Invited Review

Diffuse X-ray sky in the Galactic center

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Abstract

The Galactic diffuse X-ray emission (GDXE) in the Milky Way Galaxy is spatially and spectrally decomposed into the Galactic center X-ray emission (GCXE), the Galactic ridge X-ray emission (GRXE), and the Galactic bulge X-ray emission (GBXE). The X-ray spectra of the GDXE are characterized by the strong K-shell lines of the highly ionized atoms, and the brightest lines are the K-shell transition (principal quantum number transition of \(n = 2 \to 1\)) of neutral iron (FeK\(\alpha\)), He-like iron (FeXXV-He\(\alpha\)), and He-like sulfur (SXV-He\(\alpha\)). Accordingly, the GDXE is composed of a high-temperature plasma of \(\sim 7\) keV (HTP) and a low-temperature plasma of \(\sim 1\) keV, which emit the FeXXV-He\(\alpha\) and SXV-He\(\alpha\) lines, respectively. The FeK\(\alpha\) line is emitted from nearly neutral irons, and hence the third component of the GDXE is a cool gas (CG). The FeK\(\alpha\) distribution in the GCXE region is clumpy (FeK\(\alpha\) clump), associated with giant molecular cloud (MC) complexes (Sagittarius A, B, C, D, and E) in the central molecular zone. The origin of the FeK\(\alpha\) clumps is the fluorescence and Thomson scattering from the MCs irradiated by past big flares of the supermassive black hole Sagittarius A*. The scale heights and equivalent widths of the FeK\(\alpha\), FeXXV-He\(\alpha\), and FeXXVI-Ly\(\alpha\) \((n = 2 \to 1\) transition of H-like iron) lines are different among the GCXE, GBXE, and GRXE. Therefore, their structures and origins are separately examined. This paper gives an overview of the research history and the present understandings of the GDXE, while in particular focusing on the origin of the HTP and CG in the GCXE.

Key words: Galaxy: center — ISM: supernova remnants — X-rays: diffuse background — X-rays: ISM

1 Introduction

The center of our Milky Way Galaxy (the Galactic center: GC) and Sagittarius A* (Sgr A*) are the nearest galactic center and supermassive black hole (SMBH) from the Earth, and hence are unique and ideal laboratories for the study of various astrophysical processes. Therefore, many observations and theoretical works have been made in the wide band of electromagnetic radiations. Recent reviews of the GC and Sgr A* are found in Genzel, Eisenhauer, and Gillessen (2010) and Morris, Meyer, and Ghez (2012), which focused mainly on the infrared and radio bands, respectively. In this paper, therefore, we focus on a review of the X-ray sky near the GC and related activities of Sgr A*.

X-ray astronomy was started by the discovery of a bright extraterrestrial X-ray source with a sounding rocket (Giacconi et al. 1962). This source is now known as Sco
X-1, the brightest Galactic X-ray star. Diffuse X-ray emissions, later called the cosmic X-ray background (CXB), were also found. After many studies and debates on the origin of the CXB, at least in the energy range below \(\sim 10\) keV, a common consensus has emerged that the CXB is an integrated emission of extragalactic sources such as active galactic nuclei (AGN) and active galaxies.

The first X-ray satellite, Uhuru, discovered many point-like sources, and the majority of the bright sources are concentrated in the Galactic plane (e.g., see the fourth Uhuru catalog: Forman et al. 1978). Most of them are close binaries of a neutron star (NS) or black hole (BH) with a normal star, and are termed X-ray binaries (XBs). Sco X-1 is the brightest XB observed from the Earth. In addition to the CXB and XBs, diffuse X-rays of Galactic origin were found with Uhuru, Ariel 5, and HEAO-1. These emissions extended to a high Galactic latitude with a scale height \(\sim 500\) pc–\(1.5\) kpc. Since the surface brightness is very faint, less than \(\sim 10\%\) of the CXB, any quantitative study has been limited, which places this emission outside the scope of this review. Soon after, Galactic diffuse X-ray emission with surface brightness nearly or larger than the CXB was discovered. This emission is more concentrated along the Galactic plane, with an SH of less than a few 100 pc (see section 2). This review calls this X-ray emission the Galactic diffuse X-ray emission (GDXE).

In this review, the transition lines from the first-excited to the ground states (principal quantum number \(n = 2 \rightarrow 1\)) in neutral or low-ionization atoms, He-like (ions with two electrons) atoms, and H-like (ions with one electron) atoms are designated as \(\text{K}\alpha\), \(\text{He}\alpha\), and \(\text{Ly}\alpha\) lines, respectively. Likewise, the transition lines from the second-excited to the ground states (principal quantum number \(n = 3 \rightarrow 1\)) are the \(\text{K}\beta\), \(\text{He}\beta\), and \(\text{Ly}\beta\) lines, while the transitions from the third-excited to the ground states (principal quantum number \(n = 4 \rightarrow 1\)) are the \(\text{He}\gamma\) and \(\text{Ly}\gamma\) lines. The equivalent widths (EWs) and SH of these iron lines are expressed as \(\text{EW}_{6.4}\), \(\text{EW}_{6.7}\), \(\text{EW}_{6.97}\), \(\text{SH}_{6.4}\), \(\text{SH}_{6.7}\), and \(\text{SH}_{6.97}\), where the subscript is the energy of the lines. For brevity and/or in the case that the \(\text{Fe}\text{-K}\alpha\), \(\text{Fe}\text{XXV-He}\alpha\), and \(\text{Fe}\text{XXVI-Ly}\alpha\) lines are not resolved, the notations of \(\text{Fe}\text{-K}\alpha\) with the EW of \(\text{EW}_{6.4}\), \(\text{EW}_{6.7}\), and \(\text{EW}_{6.97}\) and with the SH of \(\text{SH}_{6.4}\) (\(\text{SH}_{6.7}\), and \(\text{SH}_{6.97}\)) are used. These and the other abbreviations and symbols used frequently in this review are summarized in table 1. After long and extensive studies, the GDXE is now decomposed into three spatial components: the Galactic center X-ray emission (GCXE), the Galactic bulge X-ray emission (GBXE), and the Galactic ridge X-ray emission (GRXE). The GDXE exhibits various atomic lines: the brightest are the K-shell transition lines from He-like Fe (\(\text{Fe}\text{XXV-He}\alpha\)), He-like S (\(\text{S}\text{XXV-He}\alpha\)), and from neutral or low-ionized Fe (\(\text{Fe}\text{-K}\alpha\)). These atomic lines are emitted from a high-temperature plasma (HTP), a low-temperature plasma (LTP), and an X-ray re-emitting cool gas (CG), respectively.

This paper reviews the early studies of the GDXE, and then moves on to reviews of the separate study of the GCXE, GBXE, and GRXE. The reviews gradually focus on the origins and structures of the HTP and CG in the GCXE and their implications. The GBXE and GRXE are also reviewed, because the origin and structure of the GCXE are closely related to those of the GBXE and GRXE. Since the EW and SH of the Fe-K\(\alpha\) lines are significantly different among the GCXE, GBXE, and GRXE, the long-standing debate on the origin and structure of the GDXE is re-examined by the separate but coordinated studies on the GCXE, GBXE, and GRXE.

The content is organized as follows. The early results taken before Chandra, XMM-Newton, and Suzaku on the GRXE are reviewed in section 2. The structure of the GRXE and its possible origin are discussed in subsection 2.1. The discoveries of the new components, the GCXE and GBXE, and their characteristics are described in subsections 2.2 and 2.3, respectively.

Section 3 gives an overview of the recent observational results of the GDXE made with Chandra, XMM-Newton, and Suzaku. Subsection 3.1 gives the global spatial structure of the Fe-K\(\alpha\), S-XXV-He\(\alpha\), and S-XXVI-Ly\(\alpha\) lines in the GDXE, along and perpendicular to the Galactic plane, which leads to the decomposition of the GDXE into the GCXE, GBXE, and GRXE. Subsection 3.2 reports on the X-ray spectra and luminosity of the GCXE, GBXE, and GRXE. The spectra are significantly different among these components, and hence verify the decomposition of the GDXE into these components. Subsection 3.3 discusses the characteristics of the HTP and CG in the central region of the GCXE, based mainly on the observed flux of Fe-K\(\alpha\) and \(\text{EW}_{6.4}\).

Section 4 reviews the local enhancements of the HTP and LTP in the GCXE obtained mainly with Suzaku. Subsections 4.1 is devoted to a description of young supernova remnants (SNRs) or candidates, which emit strong Fe-XXV-He\(\alpha\) lines, while subsection 4.2 reviews the soft X-ray spots with strong S-XXV-He\(\alpha\) lines, which are intermediate-aged SNRs or candidates.

