the inner $50\,\mathrm{pc} \times 50\,\mathrm{pc}$ portion of the Galaxy. On this level, the distribution of hot gas within the Sagittarius A complex displays an even richer morphology than at 90 cm, with the evident coexistence of both thermal and nonthermal components.[12]

Sagittarius A East is the diffuse ovoid region to the lower right in color plate 2, surrounding (in projection) a spiral-like pattern in red, which is Sagittarius A West. The central spot in this structure identifies Sagittarius A*, which is coincident with the concentration of dark matter inside 0.015 pc. The arc becomes apparent as a set of radio-emitting streamers

[12] See also Yusef-Zadeh and Morris (1987) and Pedlar et al. (1989).

interacting with the Sagittarius A complex and together with the other filamentary structures within a few hundred light-years of the center are believed to trace the large-scale magnetic field in the region.

Sagittarius A East appears to be a supernova remnant (perhaps a bubble driven by several supernovae), based primarily on recent *Chandra* X-ray observations that point to a young ($\sim 10^4$ yr) member of the metal-rich, mixed-morphology class of remnants (Maeda et al. 2002). Observations of this source also show it to be associated with a prominent ($50\,\mathrm{km\,s^{-1}}$) molecular cloud near the galactic center (see below).

At a wavelength of 6 cm (see color plate 3), Sagittarius A West shines forth as a three-armed spiral consisting of highly ionized gas radiating a thermal continuum. Each arm in the spiral is about 3 light-years long, but one or more of these may be linked to the overall structure merely as a superposition of gas streamers seen in projection. At a distance of 3 light-years from the center, the plasma moves at a velocity of about $105\,\mathrm{km\,s^{-1}}$, requiring a mass concentration of just over $3.5 \times 10^6\ M_\odot$ inside this radius. Again, the hub of the gas spiral corresponds to the very bright radio source Sagittarius A*, the dynamical center of our Galaxy.

The central 2 light-year $\times$ 2 light-year portion of Sagittarius A West is shown at 2 cm in color plate 4. This is to be compared with the corresponding infrared image of this field in color plate 5, a crowded infrared photograph of unprecedented clarity produced recently with the 8.2-meter VLT Yepun telescope at the European Southern Observatory in Paranal, Chile. (Each of the four telescopes in the Very Large Telescope [VLT] array has been assigned a name based on objects known to the Mapuche people, who live in the area south of the Bío-Bío River, some 500 kilometers from Santiago, Chile. Yepun, the fourth telescope in this set, means *Venus*, or evening star.) The sharpness of the image we see here was made possible with the use of adaptive optics, in which a telescope mirror moves constantly to correct for the effects of turbulence in Earth's atmosphere.

Sagittarius A West probably derives its heat from the central distribution of bright stars evident in color plate 5, rather than from a single point source, such as Sagittarius A*.[13] Some hot, luminous stars are thought to have been formed as recently as a few million years ago.[14] It is

[13]An early discussion of this inference was made by Zylka et al. (1995), Gezari (1996), Chan et al. (1997), and Latvakoski et al. (1999).

[14]See Tamblyn and Rieke (1993), Najarro et al. (1994), Krabbe et al. (1995), and Figer et al. (1999).

not surprising, therefore, to see a sprinkling of several IR-bright sources throughout Sagittarius A West that are probably embedded luminous stars. It is not known yet whether these particular stars formed within the gas streamer or just happen to lie along the line of sight.

On a slightly larger scale ($\sim$3 pc), Sagittarius A West orbits about the center within a large central cavity, surrounded by a gaseous and dusty circumnuclear ring.[15] Color plate 6 shows a radio-wavelength image of ionized gas at 1.2 cm (due to free-free emission) superimposed on the distribution of hydrogen cyanide (HCN), which traces the molecular gas. The picture that emerges from a suite of multiwavelength observations such as these is that this molecular ring, with a mass of more than $10^4\, M_\odot$, is clumpy and is rotating around a concentrated cluster of hot stars, known as IRS 16 (see color plate 5), with a velocity of about $110\,\mathrm{km\,s^{-1}}$, according to Güsten et al. (1987) and Jackson et al. (1993).

