AN IMAGING AND SPECTRAL STUDY OF 10 X-RAY FILAMENTS AROUND THE GALACTIC CENTER

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ABSTRACT

We report the detection of 10 new X-ray filaments using the data from the Chandra X-ray satellite for the inner 6′ (~15 pc) around the Galactic center (GC). All these X-ray filaments are characterized by nonthermal energy spectra, and most of them have pointlike features at their heads that point inward. Fitted with the simple absorbed power-law model, the measured X-ray flux from an individual filament in the 2–10 keV band is \( \sim 2.8 \times 10^{-14} \) to \( \sim 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\), and the absorption-corrected X-ray luminosity is \( \sim 10^{32} \) to \( \sim 10^{33} \) erg s\(^{-1}\) at a presumed distance of 8 kpc to the GC. We speculate the origin(s) of these filaments by morphologies and by comparing their X-ray images with the corresponding radio and infrared images. On the basis of the combined information available, we suspect that these X-ray filaments might be pulsar wind nebulae associated with pulsars of ages 10\(^3\) to 3 \times 10\(^5\) yr. The fact that most of the filament tails point outward may further suggest a high-velocity wind blowing away from the GC.

Subject headings: Galaxy: center — pulsars: general — supernova remnants

1. INTRODUCTION

The Galactic center (GC) is the only place where we can observe parsec details of various interactions in and around the Galactic nucleus. Advances in this research frontier rely primarily on observations at radio, infrared, and X-ray wavelengths, because the optical band suffers seriously from considerable extinction with \( A_V \sim 30 \) (e.g., Becklin et al. 1978). One of the most important discoveries in the GC region is perhaps the presence of many structured nonthermal radio filaments (NTFs; e.g., Yusef-Zadeh et al. 1984; Morris & Serabyn 1996; LaRosa et al. 2000). While these NTFs have been intensively studied, their origins and implications for the underlying physical processes around the GC remain largely unclear. In the current analysis of X-ray filaments around the GC region, these X-ray–emitting particles are usually expected to be fairly close to their acceleration zone and evolve very rapidly in time. Thus, X-ray study of the same region would be essential to probe the origin of these energetic particles. The Chandra Galactic Center Survey (GCS), with its unprecedented high spatial resolution of ~0.5′ and moderate spectroscopy capability, has already revealed remarkable X-ray structures (including thousands of X-ray–bright point sources and some filaments, as well as clumps of diffuse emission) within the central 200 pc of our Galaxy (e.g., Wang et al. 2002a). In this paper we mainly concentrate on the nature of those threadlike linear structures or filaments as observed in X-ray bands.

Up to this point within 15′ (~37 pc at 8 kpc) from Sgr A*, where an ~\( 4 \times 10^6 \) M\(_\odot\) black hole resides inside a compact region of less than ~1 AU (e.g., Shen et al. 2005), five X-ray filaments have been studied in detail (see also Table 1). For example, G359.95–0.04, a comet-like filament ~0.32 pc north of Sgr A*, is thought to be a ram-pressure–confined pulsar wind nebula (PWN; Wang et al. 2006). Another prominent filament, G359.89–0.08 (Sgr A-E), at ~7 pc southeast of Sgr A*, was first noticed by Sakano et al. (2003), and an interpretation of a possible PWN origin was discussed in detail by Lu et al. (2003). An alternative picture of G359.89–0.08 as a source of synchrotron emission from relativistic particles accelerated by a shock wave of the W28 supernova remnant (SNR) was suggested recently by Yusef-Zadeh et al. (2005); in that same paper, they also detected a new X-ray filament, G359.90–0.06, which coincides spatially with a radio filament ~5.8 pc southwest of Sgr A*. They explored the mechanism of inverse Compton scattering (ICS) for the X-ray emission of G359.90–0.06. Another two filaments were found in more extensive regions. Filament G0.13–0.11 in the Radio Arc region was first reported by Wang et al. (2002b) and was suspected to also be a PWN. Of particular interest is the X-ray filament G359.54+0.18; it is associated with only one strand of the obviously bifurcated radio threads (e.g., Yusef-Zadeh et al. 2005; Lu et al. 2003). A common feature shared in the X-ray energy spectra of these filaments is that they all appear to be nonthermal. It should be noted, however, that any thermal component to these sources would likely be completely absorbed and unobservable, given the high foreground column density.

In these earlier investigations, PWNe and SNRs seem to offer natural explanations for the appearance of such X-ray filaments. Indeed, it is believed that a considerable number of supernovae should have happened in the GC region (e.g., Figer et al. 1999, 2004; Wang et al. 2006). One would naturally expect to find some of their end products, such as pulsars and SNRs, in the GC region. However, no radio pulsars have yet been found within ~1 pc of the GC (Wang et al. 2006). This might be caused by difficulties in radio observations (Cordes & Lazio 1997; Johnston et al. 2006). Seeking observational clues in X-ray bands might shed new light on the search for radio pulsars embedded in the GC region.

Another tempting idea is to use these X-ray filaments as potential tracers for the magnetic field and gas dynamics around the GC region, since the magnetic fields should have played a significant role in producing such nonthermal spectra and the thread-like shapes of these filaments, and the gas motion is usually coupled with the magnetic fields (e.g., Chevalier 1992; Boldyrev & Yusef-Zadeh 2006). Magnetic fields exist on all scales of the Galaxy, as well as in other spiral galaxies, and generally trace out spiral patterns on large scales (e.g., Beck & Hoernes 1996; Zweibel & Heiles 1997; Wielebinski 2005; Ferriere 2001, 2007); great progress has been made in measuring them and inferring their influence by various means. For example, the observed