Section 5 reviews the Fe-K\(\alpha\)-line-emitting component, the CG components observed mainly with Suzaku, Chandra, and XMM-Newton. The emission mechanisms of the Fe-K\(\alpha\) line and resultant \(\text{EW}_{6.4}\) are given in subsection 5.1. Subsection 5.2 is devoted to the X-ray reflection nebula (XRN), which is a source of fluorescence and scattered X-rays from past activities (flares) of Sgr A*.
Table 1. Abbreviations and symbols frequently used in this text.

| Symbol/acronym | Explanation |
|----------------|-------------|
| GC             | Galactic center, the center of our Galaxy |
| GDXE           | Galactic diffuse X-ray emission, which is composed of GCXE, GBXE, and GRXE |
| GCXE           | Galactic center X-ray emission |
| GBXE           | Galactic bulge X-ray emission |
| GRXE           | Galactic ridge X-ray emission |
| CXB            | Cosmic X-ray background |
| NXB            | Non-X-ray background, the cosmic ray induced background |
| Fe I-\(K\alpha\) | \(n = 2 \rightarrow 1\) transition of neutral or low-ionization iron at an energy of \(\sim 6.40\) keV |
| Fe I-\(K\beta\) | \(n = 3 \rightarrow 1\) transition of neutral or low ionization iron at an energy of \(\sim 7.06\) keV |
| Fe XXV-He\(\alpha\) | \(n = 2 \rightarrow 1\) transition of He-like (two electrons are left) iron at an energy of \(\sim 6.68\) keV |
| Fe XXV-He\(\beta\) | \(n = 3 \rightarrow 1\) transition of He-like iron at an energy of \(\sim 7.88\) keV |
| Fe XXVI-Ly\(\alpha\) | \(n = 2 \rightarrow 1\) transition of H-like (one electron is left) iron at an energy of \(\sim 6.97\) keV |
| Fe I-K\(\alpha\) | Scale height, the longitude distance from the Galactic plane where the flux falls by a factor of \(1/e\) |
| Ni XXVII-He\(\alpha\) | \(n = 2 \rightarrow 1\) transition of He-like nickel at an energy of \(\sim 7.80\) keV |
| Si XVIII-He\(\alpha\) | \(n = 2 \rightarrow 1\) transition of He-like silicon at an energy of \(\sim 1.86\) keV |
| Si XXIV-Ly\(\alpha\) | \(n = 2 \rightarrow 1\) transition of H-like silicon at an energy of \(\sim 2.00\) keV |
| S XV-He\(\alpha\) | \(n = 2 \rightarrow 1\) transition of H-like sulfur at an energy of \(\sim 2.46\) keV |
| S XVI-Ly\(\alpha\) | \(n = 2 \rightarrow 1\) transition of H-like sulfur at an energy of \(\sim 2.62\) keV |
| EW\(6.4\) | Equivalent width, the flux ratio of the line to the continuum emission |
| EW\(6.7\) | Equivalent width of the 6.4 keV line (Fe I-\(K\alpha\) line) |
| EW\(6.97\) | Equivalent width of the 6.7 keV line (Fe XXV-He\(\alpha\) line) |
| EW\(6.97\) | Equivalent width of the 6.97 keV line (Fe XXVI-Ly\(\alpha\) line) |
| EW Fe-K | Equivalent width of the iron K-shell line, the sum of EW\(6.4\), EW\(6.7\), and EW\(6.97\) |
| SH\(6.4\) | Scale height of the 6.4 keV line (Fe I-\(K\alpha\) line) |
| SH\(6.7\) | Scale height of the 6.7 keV line (Fe XXV-He\(\alpha\) line) |
| SH\(6.97\) | Scale height of the 6.97 keV line (Fe XXVI-Ly\(\alpha\) line) |
| SH Fe-K | Scale height of the iron K-shell line, the mean of SH\(6.4\), SH\(6.7\), and SH\(6.97\) |
| HTP | High-temperature plasma \((kT \sim 6–7\) keV\) in the GDXE |
| LTP | Low-temperature plasma \((kT \sim 0.8–1\) keV\) in the GDXE |
| CG | Cool gas in the GDXE which emits the K-shell lines of neutral atoms |
| MC | Molecular cloud |
| CMZ | Central Molecular Zone |
| XRN | X-ray reflection nebula: the fluorescence/Thomson scattered X-ray nebula made by the flare of Sgr A* |
| NTF | Non-thermal filaments, mostly radio source |
| PWN | Pulsar wind nebula, a non-thermal X-ray source |
| CV | Cataclysmic variable, a binary of a normal star and a white dwarf |
| mCV | Magnetized CV; intermediate polar, polar, and symbiotic stars |
| non-mCV | Non-magnetized CV, or dwarf nova |
| AB | Coronal active close binary of low-mass star like RS CVn and Algol types |
| XAS | X-ray active stars; the main components are mCV, non-mCV, and AB |
| SMD | Stellar mass distribution made from the infrared flux |
| SMBH | Supermassive black hole |
| SN | Supernova |
| SNR | Supernova remnant |
| LECR | Low-energy cosmic ray |
| LECRe | Low-energy cosmic ray electrons, typical energy is a few 10 keV |
| LECRp | Low-energy cosmic ray protons, typical energy is a few 10 MeV |
| CIE | Collisional ionization equilibrium |
| IP | Ionizing plasma |
| NEI | Non-equilibrium ionization |
| RP | Recombining plasma |
Subsection 5.3 concerns the other Fe-Kα clumps, which may be unrelated to the flares of Sgr A*. Section 6 summarizes small-sized diffuse X-ray emissions, found mainly with Chandra and XMM-Newton in the central GCXE region (subsection 6.1) and outer GCXE region (subsection 6.2). These are mostly power-law (non-thermal) X-ray filaments of length \( \lesssim \) a few 10'.

Section 7 presents the activity history of Sgr A*. The past activities are suggested by the XRNe, a recombining plasma (RP), and outflows or jet-like structures pointing to Sgr A*, which are described in subsections 7.1, 7.2, and 7.3, respectively.

Section 8 specifies the methodology to the origin of the GDXE, together with a summary of the \( EW_{\text{Fe-K}} \) and \( SH_{\text{Fe-K}} \) of the magnetic cataclysmic variables (mCVs), non-magnetic cataclysmic variables (non-mCVs), or dwarf nova (DN), and coronal active binaries (ABs). The spectral fit of the GCXE, GBXE, and GRXE by a combination of mCVs, non-mCVs, and AB spectra are presented.

Section 9 discusses the origin of the GBXE, GRXE, and GCXE based on the results given in section 8. The origin of the GDXE is separately discussed in subsections 9.1 (GBXE), 9.2 (GRXE), and 9.3 (GCXE).

In the reference papers, the physical parameters, luminosity, plasma size, and other physical parameters have been derived under the assumption of a GC distance of either 8.5 or 8.0 kpc. This review, therefore, unifies the physical parameters assuming the GC distance to be 8.0 kpc. Then, an angular size of 1' and X-ray flux of \( 10^{-12} \text{erg cm}^{-2} \text{s}^{-1} \) correspond to a physical size of 2.33 pc and X-ray luminosity of \( 7.63 \times 10^{33} \text{erg s}^{-1} \), respectively. The cited errors in the reference papers were either 90% or 1σ confidence levels, depending on the physical parameters and/or authors. This paper unifies the error to be 90% confidence level, unless otherwise stated. The metallic abundances of the solar photosphere are those in Anders and Grevesse (1989).

### 2 Early studies of the Galactic diffuse X-ray emission

This section reports the starting point in the studies of the GDXE, the early results of the GRXE (subsection 2.1), GCXE (subsection 2.2), and GBXE (subsection 2.3), using the results taken before the era of Chandra, XMM-Newton, or Suzaku. In these subsections, the contents are not exactly in chronological order, but are organized in a subject-oriented style.

#### 2.1 The Galactic ridge X-ray emission

In this subsection, the history of the GRXE survey is reported. Sub-subsection 2.1.1 considers the point source fraction of the GRXE, while sub-subsection 2.1.2 looks at the GRXE spectrum. The discovery history of non-thermal emissions is given in sub-subsection 2.1.3.

##### 2.1.1 The GRXE and point sources

The global structure of the GRXE was first reported with HEAO-1 by Worrall et al. (1982). It is a diffuse X-ray emission in the 2–10 keV band along the Galactic plane. Due to the large beam size of \( 3' \times 1.5' \) (FWHM), the regions free from contamination of bright XBs were limited to \( l \gtrsim 50' \) (\( \gtrsim 7 \text{kpc from Sgr A*} \)). Nevertheless, the overall profile was estimated to be an exponential function of \( e \)-folding radius \( \sim 3.5 \text{kpc} \), with a half thickness (SH) of \( \sim 240 \text{pc} \). Extrapolating the flux distribution to a radius of \( \lesssim 7 \text{kpc} \), the total luminosity of the GRXE was estimated to be \( \sim 10^{38} \text{erg s}^{-1} \) (2–10 keV). They proposed that the most probable origin of the GRXE is an integrated emission of many unresolved faint discrete sources.

Worrall and Marshall (1983) compared the results of Worrall et al. (1982) to the number density of serendipitous sources in the Galactic plane discovered with the Imaging Proportional Counter (IPC) on board the Einstein Observatory. They concluded that X-ray point sources with a 2–10 keV band luminosity of \( 8 \times 10^{32}–3 \times 10^{34} \text{erg s}^{-1} \) are not dominant contributors to the GRXE. In particular, the contributions of Be/neutron star systems such as X Persei would be minor, because these systems have a 2–10 keV band luminosity of \( \sim 10^{33} \text{erg s}^{-1} \), and have smaller SH than the GRXE. Lower-luminosity stellar systems of \( \lesssim 4 \times 10^{32} \text{erg s}^{-1} \) were likely to be the major contributors to the GRXE. They predicted that coronal ABs and cataclysmic variables (CVs) with a 2–10 keV band luminosity of \( 2 \times 10^{30}–4 \times 10^{32} \text{erg s}^{-1} \) may contribute 43% \( \pm \) 18% of the GRXE.

Hertz and Grindly (1984) found 71 point-like sources with the IPC in the region of Galactic latitude \( |b| \leq 15' \).
In the sample, ~46%, ~31%, and ~23% were coronal emissions from non-degenerate stars, extragalactic sources, and unidentified Galactic sources, respectively. The approximate number density of the Galactic sources was consistent with CVs and other accreting white dwarfs. Faint Galactic plane sources were concentrated toward the Galactic bulge, and had a flatter number–flux relation than at higher Galactic latitude and longitude.