Most of the far infrared luminosity of the circumnuclear ring (or disk) can be accounted for by this cluster of hot, helium emission line stars, which bathe the central cavity with ultraviolet radiation, heating the dust and gas up to 8 pc from the center of the Galaxy. The IRS 16 complex consists of about two dozen blue stellar components at 2 μm and appears to be the source of a strong wind with velocity on the order of $700\,\mathrm{km\,s^{-1}}$ and an inferred mass loss rate of $4 \times 10^{-3}\, M_\odot\,\mathrm{yr}^{-1}$. These blue stars are themselves embedded within a cluster of evolved and cool stars with a radial density distribution r^{-2} from the dynamical center. However, unlike the distribution of evolved cluster members, which extend over the central 500 pc of the galactic bulge, the hot stars in IRS 16 are concentrated only within the inner parsecs.[16]

It should be pointed out that, whereas the stars orbit randomly about the galactic center, the ionized gas is part of a coherent flow with a systematic motion that is decoupled from the stellar orbits. Identifying kinematics of the ionized gas is complicated by our incomplete view of its three-dimensional geometry; in addition, the orbiting gas may be subject to nongravitational forces, for example, from collisions with the winds produced by the central cluster of hot, mass-losing stars. Even so, Yusef-Zadeh, Roberts, and Biretta (1998) have recently reported some progress

[15]A more detailed description of this structure may be found in Becklin, Gatley, and Werner (1982) and Davidson et al. (1992).

[16]See Hall, Kleinmann, and Scoville (1982), Geballe et al. (1987), and Allen, Hyland, and Hillier (1990).

in mapping the motion of the interstellar medium by combining the transverse velocities measured over nine years with the radial velocities measured for the ionized gas.

The predominant motion projected in the plane of the sky is from east to west for most of the gaseous features (see color plate 4), with the exception of only a few cases where the velocity of the ionized gas is anomalously large, possibly due to an interaction with the stellar winds. In addition, velocity gradients exceeding $600\,\mathrm{km\,s^{-1}\,pc^{-1}}$ seem to be produced by the strong gravitational potential associated with the dark matter at the location of Sagittarius A*.

1.3 X-Ray Morphology of the Central Region

A rather different—though no less interesting—view of the galactic center emerges with progressively sharper images of this region in the X-ray band. X-ray emission has been observed on all scales, from structure extending over kiloparsecs down to a fraction of a light-year, with contributions from thermal and nonthermal, pointlike and diffuse sources. In figure 1.2, which shows the 1.5 keV map produced with ROSAT (Snowden et al. 1997), we detect evidence for a large-scale outflow of hot gas from the nucleus. Resembling the morphology seen in nearby galaxies with active nuclear star formation, the hollow-cone-shaped soft X-ray feature on either side of the galactic plane points to the efflux of plasma as the agent accounting for much of the diffuse soft X-ray background in the Milky Way. The presence of various spectral features, particularly the 6.7 keV Fe XXV Kα line detected with *ASCA*, suggests further that a large fraction of this gas is so hot[17] that confinement due to gravity is not feasible, though *Chandra* has more recently forced us to refine this global conclusion (see below).

The magnified view of the central $3^\circ \times 3^\circ$ shown in figure 1.3 reveals additional evidence for the expulsion of hot matter from the nucleus, in the form of a prominent, bright soft X-ray plume that apparently connects the galactic center to the large-scale X-ray structure hundreds of parsecs above and below the galactic plane. A direct comparison of the ROSAT and IRAS 100-micron images of this region suggests that any gaps in the X-ray emissivity are likely due to X-ray shadowing by foreground interstellar, dusty gas.

[17]The ASCA Fe line observations apparently require a temperature as high as $\sim 10^8$ K. See Koyama et al. (1996).