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### TABLE 1

**Spectral Fitting Results of the X-Ray Filaments**

| Region                  | \(N_H\) \((10^{23} \text{ cm}^{-2})\) | \(\Gamma\) | \(F_X\) \((10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2})\) | \(L_X\) \((10^{33} \text{ ergs s}^{-1} \text{ d}^{-2})\) | \(\chi^2/\text{d.o.f.}\) |
|-------------------------|---------------------------------|----------|------------------------|---------------------|-----------------|
| X-Ray Filament 1 (F1, G359.936—0.038) |                                |          |                        |                     |                 |
| Whole                    | 1.0 (0.2, 1.5)                  | 0.9 (−0.3, 1.6) | 8.0 (7.3, 10.2) | 0.92 (0.84, 1.15) | 29.8/30         |
| Joint fit                |                                 |           |                        |                     |                 |
| Head (N)                 | 0.8 (0.3, 1.7)                  | 0.8 (−0.2, 2.0) |                        |                     |                 |
| Tail (S)                 | 0.8 (0.3, 1.7)                  | 1.6 (0.1, 3.3) |                        |                     |                 |
| X-Ray Filament 2 (F2, G359.934—0.037) |                                |          |                        |                     |                 |
| Whole                    | 0.9 (0.2, 2.1)                  | 0.8 (0.3, 2.0) | 4.7 (4.2, 5.3) | 0.53 (0.44, 0.97) | 13.2/20         |
| Joint fit                |                                 |           |                        |                     |                 |
| Head (NE)                | 0.9 (0, 2.7)                    | 0.8 (−0.8, 2.9) |                        |                     |                 |
| Tail (SW)                | 0.9 (0, 2.7)                    | 1.2 (−0.6, 3.4) |                        |                     |                 |
| X-Ray Filament 3 (F3, G359.965—0.053) |                                |          |                        |                     |                 |
| Whole                    | 1.4 (1.1, 1.7)                  | 2.3 (1.8, 2.8) | 11.9 (11.4, 12.5) | 2.2 (1.9, 2.78) | 72.2/71         |
| Head                     | 1.9 (1.3, 2.6)                  | 3.1 (2.2, 4.3) |                        |                     | 31/35           |
| Middle                   | 1.8 (0.6, 4.2)                  | 2.2 (0.6, 5.3) |                        |                     | 3.6/10          |
| Tail                     | 0.7 (0.3, 1.1)                  | 1.4 (0.9, 1.8) |                        |                     | 23.5/24         |
| Joint fit                |                                 |           |                        |                     |                 |
| Head                     | 1.2 (0.9, 1.5)                  | 2.0 (1.5, 2.7) |                        |                     | 17.1/14         |
| Middle                   | 1.2 (0.9, 1.5)                  | 1.5 (0.8, 2.2) |                        |                     |                 |
| Tail                     | 1.2 (0.9, 1.5)                  | 2.4 (1.7, 2.8) |                        |                     |                 |
| X-Ray Filament 4 (F4, G359.964—0.056) |                                |          |                        |                     |                 |
| Whole                    | 0.6 (0.1, 1.2)                  | 1.9 (1.2, 3.0) | 4.0 (3.4, 5.2) | 0.47 (0.41, 0.75) | 13.8/19         |
| X-Ray Filament 5 (F5, G359.959—0.028) |                                |          |                        |                     |                 |
| Whole                    | 0.8 (0.4, 1.5)                  | 1.4 (0.9, 2.5) | 4.3 (3.6, 4.8) | 0.52 (0.43, 0.79) | 19.5/24         |
| Head (SE)                | 0.5 (0, 1.4)                   | 0.9 (−0.4, 2.6) |                        |                     | 9.9/10          |
| Tail (NW)                | 0.8 (0, 5.9)                   | 0.8 (−1.2, 6.8) |                        |                     | 2.7/2           |
| Joint fit                |                                 |           |                        |                     |                 |
| Head (SE)                | 0.6 (0.2, 1.5)                  | 1.1 (−0.3, 2.1) |                        |                     |                 |
| Tail (NW)                | 0.6 (0.2, 1.5)                  | 0.9 (0.2, 1.5) |                        |                     |                 |
| X-Ray Filament 6 (F6, G359.969—0.038) |                                |          |                        |                     |                 |
| Whole                    | 0.9 (0.4, 1.4)                  | 1.4 (0.9, 2.3) | 6.6 (5.7, 7.3) | 0.84 (0.69, 1.07) | 35/40           |
| Head (SW)                | 0.7 (0, 2.5)                   | 1.1 (−0.2, 3.8) |                        |                     | 18/13           |
| Tail (NE)                | 0.7 (0, 1.5)                   | 1.3 (0.6, 2.3) |                        |                     | 25.8/23         |
| Joint fit                |                                 |           |                        |                     |                 |
| Head (SW)                | 0.8 (0.3, 1.5)                  | 1.2 (0.3, 2.3) |                        |                     |                 |
| Tail (NE)                | 0.8 (0.3, 1.5)                  | 1.6 (0.7, 2.0) |                        |                     |                 |
| X-Ray Filament 7 (F7, G359.920—0.029) |                                |          |                        |                     |                 |
| Whole                    | 0 (0, 3.6)                     | 0.9 (−0.2, 4.4) | 2.8 (1.6, 3.0) | 0.21 (0.19, 1.96) | 5.1/5.0         |
| X-Ray Filament 8 (F8, G359.970—0.009) |                                |          |                        |                     |                 |
| Whole                    | 1.5 (0.6, 3.0)                  | 2.3 (0.8, 4.6) | 3.0 (2.3, 3.5) | 0.6 (0.4, 1.7) | 12.4/12         |
| X-Ray Filament 9 (F9, G359.974−0.000) |                                |          |                        |                     |                 |
| Whole                    | 0.7 (0, 1.5)                   | 0.6 (−0.9, 1.9) | 4.7 (4.1, 5.1) | 0.41 (0.40, 0.46) | 5.8/13          |
| X-Ray Filament 10 (F10, G0.029—0.06) |                                |          |                        |                     |                 |
| Whole                    | 0.5 (0.4, 0.7)                  | 1.2 (0.9, 1.5) | 10.4 (9.9, 11.1) | 1.06 (1.02, 1.16) | 48.9/55         |
| Head                     | 1.0 (0.6, 1.6)                  | 1.8 (1.3, 2.8) |                        |                     | 27/21           |
| Middle                   | 0.4 (0, 1.1)                   | 1.0 (0, 2.0) |                        |                     | 8.7/13          |
| Tail                     | 0.3 (0, 0.9)                   | 1.0 (0.5, 1.5) |                        |                     | 22/18           |
high-energy cosmic-ray anisotropy at a few $10^{-3}$ (e.g., Amenomori et al. 2006) might be physically related to large-scale structures of Galactic magnetic fields and inhomogeneous cosmic-ray source distribution. Using diffuse synchrotron radio emission at 74 and 330 MHz frequencies produced by relativistic cosmic-ray electrons and the magnetic field around the GC, LaRosa et al. (2005) inferred a weak magnetic field of the order of ~10 $\mu$G on size scales ~125$''$ based on a minimum-energy analysis. This is about 2 orders of magnitude lower than the ~1 mG usually estimated for the GC region. Very recently, Cowin & Morris (2006) argued that the assumption of LaRosa et al. (2005) that the magnetic field and cosmic rays are in a minimum-energy state across this region is unlikely to be valid. According to their model estimates, the mean magnetic field is at least 100 $\mu$G on a scale of several hundred parsecs and peaks at approximately 500 $\mu$G at the center of the diffuse nonthermal source. This is an important issue to be settled for the GC magnetic environment. Most of the GC radio NTFs are found to be perpendicular to the Galactic plane, implying local poloidal magnetic fields of about milligauss strengths (e.g., Yusef-Zadeh & Morris 1987). However, recent observations revealed that the GC magnetic field may be more complex than a simple globally ordered dipolar field (e.g., LaRosa et al. 2004; Nord et al. 2004). It might be possible for X-ray NTFs to provide clues regarding the configuration of the local magnetic field, as well as the interaction between it and the ambient gas flow.