Warwick et al. (1985) observed the inner GRXE with EXOSAT, which had a small beam size of 0.75 × 0.75 (FWHM). The flux distribution (2–6 keV) of the unresolved emissions extended to the inner Galactic plane for longitudes |l| ≲ 40°. They found a very small SH of |b| ≲ 1°. This small SH excluded old population stars as the origin of the GRXE. The overall profile of the GRXE was an exponential shape with e-folding l and b of ~3.5 kpc and ~100 pc, respectively. The total luminosity was ~10^{38} \text{ erg s}^{-1}, consistent with the results of Worrall et al. (1982).

With the Rossi X-ray Timing Explorer (RXTE), Revnivtsev et al. (2006b) created the GRXE profile in the 3–20 keV band along the Galactic plane of |l| ≲ 100°, and perpendicular to the plane of |b| ≲ 6°, at |l| ≲ 4°. The SH at l = 20° was ~130 eV. They found the longitude profiles were similar to the infrared surface brightness distribution. Revnivtsev, Molkov, and Sazonov (2006a) further investigated the RXTE data of the inner Galaxy (|l| ≲ 25°) and the Galactic ridge emission up to |l| ≲ 120°. In order to reduce possible contamination of the GRXE by bright point sources (XBs), they used the Fe-Kα (6.7 keV) line instead of the continuum (3–20 keV) band following the Ginga results of Koyama et al. (1986b) and Koyama (1989)—see subsection 2.1.2. The SH of the Fe-Kα line was similar to that of the continuum band from Revnivtsev et al. (2006b). They found that the surface brightness distributions along the Galactic plane of the Fe-Kα lines were similar to the infrared surface brightness distribution.

Revnivtsev, Molkov, and Sazonov (2006a) and Revnivtsev et al. (2006b) assumed that the infrared distribution represents the Galactic stellar mass distribution (SMD), and then proposed that the origin of the GRXE is discrete stellar sources. The ratio of the X-ray luminosity in the 3–20 keV band to the near-infrared luminosity was L_{3-20\text{keV}}/L_{\text{1.6 \mu m}} \sim 4 \times 10^{-5}, which corresponds to ~3.5 \times 10^{27} \text{ erg s}^{-1} M_\odot^{-1}. This luminosity per stellar mass agreed within an uncertainty of ~50% with that of the solar neighborhood (Sazonov et al. 2006). Then, they suggested that observations with a sensitivity limit of ~10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} (2–10 keV) may resolve ~90% of the GRXE into discrete stellar sources.

Revnivtsev and Molkov (2012) performed deep scans with RXTE across the Galactic plane in the energy band of 4.3–10.5 keV from b = 0° to −30° at l = 18.5. The SH of the GRXE was estimated to be ~110 pc. For the point source origin, they argued that the candidate stars with SH ~260 pc contributed less than ~0.3 of the total cumulative fractional emissivity of point sources in the Galactic plane. The cumulative fractional emissivity of the GRXE in the energy band of 2–10 keV was ~3 \times 10^{32} \text{ erg s}^{-1} M_\odot^{-1}, consistent with Revnivtsev et al. (2006b) in the energy band of 3–20 keV.

One point to note is that the spatial resolution of both the GDXE and SMD were sub arc-degree. Therefore, the comparison of the GDXE distribution to the SMD did not go into the detailed spatial structure of the GDXE, but was limited to the GRXE. The scale heights show large variations from author to author, possibly due to the large and different beam sizes of each, or due to the contribution of the GBXE (subsection 2.2). These prevent assessment of the point source populations, e.g., whether high-mass stars (SH ≤ 100 pc) or low-mass stars (SH ≥ 100 pc).

### 2.1.2 K-shell lines in the GRXE and thermal plasma origin

The Gas Scintillation Proportional Counter (GSPC) on board the Tenma satellite had higher spectral resolution than ordinary proportional counters. With the GSPC, Koyama et al. (1986b) discovered an intense emission line of Fe-Kα at ~6.7 keV. Since the field of view of the GSPC is 3.1 (FWHW), the observed sky, which was free from bright XBs, was limited to eight fields in the Galactic inner disk of 280° < l < 340° (GRXE). The EW_{Fe-K} was in the range of ~500–700 eV. They concluded that the Fe-Kα line was due to an optically thin plasma, because the line center energy of ~6.7 keV was consistent with Fe XXV-HeII. The plasma temperatures were variable from region to region in the range of ~5–10 keV. They claimed that the temperature variations did not favor the origin of many faint point sources. Even from the limited sample of the eight fields, they determined that the intensity distribution in the 2–10 keV band was a disk shape with an SH of ~100–300 pc and radius of ~8 kpc. The total luminosity of the GRXE was estimated to be ~10^{38} \text{ erg s}^{-1}.

Koyama, Ikeuchi, and Tomisaka (1986a) estimated the possible contribution of unidentified SNRs to explain the Fe-Kα line, and argued that if the supernova (SN) rate was ~10 per century, the observed GRXE flux and the value of EW_{Fe-K} would be explained. However, this SN rate was ~3–10 times larger than the canonical value of ~1–3 per century. The allowed region of n_e (cm^{-3}) and t (s), where n_e and t are the electron density and the time after the shock heating, respectively, are ~10^{-3}–4 \times 10^{-1} cm^{-3} and ≤3 \times 10^{11} s. Then, the ionization parameter n_e t is

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2 Soon afterward, this 6.7 keV line was found to be a complex of the Fe I-Kα, Fe XXV-HeII, and Fe XXVI-Lyα lines (subsection 2.2).
\[ \lesssim 10^{12} \text{cm}^{-3} \text{s} \]. Therefore, the candidate sources for the origin of the GRXE were young-intermediate-aged SNRs in ionizing plasma (IP) or in non-equilibrium ionization (NEI). The candidate SNe may occur in a thin ISM so that the surface brightness of the SNRs would be below the resolving capability of the GSPC.

Koyama (1989) re-examined the thermal plasma in the GRXE using more extended GSPC data sets of 27 XB-free fields in the Galactic plane, and analyzed the X-ray spectra. The best-fit temperature and \( EW_{\text{Fe-K}} \) were \( \sim 3-14 \text{keV} \) and \( \sim 0.24-1.5 \text{keV} \), respectively. Thus, this extensive data set from the GSPC provided larger position-dependent variation of temperature and \( EW_{\text{Fe-K}} \) than those of Koyama et al. (1986b), and hence the argument of the point source origin for the GRXE (sub-subsection 2.1.1) became more unlikely.

The Large Area proportional Counter (LAC) on board the Ginga satellite surveyed the Galactic plane in the Fe-K line band with an FWHM beam size of 1.1 x 2.0 (Koyama et al. 1989). Since the \( EW_{\text{Fe-K}} \) of XBs, the brightest point sources in the GRXE region, was only \( \lesssim 50 \text{eV} \) (Hirano et al. 1987), the Fe-K\( \alpha \) line profile was free from possible contamination of bright XBs. This is an advantage of the Fe-K\( \alpha \) line over the continuum X-ray band (e.g., 2-10 keV band) for the study of the global spatial structure of the GRXE. The Fe-K\( \alpha \) line profile along the Galactic plane is shown in figure 1. The total flux of the Fe-K\( \alpha \) line was \( \sim 10^{37} \text{erg s}^{-1} \), about 10% of the 2-10 keV band flux (\( \sim 10^{38} \text{erg s}^{-1} \)).

Yamauchi and Koyama (1993) examined the center energy of the Fe-K\( \alpha \) line and the \( EW_{\text{Fe-K}} \) as a function of the plasma temperature. Since the center energy of the Fe-K\( \alpha \) line and the \( EW_{\text{Fe-K}} \) were systematically lower than those expected from a collisional ionization equilibrium (CIE) plasma of \( \sim 5-10 \text{keV} \) temperature in one solar Fe abundance, they estimated the ionization parameter \((n_{e}t)\) to be \( 10^{10}-10^{11} \text{cm}^{-3} \text{s} \). This is consistent with the scenario of Koyama, Ikeuchi, and Tomisaka (1986a) that the GRXE is the assembly of young-intermediate-aged SNRs, in which the plasma is in IP or NEI. Soon afterward, however, the energy down-shift of the Fe-K line was found to be a mixture of Fe-K\( \alpha \) (6.40 keV), Fe XXV-He\( \alpha \) (6.68 keV), and Fe XXVI-Ly\( \alpha \) (6.97 keV) lines (see the next paragraph), and hence the IP (NEI plasma) interpretation is questionable.

The X-ray CCD detectors on board ASCA had a better energy resolution than any other previous instruments. With ASCA, Yamauchi et al. (1996) and Kaneda et al. (1997) obtained X-ray spectra from the Scutum Arm region at \( l \sim 28.5 \). They resolved the Fe-K\( \alpha \) line into Fe-K\( \alpha \) (6.40 keV), Fe XXV-He\( \alpha \) (6.68 keV), and Fe XXVI-Ly\( \alpha \) (6.97 keV) lines. They also detected the bright Si XVIII-He\( \alpha \) and S XV-He\( \alpha \) lines. Therefore, the GRXE spectra were not single-temperature plasmas, but were well fitted with a two-temperature plasma model, an LTP of \( \sim 0.8 \text{keV} \) temperature for the Si XVIII-He\( \alpha \) and S XV-He\( \alpha \) lines, and an HTP of \( \sim 7 \text{keV} \) temperature for the Fe XXV-He\( \alpha \) and Fe XXVI-Ly\( \alpha \) lines.

Kaneda et al. (1997) reported that the surface brightnesses of the LTP and HTP at \( (l, b) \sim (28.5, 0^\circ) \) were \( \sim 2 \times 10^{-6} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) and \( \sim 5 \times 10^{-7} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) (0.5-10 keV), respectively. The flux of the LTP extended to \( |b| \sim 2^\circ \), larger than the HTP of \( |b| \sim 0.5 \). However, taking into account the differences in the optical depth, they proposed that the real SH of the LTP may be equal to the HTP of \( \sim 70 \text{pc} \). Yamauchi et al. (1996) found position-dependent fluctuations of the surface brightness, and concluded that point sources of luminosity larger than \( \sim 2 \times 10^{33} \text{erg s}^{-1} \) were not the major origin of the GRXE.