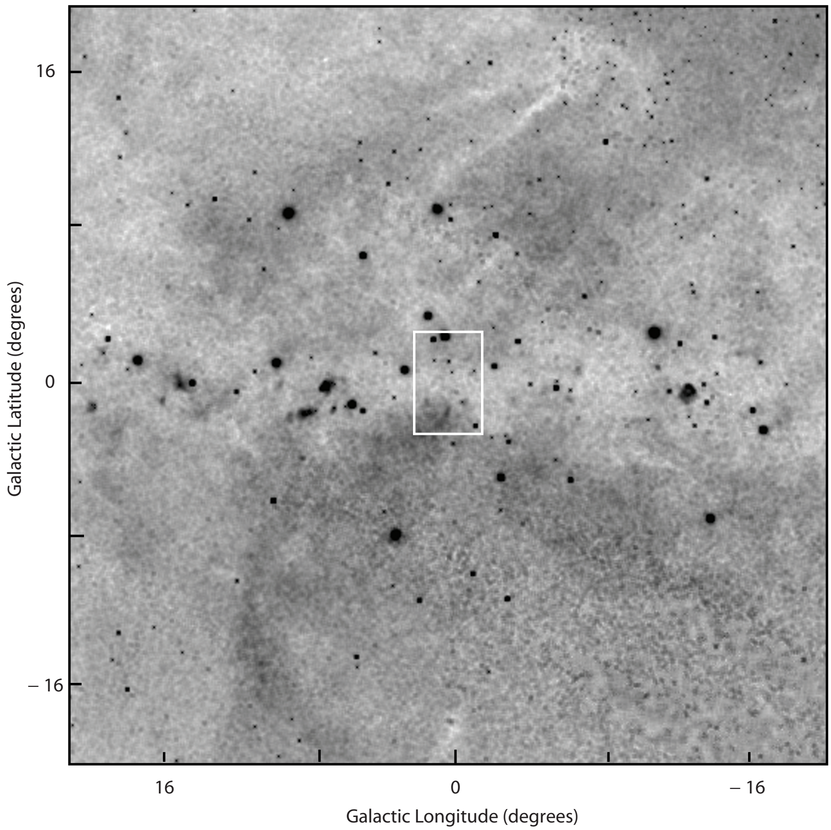


Figure 1.2 ROSAT all-sky survey of the inner $40^\circ \times 40^\circ$ region of the Galaxy in the $\sim$1.5 keV band ($1^\circ \approx 144$ pc). The hot gas emanating from the central region may be responsible for the diffuse soft X-ray background—for example, the large hollow-cone-shaped features seen on either side of the galactic plane. Resembling the morphology in nearby galaxies with active nuclear star formation, this distinct structure suggests a hot gas outflow from the nucleus. The central box marks the region targeted by ROSAT-pointed observations and is shown magnified in figure 1.3. (Image courtesy of S. L. Snowden at the Goddard Space Flight Center, and NASA)

Without a doubt, however, the most detailed X-ray view of the galactic center has been provided by *Chandra's* Advanced CCD Imaging Spectrometer (ACIS) detector, which combines the wide-band sensitivity and moderate spectral resolution of *ASCA* and *Beppo*SAX with the much higher spatial resolution ($\sim$0.5″–1″) of *Chandra's* High-Resolution Mirror Assembly (HRMA). The central rectangular box oriented along

