

## CHAPTER 1

### The Galactic Center

**Stellar radial velocity measurements**, sensing the gravitational potential at the nucleus of our Galaxy,<sup>1</sup> 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  $2.6\text{--}3.6 \times 10^6 M_{\odot}$  of nonluminous matter is concentrated within a region no bigger than 0.015 pc—a mere 800 AU.<sup>2</sup>

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.<sup>3</sup>

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

<sup>1</sup>See McGinn et al. (1989), Rieke and Rieke (1989), Sellgren et al. (1990), and Haller et al. (1996).

<sup>2</sup>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).

<sup>3</sup>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  $3.6 \times 10^7 M_{\odot}$ .

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supernova-like remnant, known as Sagittarius A East.<sup>4</sup> 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

<sup>4</sup>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\*).

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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  $200 \text{ km s}^{-1}$ . 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

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properties were later confirmed by Westerbork<sup>5</sup> and Very Long Baseline Interferometry (VLBI) observations.<sup>6</sup>

Several years later, maps of  $12.8 \mu\text{m}$  NeII fine-structure line emission from the galactic center<sup>7</sup> 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.<sup>8</sup>

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  $63 \mu\text{m}$ .<sup>9</sup> 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.<sup>10</sup> 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

<sup>5</sup>See “A Full Synthesis Map of Sgr A at 5GHz” by Ekers et al. (1975).

<sup>6</sup>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.”

<sup>7</sup>These observations were first reported by Lacy et al. (1979) and Lacy et al. (1980).

<sup>8</sup>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.

<sup>9</sup>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).

<sup>10</sup>See Brown and Lo (1982).

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book, these temporal fluctuations and a wealth of evidence accumulated since the early 1980s have rendered Sagittarius A\* the prime suspect in the radiative unclocking 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.<sup>11</sup> 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

<sup>11</sup>A description of this structure may be found in Ekers et al. (1983) and Lo and Claussen (1983).

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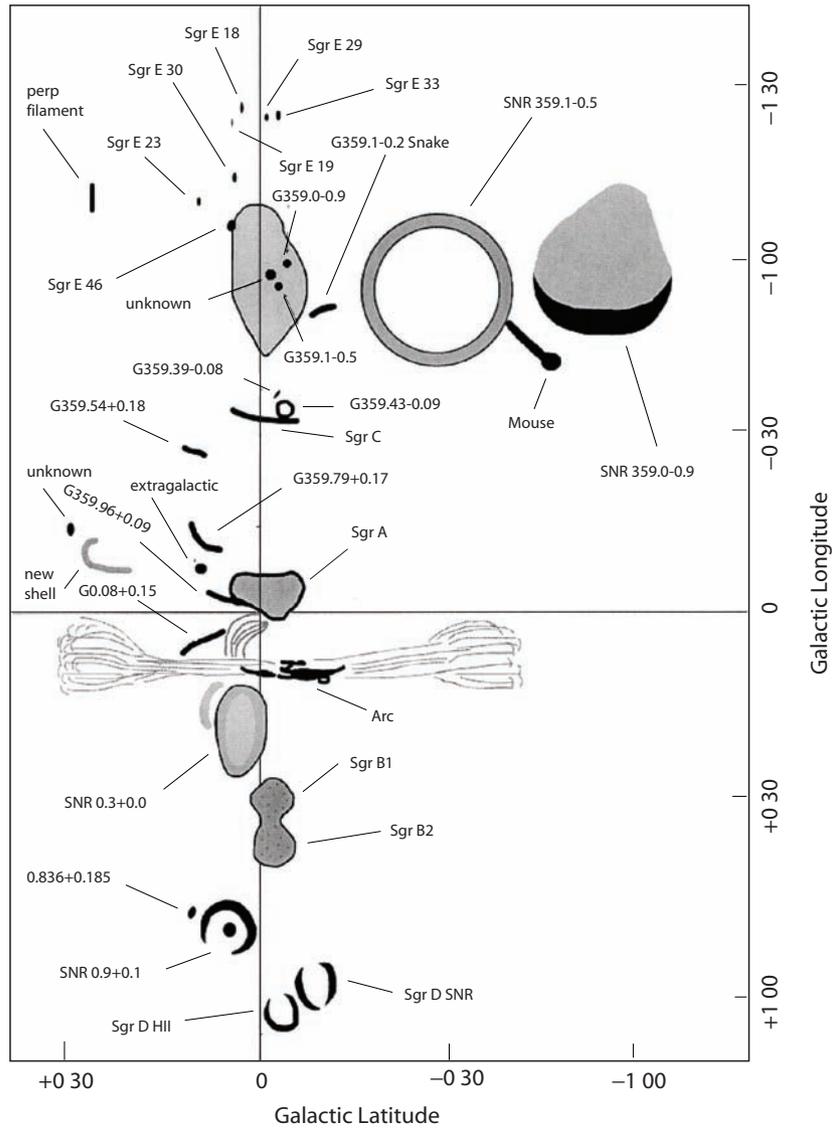


Figure 1.1 This is a schematic diagram of the extended sources shown in the 90 cm image of the galactic center in color plate 1. The perspective has been rotated so that the galactic plane is vertical in this representation. (From LaRosa, Kassim, and Lazio 2000)

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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 pc  $\times$  50 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.<sup>12</sup>

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

<sup>12</sup>See also Yusef-Zadeh and Morris (1987) and Pedlar et al. (1989).