### 2.1.3 Non-thermal emission of the GRXE

In the wide-band spectra of the LAC on board Ginga, Yamashita et al. (1996) and Yamasaki et al. (1997) found a hard X-ray tail over the hot plasma components above 10 keV (the non-thermal component) from the Galactic plane in the regions of \( l = -20^\circ-40^\circ \), at \( |b| \lesssim 3^\circ \). This non-thermal flux was smoothly extrapolated to the gamma-ray flux in the Galactic plane.

Valinia and Marshall (1998) made an averaged spectrum from the Galactic plane of \( |l| \lesssim 30^\circ \) using RXTE. The averaged spectrum in the 3-35 keV band was fitted with a model of thermal plasma with \( \sim 2-3 \text{keV} \) temperature and a power-law component of photon index \((\Gamma) \sim 1.8 \). Valinia et al. (2000) re-examined the ASCA data at \( l \sim 28.5 \), and confirmed the presence of the non-thermal emission. They proposed that the origin of the non-thermal emission was either bremsstrahlung by low-energy...
cosmic-ray (LECR) electrons (LECRE), inverse Compton scattering of ambient microwave, infrared, and optical photons by the high-energy electrons associated with the LECRe, non-thermal emission from SNRs, or discrete X-ray sources. In the bremsstrahlung origin, the LECRe produce the Fe-Kα lines at 6.4 keV (subsection 5.1), hence the Fe-Kα line energy becomes lower than 6.7 keV due to the mixture of the Fe-Kα line and the Fe XXV-Heα line in a hot plasma. This energy down-shift is consistent with the result of Yamauchi and Koyama (1995).

Valinia and Marshall (1998) and Valinia et al. (2000) proposed that the continuum shape is the sum of the non-thermal bremsstrahlung and the thermal plasma: the spectrum is a mixture of HTP and bremsstrahlung of LECRe. The best-fit temperature of the HTP by this model was reduced to $\sim 2$–3 keV from the simple model of $\sim 5$–10 keV temperature with no bremsstrahlung component. This relaxes the potential difficulty of the production and gravitational confinement of the HTP. Since the HTP temperature is typical of SNRs, they revisited the idea of Koyama, Ikeuchi, and Tomisaka (1986a) that the origin of the HTP in the Galactic disk would be multiple SNe. The SN rate was estimated to be $(0.8–2.3) \times 10^{−4}$ per century, which is not unreasonably large. This scenario, however, has the serious problem that the $\sim 2$–3 keV temperature of the HTP is too low to produce the strong Fe XXVI-Lyα line detected with ASCA (sub-subsection 2.1.2).

2.2 The Galactic center X-ray emission

X-ray observations of the Galactic center region were started from the Uhuru satellite (Kellogg et al. 1971). The early results in the 1970s were summarized by Proctor, Skinner, and Willmore (1978). After the 1980s, Galactic center observations have been made by many instruments: Einstein (Watson et al. 1981), Spacelab-2 (Kawai et al. 1988), and ROSAT (Predehl & Truemper 1994). These instruments (authors) found a hint of diffuse extended emission near the GC, in addition to many point sources.

As shown in figure 1, Ginga found a bright peak at the GC in the Fe-Kα line distribution along the Galactic plane (Koyama et al. 1989). Yamauchi et al. (1990) made an Fe-Kα line map near the GC, and found that the emission region was an ellipse of $\sim 1.8 \times 1.0$ size around Sgr A*. The EW_{Fe-K} was variable in the range $500–1300$ eV, which would be due to the position-variable EW_{6.4}, later found with ASCA. This was the first concrete result of the presence of a diffuse Galactic center emission, referred to as the Galactic center X-ray emission (GCXE). The surface brightness of the Fe-Kα line in the GCXE was about ten times larger than that of the GRXE (Koyama et al. 1989). The total X-ray luminosity was estimated to be $(0.8–2.3) \times 10^{37}$ erg s$^{-1}$.

The X-ray CCD detectors on board ASCA resolved the Fe-Kα line in the GCXE into Fe-Kα (6.40 keV), Fe XXV-Heα (6.68 keV), and Fe XXVI-Lyα (6.97 keV) lines, and found Si XIII-Heα, Si XIV-Lyα, S XV-Heα, S XVI-Lyα, Ar XVII-Heα, Ar XVIII-Heα, and Ca XIX-Heα lines, as shown in figure 2 (Koyama et al. 1996). The spectra of the GCXE were fitted with a thermal bremsstrahlung of $\sim 10$ keV temperature plus many Gaussian lines. These were similar from position to position except the in the regions of the Sgr A and Sgr B molecular cloud (MC) complexes. The plasma temperature of $\gtrsim 10$ keV was unusually high even for young SNRs. The total luminosity of the GCXE was estimated to be $10^{37}$ erg s$^{-1}$. Together with the uniformity over the GCXE, Koyama et al. (1996) suggested that the GCXE was due to a large-scale diffuse plasma with a very high temperature. In this case, however, the plasma would be very difficult to be confined by the Galactic gravity.

Tanaka et al. (2000) and Tanaka (2002) also examined the ASCA spectrum of the GCXE and those in the Scutum and Sagittarius ($l \sim 10°$) regions (GRXE). They claimed that the Fe XXV-Heα and Fe XXVI-Lyα lines were significantly broadened to $\sim 80$ eV (1 σ), corresponding to a velocity dispersion of a few thousand km s$^{-1}$, higher than the thermal velocity of the $\sim 10$ keV temperature plasma. They argued that the broadening was due to the charge exchange (CX) of low-energy cosmic-ray ions. The low-energy cosmic ray origin was consistent with the presence of a non-thermal component in the GRXE (sub-subsection 2.1.3). They also obtained the EW_{6.4}, EW_{6.7}, and EW_{6.9} to be $110$, $270$, and $150$ eV, respectively. However, these small EW_{6.4},

Fig. 2. ASCA CCD spectrum of the GCXE (from Koyama et al. 1996). In this figure, and also in other early papers, the notations of the Heα and Lyα are confusingly used by Kα, and also for the Kβ lines.
The authors named the FeI-K\ line are scattered by the molecular cloud Sgr B2 and come into an external source located in the Galactic center direction were reproduced well by a scenario whereby X-rays from an energy cutoff below ∼7.1 keV. The X-ray spectrum and the morphology were reproduced well by a scenario whereby X-rays come from nearby compact sources (XBs), which are Thomson scattering by a dense molecular gas. The scattered X-ray flux was expected to be more than 10% of the observed hard X-ray flux from the GCXE. They proposed that the remaining flux was due to the past X-ray flare of Sgr A*.

The ASCA discovery of the FeI-K\ line clump from the Sgr B2 cloud (Koyama et al. 1996) strongly supported the idea of the past X-ray flare of Sgr A*. Murakami et al. (2000) examined the Sgr B2 cloud, and found a very peculiar spectrum, a strong emission line at ∼6.4 keV, a low-energy cutoff below ∼4 keV, and a pronounced edge structure at ∼7.1 keV. The X-ray spectrum and the morphology were reproduced well by a scenario whereby X-rays from an external source located in the Galactic center direction are scattered by the molecular cloud Sgr B2 and come into our line of sight. The authors named the FeI-K\ source at Sgr B2 the X-ray reflection nebula (XRN). The 4–10 keV band luminosity of this XRN was ∼10^{35} erg s^{-1}. Soon afterward, other XRN candidates, FeI-K\ clumps, were found from the Sgr A and Sgr C MC complexes (subsection 5.1), and from other selected regions (subsection 5.2).

### 2.3 The Galactic bulge X-ray emission

In the early studies, Cooke, Griffiths, and Pounds (1969), Protheroe, Wolfendale, and Wdowczyk (1980), Warwick, Pye, and Fabian (1980), and Iwan et al. (1982) found an X-ray emission extending to a high Galactic latitude of SH ≥ 0.5–1.5 kpc. The emission also extended to a large Galactic longitude.

A secure detection of an extended emission near the GCXE with a larger SH than those of the GRXE and GCXE was made with Ginga using the Fe-K\ line distribution. Yamauchi and Koyama (1993) found largely extended Fe-K\ lines ∼5° (∼700 pc) above and below the Galactic plane, in addition to a narrow component of the SH ∼100 pc (GRXE). The longitude extension was estimated to be ∼1.4 kpc from Sgr A*. This diffuse X-ray emission was named the Galactic bulge X-ray emission (GBXE) because of the association with the Galactic bulge region. This is the third component of the GDXE recognized after the GRXE and GCXE.

Using RXTE, Valinia and Marshall (1998) examined the flux distribution in the central l = ±30° of the Galactic plane in more detail, and found two components, thin and broad disks with e-folding scales of ≤ 0.5 and ∼4°, or SHs of ≤ 70 pc and ∼500 pc, respectively. The longitude extension of the later component (SH ∼ 500 pc) was, however, not constrained.

Revnivtsev (2003) observed the area of |b| ∼ 10° around Sgr A* in the 3-10 keV band, and found that the intensity distribution in the |b| > 2° region was well described by an exponential model with an e-folding latitude of ∼3°. The e-folding longitude scale was not determined. The best-fit spectral parameters of the larger SH component (GBXE) were not significantly different from those of the smaller SH component (GRXE).