We report morphological and spectral properties of another 10 newly discovered X-ray filaments within a region of 6.5$'$$\times$6.5$'$ surrounding Sgr A$^*$ (roughly corresponding to a projected sky area of ~15 $\times$ 15 pc at a presumed distance of 8 kpc to the GC). Their plausible physical origins are discussed in § 4. All error bars in the X-ray spectrum parameter measurements are at the 90% confidence level, and we express the fitted parameters in the format of $y_{\text{fit}}$ and $y_{\text{err}}$, where $y_{\text{fit}}$ is the best-fit value and $y_{\text{err}}$ are the lower and upper limits of the 90% confidence interval, respectively. For all the images in the paper, north is up and east is to the left. We adopt a distance of 8 kpc from the solar system to the GC throughout this paper. We note that during the review process for this manuscript, Muno et al. (2008) also submitted a paper on X-ray filaments around the GC.

2. SATELLITE OBSERVATIONS AND DATA REDUCTION

This work takes advantage of a large number of observations by the Advanced CCD Imaging Spectrometer (ACIS-I) onboard Chandra aimed at Sgr A$^*$ (e.g., Baganoff et al. 2003). We utilize the archival data available in 2005 September, including the 11 observations taken before 2002 May 3, as listed by Park et al. (2005; 1561b excluded), and the three more recent observations (ObsID 3549, 4683, and 4684) taken on 2003 June 19 and 2004 July 5 and 6. The total resultant exposure time of the included 14 observations is ~760 ks. Following the standard event reprocessing procedures from the Chandra Interactive Analysis of Observations (CIAO, ver. 3.2.2), we first process individual observations, including the correction for charge transfer inefficiency, bad pixel removal, and light-curve cleaning. We then co-add the data from the 14 observations by the sky coordinates to generate the composite data set. The detailed data preparation procedures are described in Wang et al. (2006).

When placed on-axis at the focal plane of the grazing incidence X-ray mirrors, the imaging resolution (FWHM) is determined primarily by the pixel size of the CCDs of 0.492$''$. The CCDs also measure the energies of incident photons with a resolution of 50–300 eV (depending on photon energy and distance from the readout node; e.g., Baganoff et al. 2003). We use the X-ray data in the 0.5–8 keV energy band for the spectrum study. The CCD frames are read out every 3.2 s, which provides the nominal time resolution of the X-ray data (e.g., Munu et al. 2006). Here we focus on the inner ~6.5$'$ region centered around Sgr A$^*$ where the point-spread function (PSF) broadening is insignificant.

3. DATA ANALYSIS AND RESULTS ON X-RAY FILAMENTS

The source region framed for extracting the spectrum of each source is chosen in such a way that it is small enough to minimize contamination from its surroundings and yet large enough to contain the bulk of filament emission. For those X-ray filaments with a sufficient number of photons for statistics, we divide them into subregions to look for the spectral evolution along the filamentary structure. The background spectrum is extracted from one or several regions in the environs of the relevant filament under consideration. For each filament, we have used different background regions to test their effects on the final spectra. Although the best-fit parameters do vary slightly with different backgrounds, this variation is much smaller than the uncertainties of the current data statistics. Most of the X-ray spectra are modeled by the absorbed power-law continuum [hereafter $\text{phabs}(\text{po})$] in XSPEC. The Galactic coordinate of a filament is given by the position of its brightest part. Incidentally, the size of