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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 ( $50 \text{ km s}^{-1}$ ) 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  $105 \text{ km s}^{-1}$ , 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\*.<sup>13</sup> Some hot, luminous stars are thought to have been formed as recently as a few million years ago.<sup>14</sup> It is

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

<sup>14</sup>See Tamblyn and Rieke (1993), Najarro et al. (1994), Krabbe et al. (1995), and Figer et al. (1999).

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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.<sup>15</sup> 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  $110 \text{ km s}^{-1}$ , 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  $2 \mu\text{m}$  and appears to be the source of a strong wind with velocity on the order of  $700 \text{ km s}^{-1}$  and an inferred mass loss rate of  $4 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$ . 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.<sup>16</sup>

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

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

<sup>16</sup>See Hall, Kleinmann, and Scoville (1982), Geballe et al. (1987), and Allen, Hyland, and Hillier (1990).

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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  $600 \text{ km s}^{-1} \text{ pc}^{-1}$  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  $K\alpha$  line detected with ASCA, suggests further that a large fraction of this gas is so hot<sup>17</sup> 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.

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

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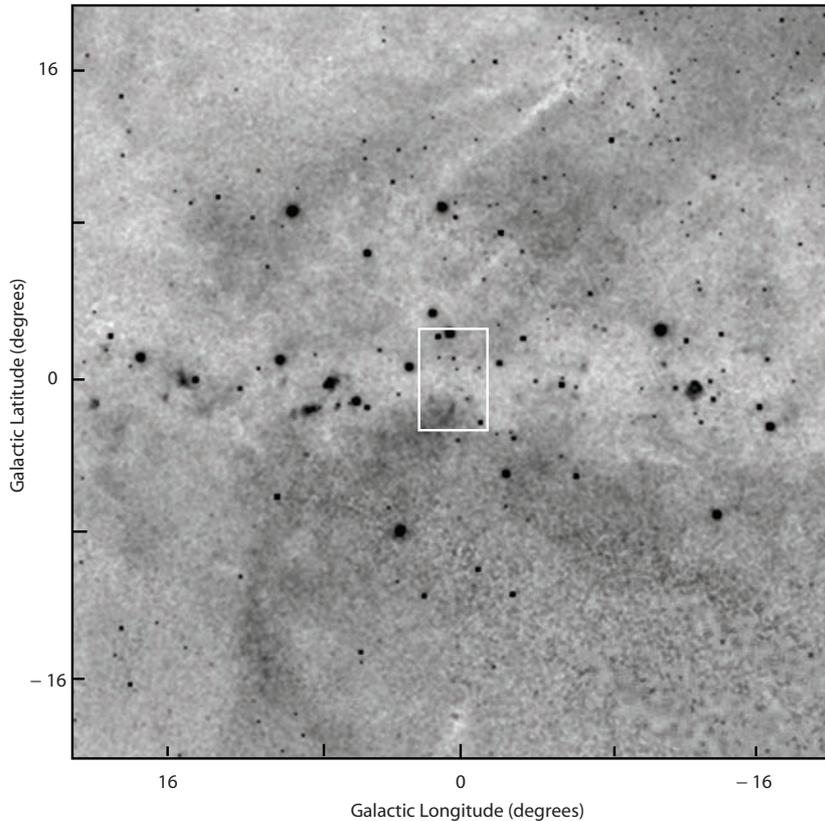


Figure 1.2 ROSAT all-sky survey of the inner  $40^\circ \times 40^\circ$  region of the Galaxy in the  $\sim 1.5$  keV band ( $1^\circ \approx 144$  pc). The hot gas emanating from the central region may be responsible for the diffuse soft X-ray background—for example, the large hollow-cone-shaped features 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 *BeppoSAX* with the much higher spatial resolution ( $\sim 0.5''$ – $1''$ ) of *Chandra's* High-Resolution Mirror Assembly (HRMA). The central rectangular box oriented along

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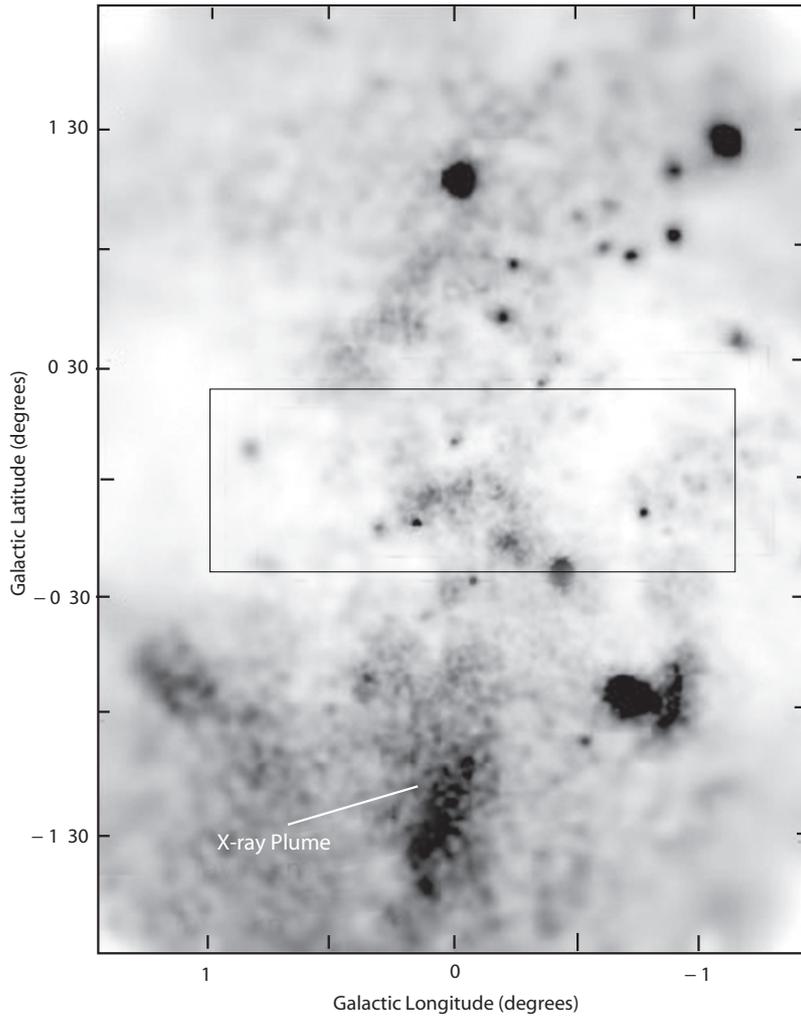