Revnivtsev et al. (2006b) examined the longitude and latitude profiles at 3.0 < |b| < 3.5 and 1° < |l| < 4°. The e-folding latitude was ∼2–3°, while the e-folding longitude was ∼8°. Thus, they confirmed the two components proposed by Yamauchi and Koyama (1993), the bulge/bar (GBXE) and the Galactic disk (GRXE). The GBXE extends more largely than the GRXE above and below the plane, with a total luminosity of ∼4 × 10^{37} erg s^{-1}. Revnivtsev, Molkov, and Sazonov (2006a) further examined the two-dimensional distribution in the Fe-Kα line for the central 15° × 15° region around Sgr A* (sub-subsection 2.1.4). They found that the linear correlations between the near-infrared and the surface brightness of the Fe-Kα line were similar between the disk and bulge. Therefore, they proposed that the populations of the unresolved X-ray point sources in the disk (GRXE) and the bulge (GBXE) were not different from each other. Revnivtsev and Molkov (2012) also found two components of SH, ∼ 110 pc and ∼260 pc, at the Galactic latitude of −5° < b < 0° at |l| = 18.5.

In summary, Ginga and RXTE discovered the new component GBXE, which has a larger SH than the GRXE. With RXTE, Revnivtsev (2003), Revnivtsev, Molkov, and Sazonov (2006a), and Revnivtsev et al. (2006b) suggested no difference in the spectra and point source compositions between GRXE and GBXE. However, the limited spectral resolutions prevented a reliable study of whether or not the spectrum of the GBXE is different from that of GRXE. Also, the limited spatial resolution prevented them obtaining a reliable SH of the GBXE (sub-subsection 2.1.1). These issues were solved later with Suzaku (section 3).

### 3 Global structure of the GDXE

This section gives an overview of the GDXE and the recent results of Chandra, XMM-Newton, Suzaku, and partly NuSTAR. From the spatial distributions of the Fe-Kα, S XV-Heα, and S XVI-Lyα lines, the GDXE is clearly decomposed into three separate components: GCXE, GBXE, and GRXE.
(subsection 3.1). The X-ray luminosity and spectra of these components are given in subsection 3.2. The spectral differences between GCXE, GBXE, and GRXE verify the decomposition of the GDXE. The detailed structure of the central region of the GCXE is discussed in subsection 3.3.

### 3.1 Decomposition of the GDXE into GCXE, GBXE, and GRXE

As described in subsections 2.1, 2.2, and 2.3, the GCXE and GBXE had been separated from the GDXE. However, a clear separation in both spatial and the spectral profiles had to await the Suzaku satellite. Uchiyama et al. (2013) made Suzaku surveys around the Galactic center regions of $|b| \leq 0.5$, $|l| \leq 1^\circ$, and additional regions of larger $|b|$ and $|l|$ in the Galactic plane. Since the position of the Galactic center, Sgr A*, is at $(l, b) = (-0.056, -0.046)$, new parameters of the Galactic coordinates $(l_1, b_1)$ are defined hereafter, shifting $l$ and $b$ by $-0.056$ and $-0.046$, respectively.

They divided the surveyed regions into many rectangles of $\Delta l = 0.1$, $\Delta b = 0.2$, and analyzed the X-ray spectra from each rectangle. These spectra were fitted with a power-law continuum plus many Gaussian lines to represent the $K_\alpha$, He$\alpha$, and Ly$\alpha$ lines of S, Ar, Ca, and Fe. The best-fit Fe-K$\alpha$ (Fe I-K$\alpha$, Fe XXV-He$\alpha$, and Fe XXVI-Ly$\alpha$) fluxes in the positive $l$, region near Sgr A* were larger than those in the negative $l$, region (Uchiyama et al. 2013). This asymmetry is mainly due to the bright SNR Sgr A East, the Arches cluster, and XRNe (see subsection 4.1 and section 5). Therefore, the line and continuum band distributions of the GDXE are made by excluding these bright local spots. The profiles are shown by the black circles in figure 3.

Figure 3 shows that the Galactic longitude and latitude distributions of the Fe-K$\alpha$, S XV-He$\alpha$, and S XVI-Ly$\alpha$ line fluxes had two exponential components: small-sized ($|l_1| \leq 1^\circ-2^\circ$), and largely extended ($|l_1| \geq 2^\circ-3^\circ$) emissions. Therefore, Uchiyama et al. (2013) fitted the flux distributions with a phenomenological formula,

$$A_1 \exp(-|l_1|/l_1) \exp(-|b_1|/b_1) + A_2 \exp(-|l_2|/l_2) \exp(-|b_2|/b_2).$$

where the unit of flux is photons s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$. The best-fit curves of the Fe-K$\alpha$, S XV-He$\alpha$, and S XVI-Ly$\alpha$ lines are given by the dotted lines in figure 3, while the best-fit parameters of these lines and those of the 2.3–5 keV and 5–8 keV band fluxes are listed in table 2. The best-fit $e$-folding longitudes ($l_1$ and $l_2$) clearly indicate that the GDXE has two components: small-sized ($|l_1| \lesssim 1^\circ$) and larger-sized ($|l_1| \geq 2^\circ-3^\circ$) emissions. These are the GCXE and GRXE, respectively.

As noted in subsection 2.3, another component, the GBXE, has been found near the GCXE. The SH of the GBXE is larger than those of the GCXE and GRXE. Therefore, the $e$-folding latitudes of the GCXE and GRXE ($b_1$ and $b_2$) in equation (1) would be contaminated by that of the GBXE, while the $e$-folding longitudes ($l_1$ and $l_2$) are not significantly affected by the GBXE. Therefore, only the parameters of $l_1$ and $l_2$ are listed in table 2; $b_1$ and $b_2$ were excluded from the original table given by Uchiyama et al. (2013).
The coexistence of the Fe XXV-Heα, Fe XXVI-Lyα, S XVI-Heα, and Fe I-Kα lines clearly indicates that the GDXE is composed of three components: HTP (for the Fe XXV-Heα and Fe XXVI-Lyα lines), LTP (for the S XVI-Heα and S XVI-Lyα lines), and CG (for the Fe I-Kα line). The profiles of figure 3 (upper panels) show that the flux ratio of Fe XXVI-Lyα/Fe XXV-Heα in the GCXE (|l| ≤ 1°) is larger than that of the GRXE (|l| ≥ 1°). An opposite trend is found in the flux ratio of S XVI-Lyα/S XVI-Heα (figure 3, lower panels). The intensity profiles of the GCXE and GRXE regions in the other key elements, Ar and Ca, are approximately in between those of S and Fe.

The temperatures of the LTP and HTP are estimated by the intensity ratios of S XVI-Lyα/S XVI-Heα and Fe XXVI-Lyα/Fe XXV-Heα, respectively. Then, the temperature of the LTP in the GCXE is lower than the GRXE, while that of the HTP in the GCXE is higher than the GRXE (see subsection 3.2). Thus, the flux distributions of the Fe XXV-Heα, Fe XXVI-Lyα, S XVI-Heα, and S XVI-Lyα lines in the GCXE and GRXE given in figure 3 (upper and lower panels) clearly demonstrate that the global spectra of the GCXE and GRXE are different from each other.

Yamauchi et al. (2016) separately estimated the e-folding latitudes (b1 and b2) using all the Suzaku archive data along and near the Galactic inner disk (|b| ≤ 3°, |l| ≤ 30°). To increase the statistics, the data were grouped according to position: (a) |l| ≤ 0.5°, (b) l = 358.5°, (c) l = 330°–350°, and (d) l = 10°–30°. Position (a) included mainly the GCXE and some fractions of the GBXE, while the main component in position (b) was the GBXE with small fractions of the GCXE. The data in positions (c) and (d) were from the GRXE.

The intensity profile perpendicular to the Galactic plane in the 5–8 keV band and Fe-Kα line fluxes were created for the regions (a)–(d). The profiles near positions (a) and (b) showed a two-component shape. As examples, the Fe-Kα line profiles for region (a) are shown in figure 4. In order to make clear the two-component structure, the profiles in regions (a) and (b) were simultaneously fitted with a two-exponential model of

\[ A_1 \exp(-|b|/b_1) + A_2 \exp(-|b|/b_2). \]

where the subscripts 1 and 2 represented the GCXE and GBXE, respectively. The free parameters of the respective normalizations (A1 and A2) and e-folding latitudes (b1 and b2) for the GCXE and GBXE were linked in the (a) and (b) regions. The best-fit profiles of the Fe-Kα lines at position (a) are shown by the two solid lines in figure 4.
Table 3. Parameters of e-folding latitude of the GCXE, GBXE, and GRXE (after Yamauchi et al. 2016). *

| Region | Component | Norm(A) | e-folding (b₁, b₂) |
|--------|-----------|---------|-------------------|
|        |           |         | (°)               |
|        |           |         |                   |
| GCXE   | Fe I-Kα   | 4.1 ± 0.2 | 0.22 ± 0.02       |
|        | Fe XXV-Heα| 11.9 ± 0.6 | 0.26 ± 0.02       |
|        | Fe XXVI-Lyα| 4.9 ± 0.2 | 0.24 ± 0.02       |
|        | 5–8 keV   | 77 ± 4   | 0.25 ± 0.02       |
| GBXE   | Fe I-Kα   | 0.31 ± 0.15 | 1.15 ± 0.36       |
|        | Fe XXV-Heα| 1.14 ± 0.34 | 2.25 ± 0.68       |
|        | Fe XXVI-Lyα| 0.40 ± 0.12 | 2.13 ± 0.66       |
|        | 5–8 keV   | 12 ± 2   | 1.96 ± 0.25       |
| GRXE§  | Fe I-Kα   | 0.26 ± 0.03 | 0.50 ± 0.12       |
|        | Fe XXV-Heα| 0.65 ± 0.02 | 1.02 ± 0.12       |
|        | Fe XXVI-Lyα| 0.09 ± 0.02 | 0.71 ± 0.29       |
|        | 5–8 keV   | 5.4 ± 0.4 | 1.04 ± 0.20       |

* Errors are 1σ confidence levels.
† In units of 10⁻⁷ photons s⁻¹ cm⁻² arcmin⁻².
‡ The parameter b₁ is the e-folding latitude of the GCXE, while b₂ is that of the GBXE or GRXE.
§ Average of the l = 10°−30° and l = 330°−350°.