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**Table 1 — Continued**

| Region     | $N_H$ ($10^{21}$ cm$^{-2}$) | $\Gamma$ | $F_X$ ($10^{-14}$ ergs s$^{-1}$ cm$^{-2}$) | $L_X$ ($10^{33}$ ergs s$^{-1}$ d$^{-1}$) | $\chi^2$/d.o.f. |
|------------|-----------------------------|----------|----------------------------------------|----------------------------------------|-----------------|
| Joint Fit: Set $N_H$ the Same and Fit All the Parameters |
| Head       | 0.7 (0.4, 1.0)              | 1.1 (0.6, 1.8) | ...                                    | ...                                    | ...             |
| Middle     | 0.7 (0.4, 1.0)              | 1.5 (0.8, 2.2) | ...                                    | ...                                    | ...             |
| Tail       | 0.7 (0.4, 1.0)              | 1.8 (1.4, 2.2) | ...                                    | ...                                    | ...             |
| Joint Fit: Set $N_H$ the Same and Fix It at a Value of 0.7 |
| Head       | 0.7                         | 1.1 (1.0, 1.3)| ...                                    | ...                                    | ...             |
| Middle     | 0.7                         | 1.5 (1.4, 1.6)| ...                                    | ...                                    | ...             |
| Tail       | 0.7                         | 1.8 (1.7, 1.9)| ...                                    | ...                                    | ...             |

**Notes.**—The spectral model used here is the absorbed power law. Relevant parameters are the hydrogen gas column density $N_H$, the X-ray photon index $\Gamma$, the observed flux in the energy 2–10 keV band $F_X$, and the unabsorbed X-ray luminosity $L_X$ in the energy 2–10 keV band. For notations here, $d_{\odot}$ denotes the distance in units of 8 kpc, and d.o.f. is the degree of freedom. Unless otherwise stated in the table as “joint fit,” both $N_H$ and $\Gamma$ are free parameters in the fitting procedure.
the filament given in this paper should only be regarded as a rough estimate.

Figure 1 gives a panoramic view of the X-ray filaments in the GC region studied here. Sgr A* is buried deep in the lower right region where the emission is saturated in Figure 1. We studied the images of each X-ray filament in detail, and the results are shown in the left panels of Figures 2 and 3. From the X-ray contours we can see that there are signs of the existence of pointlike sources in some filaments. The right panels of Figures 2 and 3 show the 0.5–8 keV count image created from the composite event file of the 14 Chandra observations as mentioned in the last section. The rectangular boxes overlaid on the images represent the source regions (including the subregions used for studying spectral evolution along a filament). Figure 4 shows the final spectra of the 10 filaments extracted from the “entire” source region. All of them can be well fitted with the phabs(po) model, implying that the X-ray emission we detected is dominated by the nonthermal component. It should be noted that if these sources emit any thermal components, they will likely be completely absorbed and unobservable. In Figure 5 we give the joint-fit spectra extracted from the subregions of filaments F1, F3, F6, and F10, whose photon counts are large enough to allow for a comparison of the subregion spectra. The spectral fitting results are summarized in Table 1.

We have also sought the counterparts of X-ray filaments in the H and K infrared bands and the 20 cm radio band. The infrared images were produced by the Two Micron All Sky Survey and were downloaded from the SkyView Web site.4 The radio data were acquired by the Very Large Array (VLA) on 2001 July 23, with a beam size of 15″ × 15″ (C. C. Lang et al. 2008, in preparation). No obvious filamentary structures were found (with an upper limit of 0.12 Jy beam⁻¹), except for filament 10, which coincides with a statistically significant radio filament. In addition to the fitting parameters for filaments summarized in Table 1, we now describe the properties of each X-ray filament as follows:

**Filament 1 (F1):** G359.936−0.038.—Filament 1 lies ~41″ (~1.6 pc) southwest of Sgr A*. The brightest part of F1 is near the celestial coordinates (l, b) = (359.936°, −0.038°). The elongation occurs almost in the exact north-south direction, with a pointlike source residing at the head in the northeast part. It has a rough length of ~17″ and a width of ~5″. Its spectra can be well fitted by phabs(po). We divided the filament into the head and tail regions and fitted their respective spectra. Although the best-fit Γ_tail appears twice as big as Γ_head, the error bars are larger than the difference. Therefore, the current data are not good enough to constrain the spectral evolution of F1.

**Filament 2 (F2):** G359.934−0.037.—Filament 2 has a size of 3″ × 9″. The most concentrated part of F2 is near the celestial coordinates (l, b) = (359.934°, −0.037°), which is ~48″ (~2 pc) southwest of Sgr A*. The elongation is along the

4 See http://skyview.gsfc.nasa.gov/cgi-bin/titlepage.pl.
Fig. 2. — *Left:* The 0.5–8.0 keV X-ray images of F1–F6 with contours overlaid. These images are smoothed adaptively with a Gaussian to achieve a signal-to-noise ratio of 10. For the same data, these contours have the same step size of 4 counts arcsec$^{-2}$ but different starting values, i.e., 20 counts arcsec$^{-2}$ for F1–F4 and 16 counts arcsec$^{-2}$ for F5 and F6. *Right:* Count maps of the same regions as in the left panels. The color bars are in logarithmic scale. For F1, F2, F5, and F6 the lower and upper limits are 4 and 120 counts arcsec$^{-2}$, respectively, while for F3 and F4 the two limits are 12 and 120 counts arcsec$^{-2}$, respectively.
northeast-southwest direction, with the head in the northeast end. Similar to F1, there is no obvious emission line, and a simple power law gives a fairly satisfactory fit.

**Filament 3 (F3): G359.965 – 0.053.** Filament 3 lies 1.3′ (≈3 pc) northeast of Sgr A* with a size of 4″ × 12″; the elongation is from northeast (NE) to southwest (SW). This filament was first mentioned by Baganoff et al. (2003) as a “curious linear feature.” They reported its existence in the 1.5–3 and 3–6 keV bands but not in the 6–7 keV band. Our analysis also shows that the bulk of F3 emission comes from photons of energies below 6 keV. The X-ray morphology clearly shows that F3 contains two concentrations. In order to study their spectral evolution, we
divide it into the “head” (the NE concentration with stronger emission), “middle” (between NE and SW), and “tail” (the SW concentration with weaker emission) regions. There appears to be a spectral steepening from the tail to the head. However, since no obvious pointlike source is detected in the head region, the head-to-tail direction does not necessarily mean the electron flow direction, as is further discussed in § 4.3.