Figure 1.3 Close-up mosaic of the central  $3^\circ \times 3^\circ$  of the Galaxy, constructed with ROSAT PSPC observations in the highest energy band (0.5–2.4 keV). The bright, soft X-ray plume apparently connects the central region to the southern large-scale X-ray cone (see figure 1.2) some 300 pc 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)

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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.<sup>18</sup>

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,<sup>19</sup> 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*<sup>20</sup> implied that the ubiquitous and strong presence of the He-like Fe  $K\alpha$  line (at  $\sim 6.7$  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  $\sim 6.7$  keV (with a Gaussian width of  $\sim 0.09$  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  $K\alpha$  line is produced—this emission is typical of X-ray binaries containing white dwarfs, neutron stars, or black holes,

<sup>18</sup>From Wang, Gotthelf, and Lang (2002).

<sup>19</sup>These observations were reported by Ebisawa et al. (2001).

<sup>20</sup>See Tanaka et al. (2000).

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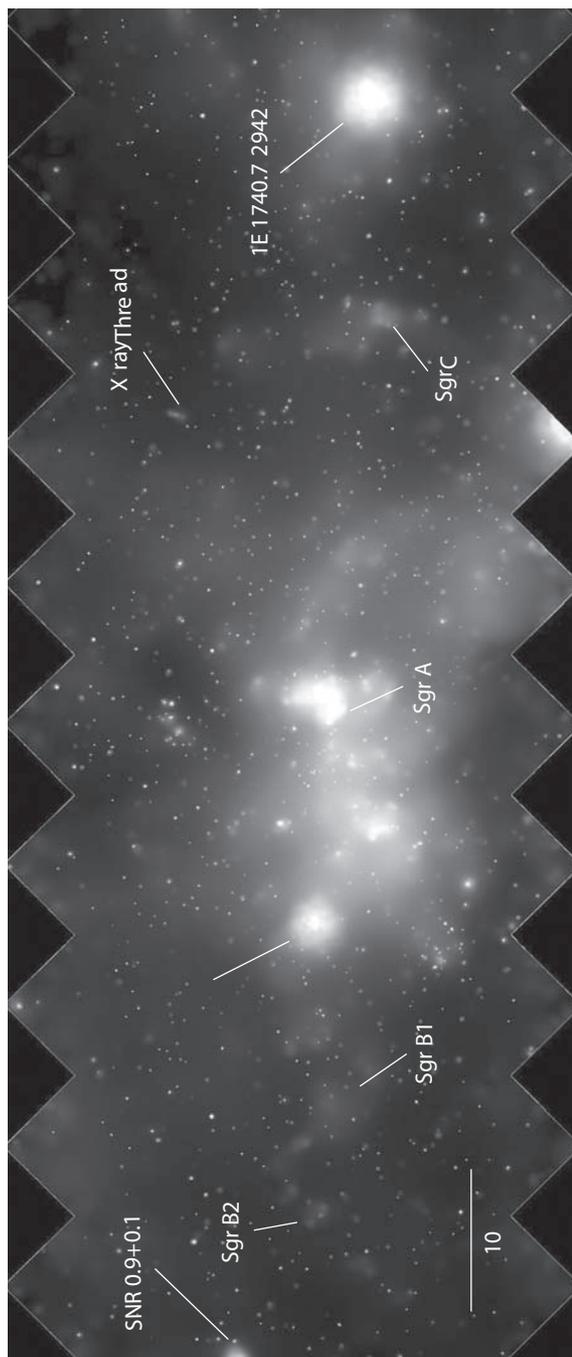


Figure 1.4 This image is the same as that in color plate 7, except here it shows the uncolorized intensity for the purpose of identifying the principal X-ray sources within the inner  $2^\circ$  of the Galaxy. At the distance to the galactic center,  $10'$  is approximately 24 pc.