Table 4. Properties of the GCXE, GBXE, and GRXE. *

| Component | Norm (A) | e-folding | Luminosity |
|-----------|---------|-----------|------------|
|           |         | (°)       | (erg s⁻¹)  |
| GCXE      | Fe I-Kα | 4.1       | 0.62       | 0.22       | 1.5 × 10⁴⁴ |
|           | Fe XXV-Heα | 12 | 0.63 | 0.26 | 5.8 × 10⁴⁴ |
|           | 5–8 keV | 77 | 0.72 | 0.25 | 3.9 × 10⁵⁵ |
| GBXE      | Fe I-Kα | 0.31 | —       | 1.15       | —          |
|           | Fe XXV-Heα | 1.1 | 10 | 2.25 | 7.5 × 10⁵⁵ |
|           | 5–8 keV | 12 | 8 | 1.96 | 5.3 × 10⁵⁶ |
| GRXE      | Fe I-Kα | 0.36 | 57 | 0.50 | 2.9 × 10⁵⁵ |
|           | Fe XXV-Heα | 1.0 | 45 | 1.02 | 1.4 × 10⁵⁶ |
|           | 5–8 keV | 7.9 | 52 | 1.04 | 1.2 × 10⁵⁷ |

* The normalizations (A) of the GCXE and GBXE are taken from Yamauchi et al. (2016) (table 3), while those of the GRXE are converted to the GC position using the e-folding (l) of Uchiyama et al. (2013) (table 2). The e-folding scales (b) are taken from Yamauchi et al. (2016) (table 3). The values of e-folding longitude (l) for the GCXE and GRXE are taken from Uchiyama et al. (2013) (table 2), while those for the GBXE are from Yamauchi and Koyama (1993) and Revnivtsev et al. (2006b). Errors are 1σ confidence levels.
† In units of 10⁻⁷ photons s⁻¹ cm⁻² arcmin⁻².

On the other hand, the profiles of regions (c) and (d) showed a one-exponential shape, and hence were fitted with the one-exponential model of

$$A \exp(-|b_1|/b_2),$$  (3)

where the e-folding latitudes (b₂) in the (c) and (d) regions were linked. The best-fit e-folding latitude of b₁ and b₂ for the Fe-Kα and the 5–8 keV band fluxes in the GCXE, GBXE, and GRXE are listed in table 3.
from the regions of GCXE, GRXE, and GBXE in the 5–10 keV band and the FeI-K line, which are associated with the highly ionized atomic lines. The spectrum of the GCXE was fitted with a two-CIE and one power-law model, from the GBXE is ignored. The spectrum of the GCXE is far brighter, and hence contamination from the GRXE. However, the regions of the GRXE were limited (2013) produced the whole spectra of the GCXE and would be contaminated by the GBXE. On the other hand, the regions of the GCXE, GBXE, and GRXE refer to those from et al. 2009; Heard & Warwick 2013a). Uchiyama et al. (2009) and GRXE—

| Line† | CE‡ | Flux§ | EW | Flux§ | EW | Flux§ | EW |
|-------|-----|-------|----|-------|----|-------|----|
| FeI-α | 6400 | 3.54 ± 0.04 | 175 ± 2 | 0.14 ± 0.02 | 84 ± 10 | 0.16 ± 0.01 | 118 ± 9 |
| Fe XXV-Heα | 6680 | 9.40 ± 0.05 | 500 ± 3 | 0.70 ± 0.02 | 463 ± 13 | 0.60 ± 0.02 | 487 ± 13 |
| Fe XXVI-Lyα | 6966 | 3.45 ± 0.04 | 198 ± 2 | 0.24 ± 0.02 | 173 ± 13 | 0.10 ± 0.01 | 96 ± 11 |
| FeI-β | 7059 | 0.44† | 26 | 0.01∥ | 14 | 0.02∥ | 19 |

χ²/d.o.f. 331/265 117/84 107/72

*Errors are 1σ confidence levels.
†Absorption depth at 7.11 keV.
‡In units of 10⁻²⁷ photon cm⁻² s⁻¹ arcmin⁻².
§Fixed to 0.125 x FeI-α.

from the e-folding longitude (l₁) in table 2. The regions and luminosities of the Fe XXV-Heα and FeI-α lines and those of the 5–8 keV band in the GCXE, GBXE, and GRXE determined in this way are summarized in table 4. Hearafter, the regions of the GCXE, GBXE, and GRXE refer to those from table 4. Studies of the GCXE, GBXE, and GRXE spectra are given in the next section (subsection 3.2).

3.2 X-ray spectra and luminosity of the GCXE, GBXE, and GRXE

Suzaku spectra in selected regions of the GCXE and GRXE have been made by several authors (Koyama et al. 2007b; Ebisawa et al. 2008; Yuasa et al. 2008; Yamauchi et al. 2009; Heard & Warwick 2013a). Uchiyama et al. (2013) produced the whole spectra of the GCXE and GRXE. However, the regions of the GRXE were limited and would be contaminated by the GBXE. On the other hand, the GCXE is far brighter, and hence contamination from the GBXE is ignored. The spectrum of the GCXE was fitted with a two-CIE and one power-law model, which are associated with the highly ionized atomic lines and the FeI-α line, respectively. The best-fit temperatures were ~0.95 keV and ~7.5 keV with an iron abundance of ~1.25 solar, while the best-fit photon index and EW of the GCXE, GBXE, and GRXE determined by the line flux ratio of Fe XXVI-Lyα/Fe XXV-Heα were ~0.37, ~0.34, and ~0.17, which correspond to CIE temperatures of ~6.8 keV, ~6.5 keV, and ~5.0 keV, respectively. Thus the plasma temperatures of the GCXE, GBXE, and GRXE determined by the line flux ratio of Fe XXVI-Lyα/Fe XXV-Heα were not largely different from each other. However, the continuum shape (bremsstrahlung) of the GCXE gave a temperature of ~15 keV, which is significantly higher than that of the GBXE and GRXE, ~5 keV (table 5). The reason for this apparent inconsistency in the temperatures is found in the different flux ratio of FeI-α/Fe XXV-Heα. The flux ratio FeI-α/Fe XXV-Heα in the GCXE was ~0.38, which is significantly larger than those for the GBXE and GRXE—~0.20 and ~0.27, respectively. This indicates that the hard X-rays of the power-law spectrum of the CG occupy a larger fraction of the GCXE, and hence give an apparently higher bremsstrahlung temperature than those of the GBXE and GRXE.
Using the parameters of the GCXE, GBXE, and GRXE regions in tables 4 and 5, the total X-ray fluxes of the GCXE, GBXE, and GRXE in the 5–8 keV band were estimated; these are also given in table 4. The 5–8 keV band luminosities of \( \sim 3.9 \times 10^{35} \text{ erg s}^{-1} \), \( \sim 5.3 \times 10^{36} \text{ erg s}^{-1} \), and \( \sim 1.2 \times 10^{37} \text{ erg s}^{-1} \) were converted to the 2–10 keV band luminosities of \( \sim 1.2 \times 10^{36} \text{ erg s}^{-1} \), \( \sim 1.6 \times 10^{37} \text{ erg s}^{-1} \), and \( \sim 3.8 \times 10^{37} \text{ erg s}^{-1} \) for the GCXE, GBXE, and GRXE. These values were smaller than the previous reports, due to the smaller e-folding longitude and latitude scales of the GCXE, GBXE, and GRXE. However, the quality of the spectra table 5 is the best; in particular, mutual mixing of the GCXE, GBXE, and GRXE spectra is minimized.

### 3.3 Iron K-shell line property of the central region of the GCXE

Koyama et al. (2007b) studied the hard X-ray spectrum in the 5–10 keV band of the central GCXE region of \( |l| < 0.3 \) and \( |b| < 0.15 \). They produced the X-ray spectrum excluding the Sgr A East SNR (sub-subsection 4.1.1), but including the bright XRNe at the northeast of Sgr A* (sub-subsection 5.2.2). This spectrum was fitted with the same model as subsection 3.2, a phenomenological model of a bremsstrahlung continuum plus many Gaussian lines. The best-fit spectrum and parameters are shown in figure 5 and table 6, respectively.

The Fe XXV-Heβ line is a blend of resonance, intercombination, and forbidden lines. The mixing ratios of...
The flux ratio of Fe XXV-He line and forbidden lines in the normal CIE plasma of temperature was more clumpy than the FeXXV-He line, showing the correlation function, which is related to the excited process of Fe XXV-He line (FeXXV-Lyα/FeXXV-Heα and Fe XXV-Heβ/Fe XXV-Heα) favoring a CIE plasma of ~6–7 keV.

The flux ratio of Fe XXVI-Lyα/Fe XXV-Heα was ~0.33, corresponding to an ionization temperature of ~6–7 keV. The flux ratio of Fe XXV-Heβ/Fe XXV-Heα ~0.1, giving an electron temperature of ~6–7 keV. Thus, the center energy and width of the Fe XXV-Heα line, and the flux ratios of the Fe XXVI-Lyα and Fe XXV-Heβ lines relative to the Fe XXV-Heα line (FeXXV-Lyα/FeXXV-Heα and Fe XXV-Heβ/Fe XXV-Heα) favored a CIE plasma of ~6–7 keV temperature for the HTP.