The two-blob morphology is somewhat unexpected, and one might wonder whether the three regions we chose are in fact coherent parts of the same source. Actually, the spectral results may cast doubt on the coherence of the head and tail. First, the $N_H$ value in Table 1 shows that the head region has a hydrogen column density of $1.9(1.3, 2.6) \times 10^{23}$ cm$^{-2}$, while the tail region has a $N_H$ value of $0.7(0.3, 1.1) \times 10^{23}$ cm$^{-2}$, which might suggest that the tail could be nearer to us than the head. Second, the spectrum of the tail shows slight signs of the 6.7 keV emission line, which is not found in the head and middle regions.

However, we find that these spectral “differences” are most likely not caused by the emitter proper. The higher $N_H$ in the head region is quite probably due to a small molecular cloud in this direction (e.g., Coil & Ho 1999, 2000). Figure 2 of Coil & Ho (2000) shows that the column density of the NH$_3$ cloud in the head region is about one-tenth of that of the streamer at R.A. $B1950.0 = 19^h42^m28^s$, decl. $B1950.0 = -29^\circ02^\prime30^\prime$, while the equivalent $N_H$ of this streamer is $\sim 1.4 \times 10^{24}$ cm$^{-2}$ (Coil & Ho 1999). So the $N_H$ of the small NH$_3$ cloud is $\sim 1.4 \times 10^{23}$ cm$^{-2}$.
4. DISCUSSION

4.1. Properties and Possible Origins of GC X-Ray Filaments

While X-ray photon numbers may not be high enough to constrain the exact shapes of the energy spectra, all spectra appear featureless, except for filament 3 showing weak iron line features (see § 3), and can be well fitted with power-law models. Fitting some of these energy spectra with thermal emission models is acceptable statistically; nevertheless, this always gives quite high temperatures, i.e., >10 keV. We are therefore inclined to the

Filament 9 (F9): G359.974−0.00.—Filament 9 is ~3.3' (~8 pc) northwest of Sgr A*. Its elongation is almost parallel to those of filaments 5 and 8. It has a width of ~4'' and a length of ~7''. The energy spectrum of filament 9 also appears to be nonthermal.

Filament 10 (F10): G0.029−0.06.—This filament lies ~5.1' (~12 pc) northeast of Sgr A*. With a width of ~6'' and a length of ~46'', it is the longest X-ray filament so far identified within the central 15 pc of the Galaxy center. The energy spectrum of filament 10 is rather flat and nonthermal, with the column density of a typical value for the absorption around the GC. To see the photon index evolution along the filament, we divide the filament into three parts: “head” (i.e., where the assumed point source resides), “middle,” and “tail” parts. We then conduct a joint fit for the energy spectra of these three regions. As listed in Table 1, there appears to be a spectral steepening from the head to the tail. No infrared counterparts are found for filament 10. But, quite interestingly, there is a 20 cm radio filament more or less coincident with F10 spatially; the implications of this spatial coincidence are discussed in § 4.2.

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view that X-ray emission from these filaments is nonthermal in nature.

Table 2 sums up the inferred parameters for these 15 nonthermal X-ray filaments in the inner 15' around the GC. In addition to the 10 filaments studied in this paper, we also include the other five filaments, namely, G359.89—0.08, G359.90—0.06, G359.95—0.04, G359.983—0.046, and G0.13—0.11, reported and studied earlier in the literature. Most of their hydrogen column density $N_H$ values are of the order of $\sim 10^{22} - 10^{23}$ cm$^{-2}$, consistent with other $N_H$ estimates around the GC region. Most of their photon indices $\Gamma$ fall within the range of $\sim 1 - 2.5$. The chance of these X-ray filaments being background extragalactic sources is very small, according to the spectral and morphological properties. For instance, it would be very difficult to explain the linear filamentary morphology using the hypothesis of extragalactic origin. Therefore, these X-ray filaments are most likely unique objects around the GC region.

As already discussed in § 1, there were suggestions that these X-ray filaments may be low pressure—confined PWNe (Wang et al. 2002b, 2006), synchrotron emission from magnetohydrodynamic (MHD) shock—associated SNRs, or emission resulting from ICS (Yusef-Zadeh et al. 2005; Figer et al. 1999). The nonthermal X-ray emission mechanisms may be either synchrotron emission or ICS. MHD relativistic pulsar winds (Michel 1969; Goldreich & Julian 1970; Kennel & Coroniti 1984a, 1984b; Lou 1996, 1998) and MHD shock interactions of magnetized outflows (e.g., Yu & Lou 2005; Yu et al. 2006; Lou & Wang 2006, 2007) with the interstellar medium (ISM) in SNRs and PWNe could provide the high-energy electrons needed in these two radiation mechanisms (e.g., Sakano et al. 2003; Lu et al. 2003; Wang et al. 2006). If these X-ray filaments are SNRs, their elongations would probably represent MHD shock fronts; therefore, one would not expect to see a tendency toward spectral softening along a filament. The two bright filaments F3 and F10 both show evidence for such a softening tendency. The fact that most of these filaments have pointlike sources at the heads also indicates that they are not of SNR origin. On the other hand, as nonthermal X-ray emission is only detected in several SNRs within the entire Galaxy, it is highly unlikely that there are so many nonthermal SNRs around the GC region. For this reason, we would argue that most of these X-ray filaments are not SNRs. Observed properties of these X-ray filaments may be more consistent with those of PWNe. The typical feature of a PWN is a nonthermal X-ray spectrum with a photon index of 1.1—2.4 and an X-ray luminosity $L_X$ ranging from $4 \times 10^{32}$ to $2 \times 10^{37}$ erg s$^{-1}$ in the 0.2—10 keV band (e.g., Gaensler & Slane 2006; Kaspi et al. 2006). The $\Gamma$ and $L_X$ of these 10 filaments are consistent with the values of a PWN. The existence of pointlike X-ray sources as indicated by the image study also tends to favor a PWN scenario.