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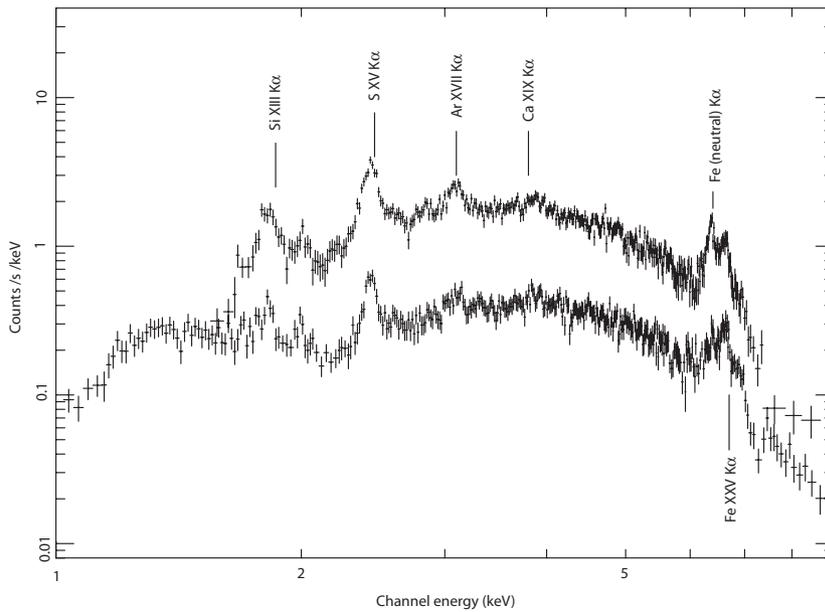


Figure 1.5 The *Chandra* spectrum of the diffuse X-ray flux enhancement above the surrounding background (upper curve) is shown in comparison with that of the accumulated point-source radiation (lower curve), both centered on Sagittarius A\* and oriented along the galactic plane. The latter excludes 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.<sup>21</sup> Rather than being attributed to the diffuse emission, the He-like Fe  $K\alpha$  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

<sup>21</sup>Sample spectra of these sources have been reported by Barret et al. (2000) and Feng et al. (2001).

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alone. Nearly half of the detected diffuse emission in the 5–8 keV band is due to the Fe 6.4 keV line, part of which is likely due to the fluorescent radiation from discrete sources. The intensity profile shown in color plate 7 and figure 1.4, when compared with maps of HCN and CO in the central 630 pc of the Galaxy,<sup>22</sup> does in fact show that the distribution of the line emission tends to be correlated with lumpy dense molecular material (see figure 1.6). The problem is that the known population of bright X-ray objects in the galactic center region is not sufficient to produce this fluorescence.<sup>23</sup> Instead, it is likely that certain X-ray sources—possibly even the supermassive black hole itself—may have varied greatly in the past, so that their averaged luminosity was several orders of magnitude higher than today. Much of the present 5–8 keV diffuse emission could then be due to this past discrete-source irradiation of the molecular clouds, producing the scattered/fluoresced photon field that we observe now.

The *Chandra* observations also indicate that the 4–6 keV X-ray band, lacking any prominent emission line, differs considerably in profile compared to the distribution of 6.4 and 6.7 keV line flux. According to Wang, Gotthelf, and Lang (2002), the softer X-ray emission may be due to a combination of thermal hot gas, scattered point-source radiation, and the additional contribution of bremsstrahlung processes associated with nonthermal cosmic ray electrons. Perhaps surprisingly, the most prominent nonthermal radio filaments (see color plate 2) do not produce an enhanced X-ray flux, suggesting that inverse Compton scattering of the microwave background radiation is not an important contributor to the observed diffuse X-ray emission.

In fact, the scant correlation between diffuse X-ray and radio features extends even beyond the nonthermal filaments. But this situation is particularly acute for them because out of the eight most prominent cases known, only one has a direct X-ray counterpart, G359.54 + 0.18, shown in figure 1.7. A comparison between the radio and X-ray maps therefore provides a particularly useful perspective on the interplay among the various discrete and diffuse components in this portion of the Galaxy.

<sup>22</sup>See Jackson et al. (1996) and Price et al. (2001).

<sup>23</sup>This point is made observationally by Murakami, Koyama, and Maeda (2001) and theoretically by Fromerth, Melia, and Leahy (2001).