Then, Koyama et al. (2007b) fitted the GCXE spectrum with a model of CIE plasma, and found that the temperature and iron abundance were consistent with those of Uchiyama et al. (2013) and Nobukawa et al. (2016) in the whole GCXE area of |l| < 0.6 and |b| < 0.25 (see subsections 3.1 and 3.2). This indicates that the HTP spectrum in the central GCXE region of |l| < 0.3 and |b| < 0.15 was nearly the same as the whole GCXE: no significant variation of the HTP was found over the whole GCXE region.

Koyama et al. (2009) found a correlation between the EW_{6.7} and the EW_{6.4} taken from small areas of 4.5 × 4.5. The correlation plots are shown in figure 6. The solid line shows the correlation function, which is EW_{6.4} + 2 × EW_{6.7} = 1.2 keV.

The scattered correlation plots indicate that the mixing ratios of the HTP (Fe XXV-Heα) and CG (Fe I-Kα) were different from position to position. In the extreme case, where the EW_{6.7} was 0 keV (HTP = 0), the EW_{6.4} was ~1.2 keV, or the CG had an EW_{6.4} of ~1.2 keV. This large EW_{6.4} favored that the origin of the Fe I-Kα line was due to the irradiation of MCs by external X-ray sources or low-energy cosmic-ray protons (LECRPs; see section 5).

EW_{6.7} was ~0.6 keV at EW_{6.4} = 0 keV (CG = 0). This value was consistent with Koyama et al. (2007b) stating that the HTP has a CIE spectrum with a temperature of ~6–7 keV and abundances nearly of one solar.

Figure 6 shows that the scatter of the EW_{6.4} was larger than that of the EW_{6.7}, which means that the Fe I-Kα flux (CG) was more clumpy than the Fe XXV-Heα flux (HTP). The EW_{6.4} and EW_{6.7} of the west region of Sgr A* (GC west), where is free from the bright Fe I-Kα and Fe XXV-Heα spots, are given by the filled circles in figure 6. The EW_{6.4} and EW_{6.7} were concentrated in the small parameter space of EW_{6.4} ~150 eV and EW_{6.4} ~180 eV, which were consistent with those of the whole GCXE (table 5), but were significantly larger than the ASCA results of Tanaka (2002). Since Suzaku had a larger correcting area and better spectral resolution, the results of Suzaku should be more reliable than those of ASCA.

The large and scattered EW_{6.4} of the GC east (open circles in figure 6) are due to the XRNe (open squares) and/or the Fe I-Kα line contamination of the surrounding XRNe. The XRNe are associated with non-thermal power-law emissions (sub-subsection 5.2.2). Yuasa et al. (2008) discovered a power-law emission from the GCXE with a photon index of ~2. Most would be due to the XRNe, because Mori et al. (2015) found hard X-ray excesses in the 10–20 keV band with NuSATR at the positions of the XRNe in the Sgr A complex, MC1, MC2, Bridge, and G0.11–0.11, and in another Fe I-Kα source, the Arches cluster (see tables 9 and 11). The photon indices of MC1 and Bridge were ~2.2 and ~1.8, respectively, similar to the power-law emission of Yuasa et al. (2008).

In the close vicinity of Sgr A* (4′–13′ from Sgr A*), using XMM-Newton, Heard and Warwick (2013a) found that the EW_{6.4}, EW_{6.7}, and EW_{6.97} were ~220 eV, ~730 eV, and ~320 eV, respectively, which were 1.3–1.5 times larger than those of the whole GCXE region (Nobukawa et al. 2016). The larger EW_{6.4} would be due to a lower continuum flux than Nobukawa et al. (2016); Heard and Warwick (2013a) assumed a 7.5 keV plasma for the continuum...
flux, while Nobukawa et al. (2016) included a power-law component associated with the Fe I-Kα line, with a best-fit bremsstrahlung temperature of \( \sim 15 \) keV, significantly higher than 7.5 keV.

Uchiyama et al. (2013) more explicitly fitted the GCXE spectra with a model of 7.3 keV plasma and any power-law component of the same flux as Uchiyama et al. (2013), not including a power-law component. Adding a power-law component associated with the Fe I-Kα line revised the Fe abundance to be \( \sim 0.81 \) keV and \( \sim 7.7 \) keV. The best-fit Fe abundance was \( \sim 0.7 \) solar. However, their model did not include a power-law component. Adding a power-law component of the same flux as Uchiyama et al. (2013), the Fe abundance was revised to be \( \sim 1.1 \) solar, in agreement with Uchiyama et al. (2013).

Muno et al. (2004a) produced the Chandra X-ray spectrum in the region of \(<9^\circ\) from Sgr A*. They fitted the spectrum with a two-CIE model, and found that the best-fit temperatures were \( \sim 0.81 \) keV and \( \sim 7.7 \) keV. The best-fit Fe abundance was \( \sim 0.7 \) solar. However, their model did not include a power-law component. Adding a power-law component of the same flux as Uchiyama et al. (2013), the Fe abundance was revised to be \( \sim 1.1 \) solar, in agreement with Uchiyama et al. (2013).

In the 3.5–5\(^{\circ}\) ring around Sgr A*, H. Uchiyama et al. (2017 private communication) analyzed the Suzaku spectrum. In order to take into account the over-flow flux from the bright SNR Sgr A East, they did a simultaneous fit for the GCXE and Sgr A East. The best-fits \( EW_{6.6} \), \( EW_{6.7} \), and \( EW_{6.97} \) in the GCXE were \( \sim 160 \) eV, \( \sim 520 \) eV, and \( \sim 190 \) eV, respectively, in good agreement with Nobukawa et al. (2016) for the whole GCXE spectrum (table 5).

In summary, in spite of the significant enhancement of the GCXE fluxes near Sgr A* (subsection 9.3), the \( EW_{6.7} \) and \( EW_{6.97} \) are nearly the same in all the GCXE regions. The \( EW_{6.6} \) is highly variable from position to position in the GCXE.

4 Local diffuse hot plasma

This section reviews local hot plasmas in the hard X-ray band, or Fe XXV-He\( \alpha \)-emitting plasmas (subsection 4.1), and those in the soft X-ray band, or Si XV-He\( \alpha \)-emitting plasmas (subsection 4.2). The relevant region is \(|l| \lesssim 1^\circ\) and \(|b| \lesssim 0.5^\circ\), which includes the full GCXE region (subsection 3.1).

4.1 Hot plasmas with the Fe XXV-He\( \alpha \) line (HTP)

This section reports on individual local hot plasmas with the Fe XXV-He\( \alpha \) line. The 2–10 keV band luminosity of Sgr A East is \( \sim 10^{35} \) erg s\(^{-1}\) and \( \lesssim 10\% \) of the GCXE, while that of the sum of the other hot diffuse sources with the Fe XXV-He\( \alpha \) line is \( \lesssim 6 \times 10^{34} \) erg s\(^{-1}\) (2–10 keV), only \( \lesssim 5\% \) of the GCXE luminosity.

4.1.1 Sgr A East, the brightest SNR in the GCXE region

Sgr A East is a non-thermal radio shell with a size of 3.6–2.7 \((\text{Ekers et al. 1983})\). Within 20 pc \((\sim 10^\circ)\) of Sgr A*, Sgr A East is a unique object surely identified as a young SNR. Roberts, Romani, and Kawai (2001) found diffuse hard X-ray emissions from the position of Sgr A East with ASCA. Then, Sakano et al. (2002) detected K-shell lines from highly ionized Si, S, Ar, Ca, and Fe, and established that Sgr A East has a thermal plasma.

Sakano et al. (2004) produced XMM-Newton spectra for three annular regions of Sgr A East, of radius \( r < 28^\circ\) (Center), \( 28^\circ < r < 60^\circ\) (Middle), and \( r > 60^\circ\) (Outer). The spectra were fitted with two thermal plasmas with temperatures of \( \sim 0.9 \) keV and \( \sim 3 \) keV (Center), \( \sim 1 \) keV and \( \sim 5.5 \) keV (Middle), and \( \sim 0.9 \) keV and \( \sim 4.4 \) keV (Outer). The highly ionized Fe-rich ejecta showed a significant concentration toward the center: the Fe abundances were \( \sim 4 \) solar, \( \sim 1.5 \) solar, and \( \sim 0.5 \) solar in the Center, Middle, and Outer, respectively. The other elements, S, Ar, and Ca, were roughly uniformly distributed in the range of \( \sim 1–3 \) solar. The authors inferred that Sgr A East is a young SNR either of Type Ia (Ia-SNR) or a core-collapsed SNR (CC-SNR) of a relatively low-mass progenitor star.

With Chandra, Maeda et al. (2002) found a diffuse plasma of \( \sim 2 \) keV temperature and abundances of \( \sim 4 \) solar inside the radio shell. They proposed that Sgr A East is a CC-SNR with a progenitor star mass of \( \sim 13–20 \) M\( _{\odot} \), and that Sgr A East is a member of the young mixed-morphology group (MM-SNR; Rho & Petre 1998). Park et al. (2005) confirmed the center-filled X-ray structure. They made X-ray spectra from the three regions, named Center, North, and Plume. The spectra were fitted with two thermal plasmas of \( \sim 1 \) keV and \( \sim 5 \) keV in the Center, but in the North the temperatures were \( \sim 1 \) keV and \( \sim 11 \) keV. The Fe abundance showed a clear concentration toward the SNR center, from \( \sim 1 \) solar (Plume) and \( \sim 2.5 \) solar (North) to \( \sim 6 \) solar (Center). The iron mass of Sgr A East was estimated to be \( \lesssim 0.27 \) M\( _{\odot} \). The abundances of lighter elements, S, Ar, and Ca, were roughly 1 solar, but were higher in the Plume and North than in the Center. Therefore, the plasma in the North and Plume would be shock-heated ISM.