We may estimate the ages of the putative pulsars with the X-ray luminosities of these X-ray filaments. Li et al. (2007) studied statistically the nonthermal X-ray emission from young rotation-powered pulsars and PWNe. They noted that there exists a correlation between the pulsar age $\tau$ and the 2—10 keV PWN luminosity $L_{X,PWN}$, which can be expressed as $L_{X,PWN} = 10^{41.7} \tau^{-2.0 \pm 0.3}$. The X-ray luminosities of these 10 filaments are in the range of $(0.2—2.2) \times 10^{33}$ erg s$^{-1}$. Using this empirical formula, the ages of these putative pulsars are possibly between $\sim 10^5$ and $3 \times 10^5$ yr. However, given the dispersion about the above empirical relationship (Li et al. 2007), the estimate may be uncertain, probably by a factor of 10.

Since the ages of pulsars with bright PWNe are usually younger than a few tens of thousands of years, one may doubt if a pulsar at the age of several $10^5$ yr can produce a detectable X-ray nebula. However, the PWN of a relatively old pulsar can be enhanced in surface brightness and thus become detectable if the pulsar wind materials are confined to one direction. PSR B0355+54 is $\sim 5.6 \times 10^5$ yr old. It converts $\sim 1$% of its spin-down luminosity to the cometary X-ray nebula (e.g., Tepedelenlioglu & Ogelman 2007). The old pulsar PSR B1929+10 ($\tau \sim 3 \times 10^6$ yr) also converts $2.1 \times 10^{-4}$ of its spin-down luminosity, $\sim 3.9 \times 10^{33}$ ergs s$^{-1}$, into the emission of the cometary nebula (e.g., Becker et al. 2006). The X-ray filaments identified in the GC region are similar to these two systems and thus probably powered by pulsars.

Now we discuss whether the number of X-ray filaments, if identified with PWNe, would be consistent with the estimated star formation rate in the GC region. According to Figer et al.
(2004), the star formation rate at the GC is about $10^{-7} \, M_\odot \, \text{yr}^{-1} \, \text{pc}^{-3}$, which is some 250 times higher than the mean star formation rate in the Galaxy. In the field of view of our Figure 1, we take a radius of about 7 pc and estimate the star formation rate to be $1.4 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$. If the mean mass of a star is $10 \, M_\odot$, the frequency of supernova explosions would be $1.4 \times 10^{-4} \, \text{yr}^{-1}$, leading to about 40 pulsars in the field of Figure 1 younger than $\sim 3 \times 10^3 \, \text{yr}$ as estimated above. This number is roughly consistent with the 15 candidate PWNe identified in the 15 candidate PWNe.

4.2. G0.029−0.06 (F10) and Its Radio Counterpart

Filament 10 bears certain unique features, noted here. First, it has the longest linear structure with the entire image slightly bent toward the northeast, more or less like an arc. Second, it is the farthest away from Sgr A* and thus has much less contamination from the strong diffuse X-ray emission of Sgr A*. Third, there is an obvious 20 cm radio NTF spatially coincident with X-ray filament 10 (see Fig. 7).

The spectral indices for different regions along filament 10 show evidence of spectral steepening from the head to the tail (see Table 1). When $N_{\text{HI}}$ is fixed at the best-fit value $\sim 7 \times 10^{22} \, \text{cm}^{-2}$, the $\Gamma$ values for the head, middle, and tail regions are 1.1 (1.0, 1.3), 1.5 (1.4, 1.6), and 1.8 (1.7, 1.9), respectively. This might suggest an energetic particle flow direction from the southeast (head) to the northwest (tail). A pulsar moving through the magnetized ISM seems to give a plausible explanation of this scenario. Indeed, the morphology of F10 does imply a point source in the head region. The corresponding PSF at G0.029−0.06 is an ellipse with a size of $\sim 2'' \times 4''$. For an updated X-ray versus spin-down luminosity correlation of rotation-powered pulsars, a modified empirical relation is given by equation (3) of Possenti et al. (2002), namely, $\log L_{\text{X}}(\dot{E} = 10^5 \, \text{ergs s}^{-1}) = 1.34 \log \dot{E} - 15.34$, where $L_{\text{X}}(\dot{E} = 10^5 \, \text{ergs s}^{-1})$ is the X-ray luminosity in the 2−10 keV energy band; using this empirical relation, we would have $\dot{E} \sim 10^{38} \, \text{ergs s}^{-1}$. Since PSRs J1747−2958 and B1929+10 convert about 2.5% and $2.1 \times 10^{-4}$ of their spin-down powers to their cometary X-ray nebulae (e.g., Gaensler et al. 2004; Becker et al. 2006), the ratio $L_{\text{X}}/\dot{E}$ of F10 ($\sim 10^{-3}$) indicates that the above estimate for $\dot{E}$ is reasonable.