#### SAGITTARIUS A EAST

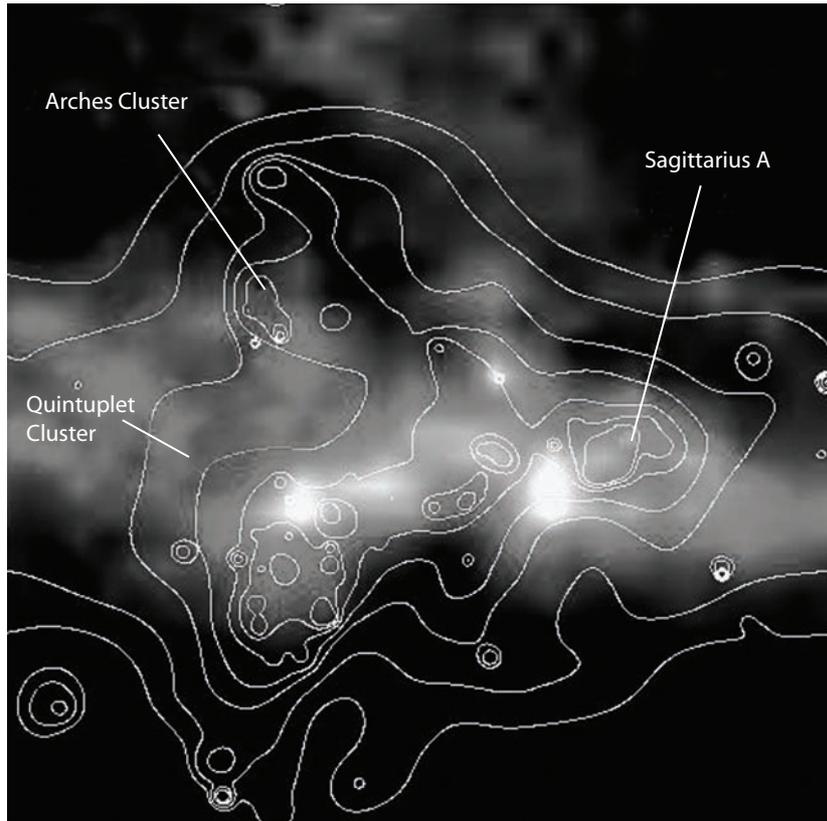


Figure 1.6 This composite image shows the 6.4 keV line intensity contours superimposed on the HCN  $J = 1 \rightarrow 0$  emission map of the inner  $\sim 25 \text{ pc}^2$  region of the Galaxy. A continuum contribution in the 4–6 keV and 7–9 keV bands has been subtracted. This comparison illustrates the fact that X-rays in different energy bands arise in different regions, suggesting diverse origins. The 6.4 keV emission may be globally correlated with dense molecular gas tracers but not on scales smaller than a few arcminutes. (X-ray image courtesy of Q. Daniel Wang at the University of Massachusetts, Amherst, and NASA; the HCN map is from Jackson et al. 1996)

#### 1.4 SAGITTARIUS A EAST

Let us now turn our attention to the X-ray glow from the inner parsecs of the Galaxy. We cannot help but notice first the high-energy shroud encasing the  $20 \text{ pc} \times 20 \text{ pc}$  region surrounding Sagittarius A\* (see figure 1.8). The primary origin of these X-rays appears to be

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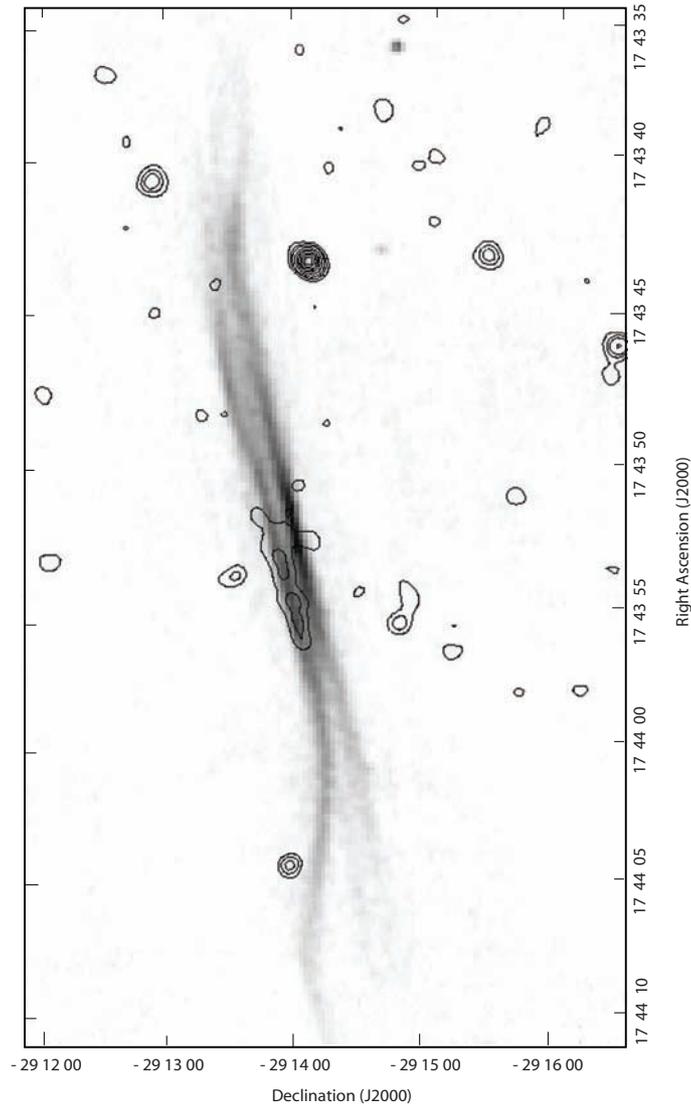


Figure 1.7 The spatial coincidence of the radio nonthermal filament G359.54 + 0.18 (continuum image) and a *Chandra*-discovered X-ray “thread” (shown with contours) argues convincingly for a physical association between these two features. The X-ray thread is about 1' long and has a width that is not adequately resolved on an  $\sim 1''$  scale. It also displays a flat spectrum, consistent with its inferred nonthermal origin. (X-ray contour image courtesy of Q. Daniel Wang et al. at the University of Massachusetts, Amherst, and NASA; radio continuum image from Yusef-Zadeh, Wardle, and Parastaran 1997)