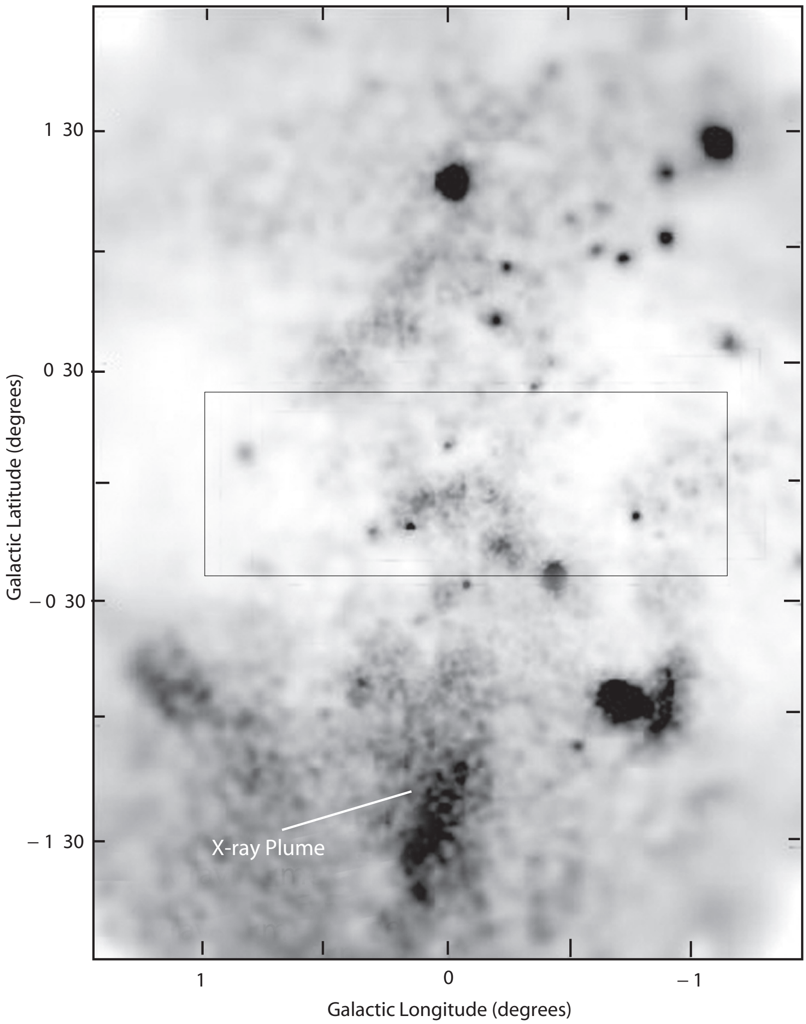


Figure 1.3 Close-up mosaic of the central 3° × 3° of the Galaxy, constructed with ROSAT PSPC observations in the highest energy band (0.5–2.4 keV). The bright, soft X-ray plume apparently connects the central region to the southern large-scale X-ray cone (see figure 1.2) some 300 pc away from the plane. The plume is the most prominent and coherent vertical diffuse soft X-ray feature seen at the galactic center; it may represent the hot gas outflow from the nucleus into the surrounding halo. The central rectangular box oriented parallel to the galactic plane outlines the field mapped out by the more recent *Chandra* survey, shown in color plate 7 and figure 1.4. (Image courtesy of L. Sidoli at INAF-IASF Milano, T. Belloni at INAF-Osservatorio di Brera, and S. Mereghetti at INAF-IASF Milano)

the galactic plane in figure 1.3 outlines the field mapped out in the 1–8 keV range by the most complete *Chandra* survey to date. This study consists of thirty separate pointings, all taken in July 2001; a mosaic of these observations is shown in color plate 7, covering a field of view $\sim 2^\circ \times 0.8^\circ$ centered on Sagittarius A. The saw-shaped boundaries of this map, plotted in galactic coordinates, result from a specific roll angle of the observations.[18]

The high spatial resolution of the *Chandra* X-ray Observatory (see color plate 7 and figure 1.4) allows for a separation of the discrete sources from the diffuse X-ray components pervading the galactic-center region. This analysis has led to a detection of roughly 1,000 discrete objects within the inner $2^\circ \times 0.8^\circ$, very few of which were known prior to this survey. Their number and spectra indicate the presence of numerous accreting white dwarfs, neutron stars, and solar-size black holes. Based on a comparison with the source density in another (relatively blank) region of the galactic plane,[19] one can estimate that as many as half of these discrete objects could be luminous background active galactic nuclei. Most of the other sources have a luminosity $\sim 10^{32}$–10^{35} ergs s^{-1} in the 2–10 keV band.

One of the fundamental questions that motivated the *Chandra* survey concerns the relative contribution of the point-source and diffuse components to the overall X-ray emission from the center of the Milky Way. For example, earlier observations with *ASCA*[20] implied that the ubiquitous and strong presence of the He-like Fe Kα line (at ~ 6.7 keV) throughout the central region required the existence of large quantities of $\sim 10^8$ K gas—a situation that is very difficult to explain on physical grounds.

A direct comparison of the accumulated point-source spectrum within the central region to that of the diffuse emission (see figure 1.5) reveals a distinct emission feature centered at ~ 6.7 keV (with a Gaussian width of ~ 0.09 keV) in the former but not the latter. The characteristics of this feature agree with those inferred previously with *ASCA*; that is, the high-resolution *Chandra* measurements seem to have resolved the issue of how the He-like Fe Kα line is produced—this emission is typical of X-ray binaries containing white dwarfs, neutron stars, or black holes,

[18]From Wang, Gotthelf, and Lang (2002).

[19]These observations were reported by Ebisawa et al. (2001).

[20]See Tanaka et al. (2000).