The arclike X-ray morphology of F10 and its coincidence with a radio NTF might be a good indicator of its interaction with the interstellar magnetic field environment of the GC region (Lang et al. 1999; Wang et al. 2002b). Similar to the discussion about G0.13−0.11 by Wang et al. (2002b), we may estimate the magnetic field strength $B$ in the current context. First, the lifetime $\tau$ of synchrotron X-ray–emitting particles is given by $\tau \sim (1.3 \, \text{yr}) \epsilon^{-0.5} B^{-1.5} \, \text{mG}$, where $\epsilon$ is the X-ray photon energy in units of

![Fig. 7.—The 20 cm radio contours superimposed onto the X-ray image of F10. The radio data were obtained by the VLA on 2001 July 23, with a beam size of $15'' \times 15''$. The contours are at 0.14, 0.15, 0.16, and 0.17 Jy beam$^{-1}$ (C. C. Lang et al. 2008, in preparation). The X-ray image is smoothed adaptively so as to achieve a signal-to-noise ratio of 8, and the gray scale changes from 5 to 20 counts arcsec$^{-2}$ logarithmically.](image_url)
keV (a value of 4 keV is adopted here) and $B_{\text{mag}}$ is the magnetic field strength in the filament volume in units of milligauss. The simulations of Bucciantini et al. (2005) show that the average flow speed in the tail is about 0.8c~0.9c. For a sustained X-ray linear structure, we estimate by requiring $\tau \geq L_{\text{obs}}/(0.85c)$. Adopting a characteristic angular length $L_{\text{obs}}$ of 47" ($\sim$2pc), we thus infer a magnetic field strength $B \sim 0.3$ mG, similar to those in the bright radio NTFs (e.g., Yusef-Zadeh & Morris 1987; Lang et al. 1999).

We try to outline a few plausible scenarios in the present context and discuss relevant aspects qualitatively. Magnetized neutron stars move with peculiar speeds in the range of a few tens of kilometers per second (mean space velocities of $\sim$300~400 km s$^{-1}$ for young pulsars; Hobbs et al. 2005; Faucher-Giguère & Kaspi 2006) to well over 1000 km s$^{-1}$ ($\sim$1600 km s$^{-1}$), and the surrounding ISM is generally magnetized. Generally speaking, a typical peculiar velocity of a neutron star is supersonic and super-Alfvénic in the magnetized ISM. Neutron stars or pulsars have different ranges of surface magnetic field strengths: $10^9$~$10^{10}$ G for millisecond pulsars in binaries, $10^{11}$~$10^{12}$ G for a wide range of pulsars, and $10^{14}$~$10^{15}$ G inferred for several magnetars. Several situations may happen: (1) If a pulsar does not involve an active pulsar wind, its peculiar motion through the surrounding magnetized ISM would sustain an MHD bow shock by its magnetosphere, as well as a magnetotail. The faster the pulsar moves, the more linear the system would appear. This is basically like a bullet moving through the air supersonically and generating a Mach cone or wake. Relativistic electrons can be produced at the MHD bow shock, and synchrotron emission can be generated and sustained at the same time. (2) In a binary system, the fast wind (say, with a speed higher than 1000 km s$^{-1}$) from a companion star can blow toward a spinning magnetized pulsar in orbital motion. Here the situations of a companion fast wind blowing across a magnetized pulsar and a pulsar moving through the ISM with a high speed are more or less equivalent. Again, an MHD bow shock and a magnetotail can form in association with the pulsar system. The stronger the companion wind and the faster the movement of the pulsar, the more linear the pulsar system would appear. Relativistic electrons and/or positrons can be generated and sustained to power synchrotron emission in the bow shock draped around the pulsar magnetosphere. For such a system, one might be able to detect the presence of the companion by various independent means. (3) For a pulsar emitting an active pulsar wind and having misaligned magnetic and spin axes, spiral forward and reverse shock pairs can be generated in the relativistic pulsar wind as a result of inhomogeneous wind, and eventually the pulsar wind is stopped by the ISM through an MHD termination shock (e.g., Lou 1993, 1996, 1998). (4) Case 3 can also happen for a pulsar moving with a high peculiar velocity through the magnetized ISM. (5) Case 3 can also happen for a pulsar in binary orbital motion when the companion blows a powerful wind with a speed higher than 1000 km s$^{-1}$. In both case 2 and case 5, the center of mass of the binary system may also move with a high speed through the ISM. One can further speculate several possible combinations along this line of reasoning (e.g., Chevalier 2000; Toropina et al. 2001; Romanova et al. 2005).

There are two clumps (hereafter referred to as the “east” and “west” clumps) of diffuse X-ray emission surrounding filament 10. Although the west clump is also elongated, it is not called a filament because it contains many substructures. To see if these clumps are physically related to F10, we extract their energy spectra separately (see Fig. 6, middle and bottom). The fitted parameters are listed in Table 3. The much higher absorbing column densities of the two clumps indicate strongly that they are located farther away from us than F10 is, while these two clumps themselves are at almost the same distance (see Table 3). Moreover, their X-ray emission is very likely powered by the same mechanism, as hinted by the characters of their spectra, which can be fitted well with an absorbed power-law model plus a 6.4 keV emission line. The total emission comes mostly from the photon energy 4~7 keV band, with a strong 6.4 keV neutral Fe K line. In contrast, the Fe line feature is not present in the spectrum of F10. A possible explanation for this nonthermal, apparently broadened iron line emission at 6.4 keV is the collision of low-energy cosmic-ray electrons with iron in molecular clouds (e.g., Valinia et al. 2000) or the radiative illumination from the GC massive black hole that was suggested to be very bright in the past (e.g., Koyama et al. 1989). In conclusion, F10 and the surrounding clumps do not seem to interact directly.