SAGITTARIUS A EAST

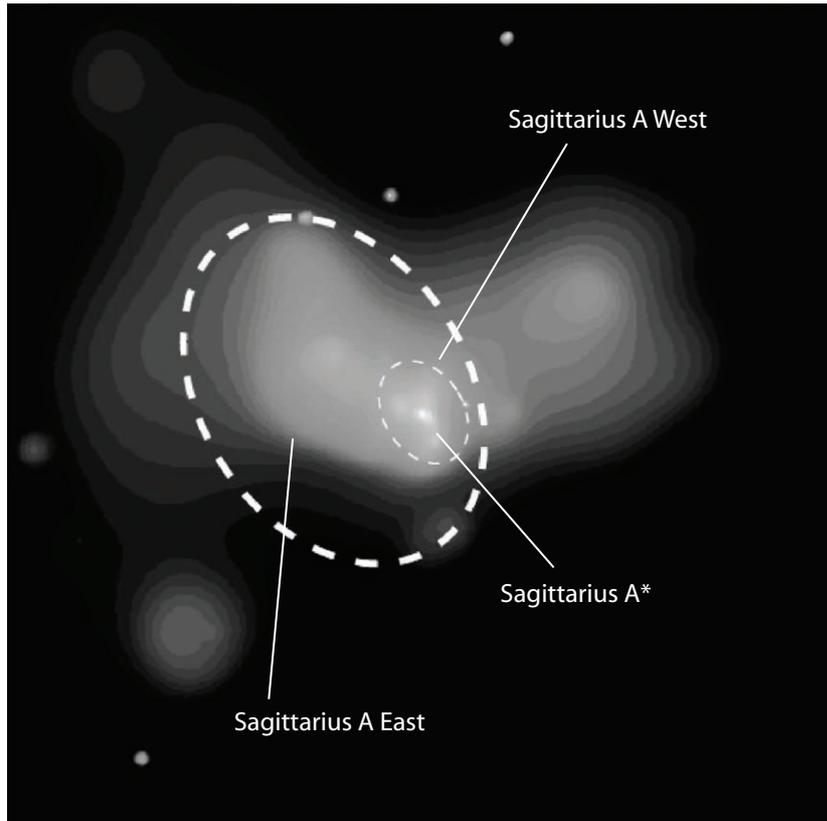


Figure 1.8 This image shows the smoothed X-ray intensity detected by *Chandra* in the 1.5–3.0 keV band from the inner  $8'.4 \times 8'.4$  ( $\sim 20 \text{ pc} \times 20 \text{ pc}$ ) of the Galaxy, centered on Sagittarius A\*. The large and small white dashed ellipses identify the Sagittarius A East nonthermal shell and the outer boundary of Sagittarius A West, respectively. Compare with color plates 2 and 3. (Image from Maeda et al. 2002)

Sagittarius A East, a nonthermal radio source with a supernova-like morphology located near the galactic center (see color plate 2). Its elliptical structure is elongated along the galactic plane with a major axis of length 10.5 pc and a center displaced from the apparent dynamical nucleus by 2.5 pc in projection toward negative galactic latitudes. The actual distance between Sagittarius A\* and the geometric center of Sagittarius A East has been estimated at  $\sim 7 \text{ pc}$ .<sup>24</sup>

<sup>24</sup>See Yusef-Zadeh and Morris (1987) and Pedlar et al. (1989).

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Broadband radio observations of Sagittarius A East have placed it among the supernova remnants detected at 1,720 MHz, the transition frequency of OH maser emission.<sup>25</sup> In general, the detection of this line establishes the presence of shocks at the interface between the supersonic outflow and the dense molecular cloud environment with which the remnants are known to be interacting. In the case of Sagittarius A East, several maser spots with velocities  $\approx 50 \text{ km s}^{-1}$  have been resolved in the region where this remnant is interacting with the dense molecular cloud known as M-0.02-0.07, at the southeastern boundary. An additional spot has been observed near the northern arm of Sagittarius A West<sup>26</sup> (the  $\sim 6$  pc minispiral structure of ionized gas orbiting about the center; see color plate 3) at a velocity of  $134 \text{ km s}^{-1}$ . The detection of these OH masers is a principal reason behind the identification of Sagittarius A East as the remnant of a powerful explosion.

At least one of these OH maser lines shows Zeeman splitting, from which a magnetic field strength of 2–4 mG has been estimated within the remnant's nonthermal radio shell. The remnant's intricate physical properties have received additional clarification with X-ray observations early in the *Chandra* mission,<sup>27</sup> as illustrated in figure 1.9. The smoothed broadband X-ray intensity map is here overlaid with radio contours from a 20 cm VLA image of the same region. We shall see shortly that the existence of relativistic particles within this unusually strong magnetic field makes Sagittarius A East a unique particle accelerator in the Galaxy, contributing significantly to the cosmic ray and gamma ray flux emerging from the nucleus.

Figures 1.8 and 1.9 provide evidence that no significant X-ray continuum or line emission is occurring at the location of the radio shell itself. Instead, the source of this diffuse X-ray flux appears to be associated with a hot, optically thin thermal plasma located within the cavity. Also, a division of the X-ray emissivity into soft and hard energy bands shows that the morphology is spectrally dependent (compare figure 1.8 with 1.10), characterized by a half-power radius  $\sim 20''$  at 6–7 keV, compared with  $\sim 30''$  at lower energies. Overall, the X-ray-emitting region appears to be concentrated within the innermost 2 pc of this remnant.

<sup>25</sup>A survey of supernova remnants W28, W44, and IC 443, detected at 1,720 MHz, is given by Claussen et al. (1997).

<sup>26</sup>See Yusef-Zadeh et al. (1996).

<sup>27</sup>This was reported by Maeda et al. (2002).