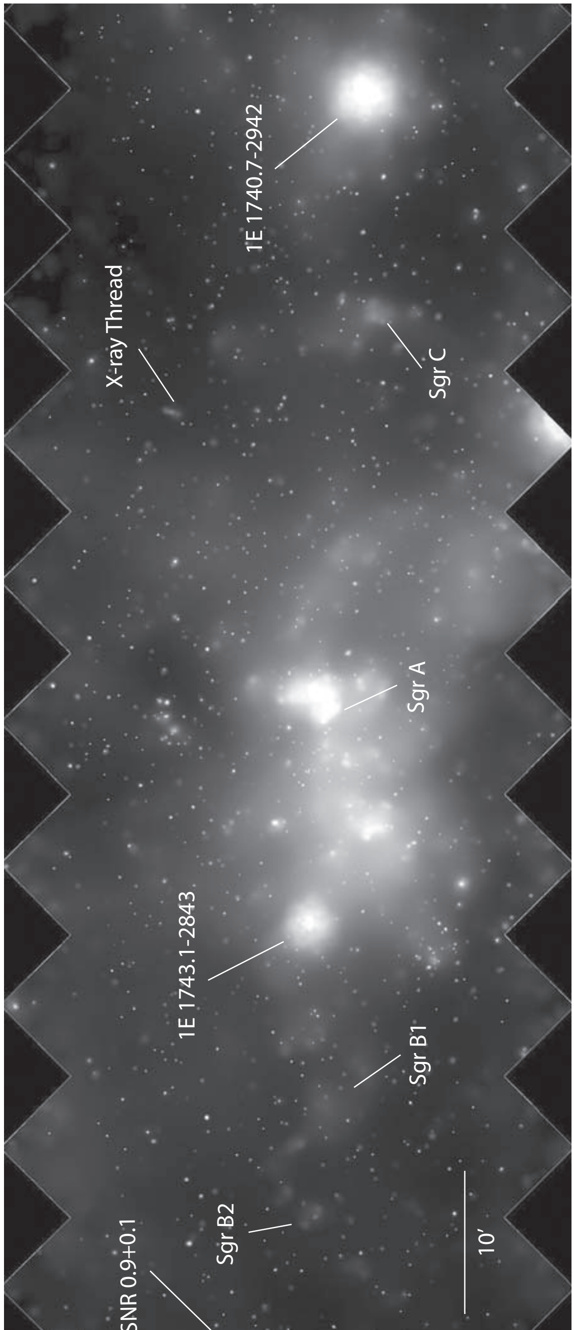


Figure 1.4 This image is the same as that in color plate 7, except here it shows the uncolorized intensity for the purpose of identifying the principal X-ray sources within the inner 2° of the Galaxy. At the distance to the galactic center, 10′ is approximately 24 pc.

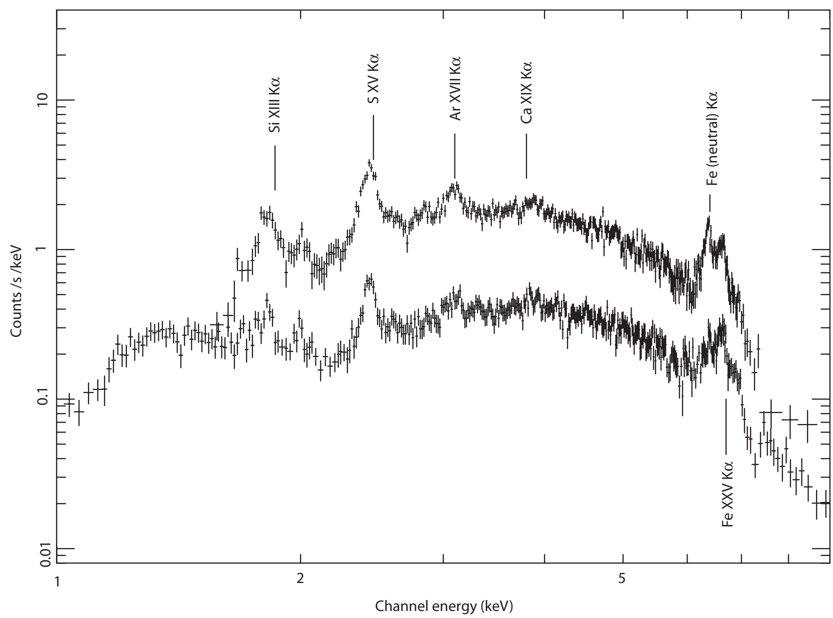


Figure 1.5 The *Chandra* spectrum of the diffuse X-ray flux enhancement above the surrounding background (upper curve) is shown in comparison with that of the accumulated point-source radiation (lower curve), both centered on Sagittarius A* and oriented along the galactic plane. The latter excludes regions around the two brightest sources (1E 1740.7–2942 and 1E 1743.1–2843; see figure 1.4) in order to minimize spectral pileup. This comparison seems to settle the issue of how the He-like Fe line is produced (see text). (From Wang, Gotthelf, and Lang 2002)

particularly during their quiescent state.[21] Rather than being attributed to the diffuse emission, the He-like Fe Kα line is instead found largely due to these discrete X-ray source populations.

On the other hand, the line emission from ions such as S XV, Ar XVII, and Ca XIX is quite prominent in the diffuse X-ray spectrum, which together with the weaker He-like Fe line, now points to the presence of an optically thin thermal plasma with a characteristic temperature of $\sim 10^7$ K—typical of young supernova remnants.

Still, the overall spectrum of the diffuse X-ray emission (figure 1.5) is considerably harder than one would expect for a thermal component

[21]Sample spectra of these sources have been reported by Barret et al. (2000) and Feng et al. (2001).