### 4.3. X-Ray NTFs as Tracers of the Small-Scale Magnetic Fields and Gas Dynamics

The orientation of the X-ray filaments provides an opportunity to probe the physics conditions of the GC region. As discussed in § 4.1, the cometary shapes of the X-ray filaments imply that the pulsar wind particles are confined to one direction by the ambient materials. The mechanism shaping the filamentary structure could be ordered magnetic fields (e.g., Yusef-Zadeh & Morris 1987; Lang et al. 1999) and/or high relative velocity between the pulsars and the surrounding gas (e.g., Wang et al. 1993; Shore & LaRosa 1999). The magnetic field could be the product of the gas motion, and the magnetic field could also control the motion of the gas (e.g., Heyvaerts et al. 1988; Chevalier 1992). Radio NTFs suggest that the magnetic field is poloidal at a large scale (e.g., Yusef-Zadeh & Morris 1987; Lang et al. 1999), with some more complex smaller structures around the GC region (e.g., Nord et al. 2004). By looking at the X-ray images shown in Figures 1–3, there seems to be a tendency for the PWN tails to point away from the GC, indicating that the pulsar wind particles are blown outward. This might imply the presence of a Galactic wind of hot plasma blowing away from the center, given the high star formation rate (and so plenty of hot gas) in this region. Pulsars may have typical peculiar velocities of $\sim$400 km s$^{-1}$ (e.g., Hobbs et al. 2005; Faucher-Giguère & Kaspi 2006), and we would expect

| Region          | $N_{\text{H}}$ (10$^{21}$ cm$^{-2}$) | $F_X$ (10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | $L_X$ (10$^{31}$ ergs s$^{-1}$) | $\text{LineE}$ (keV) | $\text{EW}$ (keV) | $\chi^2$/d.o.f. |
|-----------------|----------------------------------|----------------------------------------|--------------------------------|---------------------|-----------------|----------------|
| East clump.......| 1.4 (1.2, 1.6)                   | 1.0 (0.5, 1.2)                         | 6.1 (5.9, 6.6)                | 8.1 (7.5, 8.4)      | 6.42 (6.41, 6.43)| 0.75 (0.68, 0.83)| 112/135          |
| West clump.......| 2.3 (1.6, 2.9)                   | 1.0 (0.4, 1.6)                         | 5.4 (5.0, 5.7)                | 8.7 (7.8, 10.9)     | 6.39 (6.38, 6.40)| 1.07 (0.94, 1.23)| 126/114          |

Notes.—Spectral model: $N_{\text{H}}$ (power law + Gaussian). The relevant parameters are as follows: $N_{\text{H}}$, hydrogen gas column density; $\Gamma$, photon index; $F_X$, absorbed flux in the 2–10 keV band; $L_X$, X-ray luminosity in the 2–10 keV band; LineE, line center energy; EW, equivalent width of the line; $\chi^2$/d.o.f.: $\chi^2$ divided by the number of degrees of freedom (d.o.f.).
them to move in random directions. The tendency for the structures of 10 PWNe to orient away from the center seems to suggest that the Galactic wind has a speed comparable to or greater than ~400 km s⁻¹.

In the above scenario, the particle flow direction of X-ray filament 3 should be from the southwest (closer to Sgr A*) to the northeast. This suggests that the pulsar, the origin site of the particles, is actually in the tail region defined in Figure 2. Then the evident spectral steepening from the southwest to the northeast (see § 3) can be naturally explained. Therefore, the spectral evolution along F3 also supports the existence of a radial high-velocity wind in the GC region.

While the X-ray filaments may not completely overlap with their radio NTFs, their overall orientations are similar. This is supported by the four X-ray NTFs (including filament 10 in our analysis) that have radio counterparts: G359.54+0.18 is overlaid exactly on the northern part of the two radio filaments (e.g., Yusef-Zadeh et al. 2005; Lu et al. 2003); G359.89−0.08 and its radio counterpart Sgr A-E overlap partly and extend in the same direction, with a centroid offset of ~10⁷ (e.g., Yusef-Zadeh et al. 2005; Lu et al. 2003); and G359.90−0.06 (Sgr A-F; e.g., Yusef-Zadeh et al. 2005) and G0.029−0.06 (F10) also show similar spatial properties. Generally speaking, the X-ray NTFs tend to be shorter than the radio NTFs. This centroid offset and smaller extent of X-ray filaments could both be explained by the much shorter synchrotron cooling lifetime in X-ray than in radio (e.g., Ginzburg & Syrovatskii 1965).

5. SUMMARY AND DISCUSSION

To summarize, the most important properties of the GC X-ray filaments in this Chandra data analysis are their nonthermal spectra and, of course, the apparent threadlike linear morphology with pointlike sources residing at the “head.” The scenario of pulsars plowing through the ISM and high-energy particles from the PWN interacting with the surrounding magnetic field seems to be a plausible interpretation. However, this relationship with pulsars can only be confirmed by the direct detection of periodic flux variations from the putative point sources. Future faster timing, higher sensitivity, and spatial resolution of X-ray instruments, together with radio and near-infrared follow-up observations, should help to reveal the true identity of these X-ray filaments. Meanwhile, these filaments could also provide some clues in the search for GC pulsars, as well as the study of small-scale magnetic field structures and gas dynamics around the GC.

From our work, one might get the impression that there are many pulsar bow shocks within ~15 pc of the GC. Actually, in this scenario, there should be even more due to the unavoidable projection effect; some X-ray–bright sources may be heading directly toward or away from us with their tails behind or in front superposed with their heads. We now only catch those suspects readily identified by their linear or arclike morphologies. By all astronomical standards, our GC is not very active at the present epoch even though there is a black hole with a mass of ~4 × 10⁶ M☉ lurking at the center near Sgr A* (e.g., Shen et al. 2005). Nevertheless, the neighborhood of our GC might have been active in the past with starbursts, magnetized Galactic winds, and so forth. While interacting with winds or flows of the ISM, the compact remnants of these massive stars (produced during the starburst phase) with a distribution of peculiar speeds might then have a higher concentration around the GC. A typical peculiar speed of a few hundred kilometers per second would be supersonic and super-Alfvenic in the magnetized ISM. With the projection effect taken into account, the physical linear extension of such a PWN should be jointly determined by the direction of the local ISM flow and of the remnant peculiar velocity.

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