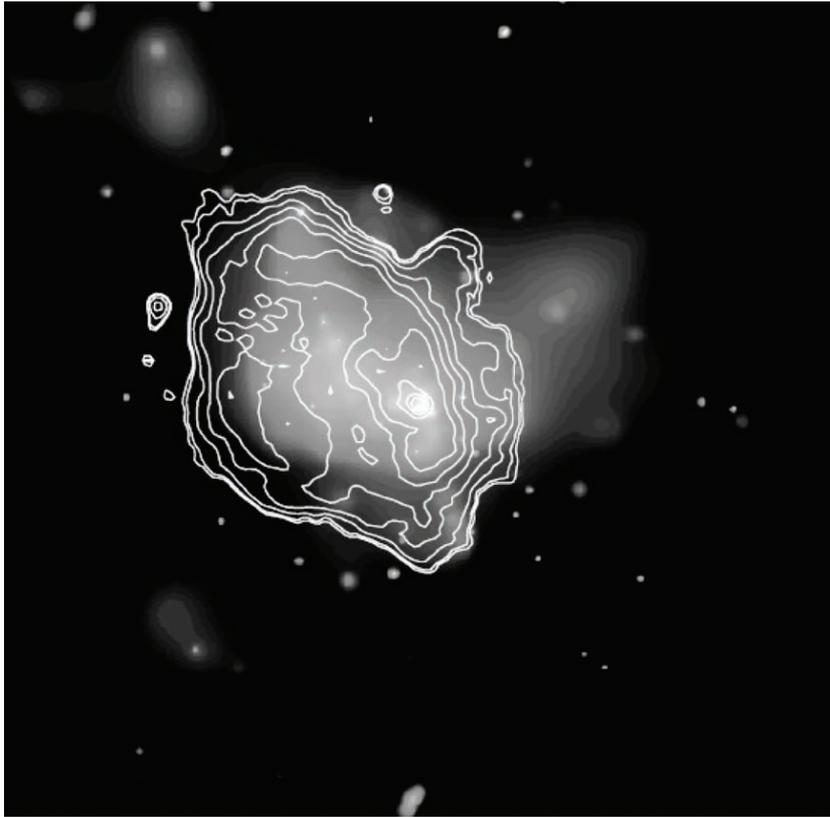


Figure 1.9 In this image, the smoothed broadband X-ray intensity map (1.5–7.0 keV) is overlaid with radio contours from a 20 cm VLA image of Sagittarius A. The outer oval-shaped radio structure is associated with synchrotron emission from the shell-like nonthermal radio source Sagittarius A East. (Image from Maeda et al. 2002)

The X-ray spectrum of Sagittarius A East contains strong  $K\alpha$  lines from highly ionized ions of S, Ar, Ca, and Fe, for which a simple isothermal model yields an electron temperature  $\sim 2$  keV. The inferred metallicity is overabundant by a factor of four compared with solar values, concentrated toward the middle. Maeda et al. (2002) conclude from this that Sagittarius A East is probably the result of a Type II supernova explosion, with a  $13\text{--}20 M_{\odot}$  main-sequence progenitor, and that the combination of its radio and X-ray properties classifies it as a metal-rich “mixed morphology” remnant. However, the size of the Sagittarius A East shell is the smallest known for this category of sources,

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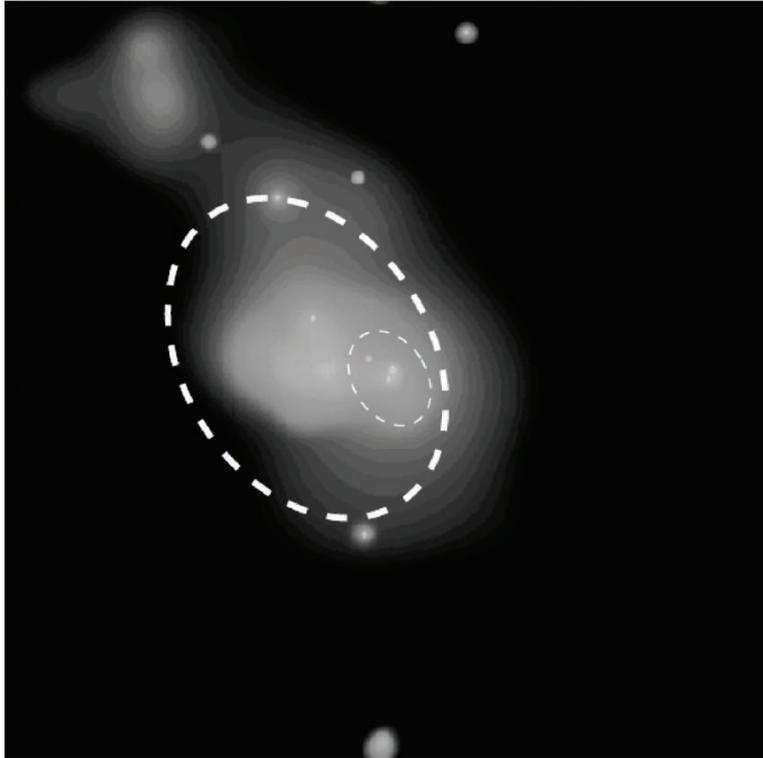


Figure 1.10 This image is the same as that of figure 1.8, except this image shows only the X-ray intensity within the 6.0–7.0 keV band. A comparison between this figure and figure 1.8 shows that the structure of Sagittarius A East is spectrally dependent. The half-power radius of the emission is  $\sim 20''$  in the 6.0–7.0 keV band, compared to  $\sim 30''$  at lower energies. The hard emission is concentrated toward the center. (Image from Maeda et al. 2002)

implying that the ejecta have been expanding into a uniquely dense interstellar medium. For a 10,000-year-old structure, the implied ambient density is  $\sim 10^3 \text{ cm}^{-3}$ , fully consistent with the observed properties of the  $50 \text{ km s}^{-1}$  M–0.02–0.07 molecular cloud, into which Sagittarius A East is apparently expanding.

The identification of Sagittarius A East as a supernova remnant has been further strengthened by the EGRET detection of a  $\sim 30 \text{ MeV}$ – $10 \text{ GeV}$  continuum source (3EG J1746–2852) within  $1^\circ$  of the galactic center<sup>28</sup>—a notable development because supernova remnants detected

<sup>28</sup>See Mayer-Hasselwander et al. (1998).

at 1,720 MHz also tend to be clearly associated with EGRET sources.<sup>29</sup> This connection, however, is subject to two important caveats. First, nonthermal radio emission observed from Sagittarius A East at 6 cm and 20 cm is characterized by a spectral index of  $\sim 1$ , which requires an underlying population of nonthermal leptons (primarily electrons and positrons) with a power-law distribution index  $p \sim 3$ .<sup>30</sup> In contrast, typical supernova remnants display radio emission characterized by a spectral index  $\sim 0.5$  and an attendant lepton index  $p \sim 2$ . Second, the implied gamma ray luminosity of Sagittarius A East ( $\sim 2 \times 10^{37}$  ergs  $s^{-1}$ ) is roughly two orders of magnitude greater than that of the other remnants detected by EGRET.

Thus, although the *Chandra* observation may have resolved the mystery surrounding the birth of Sagittarius A East, it may have created another in terms of its relatively large gamma ray luminosity. Of course, it is quite plausible that 3EG J1746–2852 is not associated with Sagittarius A East at all. For example, the primary source of gamma rays may be the filaments in the arched magnetic field structure to the north of the galactic center (see figure 1.7).<sup>31</sup>

Given the striking similarity between the gamma ray spectrum of 3EG J1746–2852 and that of the EGRET supernova remnants, however, the association of this high-energy source with Sagittarius A East is probably real. In that case, the mechanism responsible for producing Sagittarius A East’s broadband spectrum would be the decay of neutral and charged pions created in collisions between shock-accelerated protons and the ambient medium.<sup>32</sup> In this scenario, the neutral pions decay directly into two photons ( $\pi^0 \rightarrow \gamma\gamma$ ), while the charged pions decay into muons and subsequently into “secondary” relativistic electrons and positrons ( $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ , with  $\mu^\pm \rightarrow e^\pm \nu_e \nu_\mu$ ). In this fashion, not only does the cascade initiated by the shock-accelerated protons produce Sagittarius A East’s gamma ray spectrum, but it also self-consistently accounts for its radio emission via leptonic synchrotron processes involving the decay products.<sup>33</sup>

<sup>29</sup>This category of sources is described fully by Esposito et al. (1996), Combi, Romero, and Benaglia (1998), and Combi et al. (2001).

<sup>30</sup>See Pedlar et al. (1989).

<sup>31</sup>This model was developed by Pohl (1997) and argued on the basis of circumstantial observational evidence by Yusef-Zadeh et al. (2002).

<sup>32</sup>See Gaisser, Protheroe, and Stanev (1998) and Melia et al. (1998).

<sup>33</sup>This scenario is described by Fatuzzo and Melia (2003).

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But this is where the kinship between Sagittarius A East and the other EGRET supernova remnants ends, for the element that binds them—the interaction between their supersonically expanding ejecta with a dense molecular cloud environment—at the same time renders Sagittarius A East unique in the Galaxy. Its singularly high gamma ray luminosity, as well as its unusually steep radio spectral index, appears to be due to the high density ( $\sim 10^3 \text{ cm}^{-3}$ ) and strong magnetic field ( $\sim 2\text{--}4 \text{ mG}$ ) of the surrounding medium. While the greater density enhances the particle collision rate—and hence the luminosity—the intense magnetic field facilitates the acceleration of particles to energies ( $\sim 10^{18} \text{ eV}$ ) not seen in any other remnant.<sup>34</sup>

Yet the bremsstrahlung emission due to the shock-accelerated leptons is at best  $\sim 10^{32} \text{ ergs s}^{-1}$ , roughly an order of magnitude weaker than the X-ray luminosity inferred by *Chandra*. So whereas the radio and gamma ray photons from Sagittarius A East are produced primarily in its shell, the X-rays are evidently emitted instead by a thermal plasma within its cavity (see figures 1.8 and 1.10).

The environment occupied by Sagittarius A East is about as close as we can get to the nucleus without beginning to sense the influence of dark matter concentrated within. And so we will end our brief survey of the galactic center here. In chapter 2, we shall start to focus on the nature of strong gravity pervading the inner 0.01 pc of the Galaxy—a region 1,000 times smaller than the unusual remnant we have been exploring in this section.

<sup>34</sup>An early treatment of this acceleration mechanism in the presence of strong magnetic fields was made by Jokipii (1992). The most recent analysis of relativistic particle acceleration in Sagittarius A East may be found in Crocker et al. (2005).