Park et al. (2005) found a hard point-like source, CXO/GC J174545.5–285829 (Cannonball), at the northern edge of the SNR. It had a power-law spectrum of index \( \sim 1.6 \), which is typical of the non-thermal synchrotron emission from an NS magnetosphere. The absorption \( (N_H)\) was \( \sim 17 \times 10^{22} \) cm\(^{-2}\), similar to that of Sgr A East of \((13–19) \times 10^{22} \) cm\(^{-2}\), and hence Cannonball was associated with the Sgr A East SNR at the same distance. Then, the X-ray luminosity was estimated to
be $\sim 3 \times 10^{33} \text{erg s}^{-1}$ (2–10 keV), which is typical of a pulsar and/or pulsar wind nebula (PWN). From these facts, the authors suggested that Sgr A East is a CC-SNR, and Cannonball is a high-velocity NS born in the CC-SN.

Koyama et al. (2007c) obtained a high-quality X-ray spectrum of Sgr A East with Suzaku (figure 7). They discovered many K-shell emission lines from highly ionized atoms: $\text{S XV-He}\alpha$, $\text{S XVI-Ly}\alpha$, $\text{S XVII-He}\alpha$, $\text{Ar XVII-Ly}\alpha$, $\text{Ar XVIII-Ly}\alpha$, $\text{Ca XIX-He}\alpha$, $\text{Fe XXV-He}\alpha$, $\text{Fe XXVI-Ly}\alpha$, $\text{Ni XXVII-He}\alpha$, and $\text{Fe XXV-He}\gamma + \text{Fe XXVI-Ly}\beta$. The flux ratios of these lines indicated that Sgr A East has at least two thermal plasmas. With a two-temperature CIE model fit, the plasma temperatures were found to be $\sim 1.2$ keV and $\sim 6.0$ keV, the mean abundance of Fe was $\sim 2.6$ solar, while the other elements were $\sim 1$ solar. The total and iron masses were $\sim 27 M_\odot$ and $\sim 0.15 M_\odot$, respectively, consistent with a CC-SN origin. As shown in figure 7 (lower panel), a hint of the Mn $\text{XxIV-He}\alpha$ line was found at 6.1 keV, but no hint of the Cr $\text{XXIII-He}\alpha$ line at 5.6 keV was found in spite of a larger solar abundance than Mn.

In addition to the two CIE plasmas, a non-thermal component was found, which occupied the major fraction above $\sim 7$ keV (see figure 7). Perez et al. (2015) and Morii et al. (2015) found strong hard X-rays in the 10–40 keV band with NuSTAR from regions including some fractions of Sgr A East. The flux at the Fe $\text{XXV-He}\alpha$ lines was nearly comparable to the thermal emissions, which roughly agreed with the power-law component of Koyama et al. (2007c). Perez et al. (2015) proposed that the origin of the power-law component is many faint mCVs in the region of Sgr A East. In this case, a significant $\text{Fe I-K}\alpha$ line flux should be observed, because mCVs are strong $\text{Fe I-K}\alpha$ emitters (table 14).

Another possibility for the power-law component was an assembly of the non-thermal filaments listed in table 12 (Muno et al. 2008) plus unresolved non-thermal sources. These would be due to synchrotron emissions by HECRe accelerated by a shock wave of Sgr A East. The LECRe and possibly LECRp may ionize the Fe $\text{XXV}$ to higher ions of Fe $\text{XXVI}$, and hence may emit extra Fe $\text{XXVI-Ly}\alpha$ lines. This may lead to a large flux ratio of Fe $\text{XXVI-Ly}\alpha$/Fe $\text{XXV-He}\alpha$ of $\sim 0.05$, corresponding to a plasma temperature of $\sim 4–6$ keV, an unusually high SNR among known SNRs. The center energy of the Fe $\text{XXV-He}\alpha$ at $\sim 6.65$ keV was also among the highest normal CC-SNRs.

H. Uchiyama et al. (2017 private communication) reanalyzed the Suzaku spectrum of Sgr A East by simultaneous fitting with the GCXE spectrum of nearby sky (see subsection 3.3). They found a hint of recombining plasma (RP) in Sgr A East. These very high-temperature plasmas of $\sim 4–6$ keV, RP, and a strong power-law component are unusual even in normal CC-SNRs, where the presence of circumstellar matter (or MC), a possible origin for making an RP, is more likely than Type Ia SNRs. These unusual structures would be related to extreme environments at the Galactic center (GC) region.

Sgr A East is an SNR of $\sim 10^3$ yr, and is located in the close vicinity of Sgr A*. Maeda et al. (2002) predicted that the dust/molecular ridge was compressed by the forward shock of the SN Sgr A East. When the blast wave passed over the black hole Sgr A*, the compressed dense dust and gas had accreted onto Sgr A*, and produced X-ray flares around a few 100 yr ago (subsection 5.2).

Totani (2006) proposed another idea, that the mean accretion rate onto Sgr A* during the past $\sim 10^7$ yr had been much higher than the current rate. The accretion energy in the past was sufficient to produce and keep the HTP gas in the GCXE. Also, a significant amount of positrons should have been created, which might produce the observed $511$ keV annihilation line from the Galactic bulge. After the passage of the blast wave of the SN Sgr A East of around a few 100 years ago, the ambient gas had been cleaned up, leading Sgr A* to the present quiet level (subsection 7.1).

Sgr A East is one of the brightest Fe $\text{XXV-He}\alpha$ sources in the GCXE region. The 2–10 keV band luminosity is $\sim 10^{35}$ erg s$^{-1}$ (Maeda et al. 2002; Sakano et al. 2004; Koyama et al. 2007c), which is only $\sim 8$% of the GCXE.

### 4.1.2 G0.61+0.01
Although the Fe $\text{XXV-He}\alpha$ line is smoothly distributed over the Sgr B region, Koyama et al. (2007a) found a local excess of $\sim 5' \times 2.4$ size with Suzaku (see figure 8, left). The position of the center was $(l, b) = (0.61, 0.01)$, and it was named Suzaku J1747.0–2824.5 (G0.61+0.01). The deep
XMM-Newton image shows a hint of very weak enhancement near this position in the low-energy band of 2–4.5 keV (Ponti et al. 2015). This source was therefore very peculiar, dominant mainly in the Fe XXV-Heα line (see figure 8, right).

The X-ray spectrum was fitted with an IP (NEI) plasma model (Koyama et al. 2007a). The best-fit plasma temperature, ionization time scale, and iron abundance were $\sim 3$ keV, $n_t \sim 2 \times 10^{11}$ cm$^{-3}$, and $5.1^{+1.2}_{-1.1}$ solar, respectively. Then the dynamical age and ionization age were estimated to be $\sim 4 \times 10^3$ yr and $\sim 7 \times 10^2$ yr, respectively. From these results, G0.61+0.01 is likely a new ejecta-dominant Type Ia SNR. The absorption column density, $N_{\text{HI}}$, was $\sim 1.6 \times 10^{23}$ cm$^{-2}$, and hence this SNR would be behind the Sgr B MC complex. Assuming a distance of 8 kpc, the plasma mass was estimated to be $\sim 1.3 M_\odot$, a little smaller than the typical ejecta mass of a Ia SNR.

Faint emissions extend around G0.61+0.01 (figure 8, left). The south of this emission would be another SNR G0.570–0.001 (see sub-subsection 4.1.3), but the northeastern emission was part of G0.61+0.01. In this case, the whole plasma of G0.61+0.01 may be a bit larger than $\sim 1.3 M_\odot$, consistent with the ejecta of a young Type Ia SNR. The X-ray luminosity of G0.61+0.01, including the faint emission at the northeast, would be at most $\sim 2 \times 10^{34}$ erg s$^{-1}$ (2–10 keV), only $\sim 1\%$ of the GCXE flux.

4.1.3 G0.570–0.018 and G0.570–0.001
Senda, Murakami, and Koyama (2002) found a faint X-ray emission in the hard X-ray band images of Chandra and ASCA. The Chandra position was $(l, b) = (0.570, 0.018)$, and hence it was named G0.570–0.018/CXO J174702.6–282733. They fitted the Chandra spectrum with a phenomenological model of a thermal bremsstrahlung plus a Gaussian line at $\sim 6.5$ keV (Fe-Kα line), and obtained the center energy and $EW_{\text{Fe-K}}$ to be $6.5 \pm 0.03$ keV and $4.1^{+4.4}_{-1.0}$ keV, respectively. These are consistent with the ASCA results of $6.60^{+0.12}_{-0.09}$ keV and $3.7^{+3.0}_{-1.2}$ keV. Then, they fitted the ASCA and Chandra spectra simultaneously with a physical model of IP (NEI) plasma. The best-fit temperature ($kT$), ionization parameter ($n_t$), and iron abundance were $\sim 6$ keV, $\sim 2 \times 10^{10}$ cm$^{-3}$ s$^{-1}$, and $\sim 4.5$ solar, respectively. The absorption was $\sim 1.4 \times 10^{23}$ cm$^{-2}$, and hence this source would be behind the Sgr B complex. Assuming a distance of 8 kpc, the X-ray luminosity (2–10 keV) was estimated to be $\sim 10^{34}$ erg s$^{-1}$, which is only $\sim 1\%$ of the GCXE flux.

The Chandra morphology was a ring-like structure of $\sim 10'$ radius plus a tail $\sim 20'$ long. From this small ring and high plasma temperature, Senda, Murakami, and Koyama (2002) proposed that G0.570–0.018 is a very young SNR of $\sim 100$ yr. The tail would be outflow plasma from this young SNR. However, the INTEGRA/IBIS γ-ray and VLA radio observations by Renaud et al. (2006) revealed neither the $^{44}$Ti γ-ray line nor the radio continuum feature from this very young SNR candidate.

Inui et al. (2009) produced spectra from ASCA (observed in 1994), Chandra (2000), XMM-Newton (2001), XMM-Newton (2004), and Suzaku (2005) for the circle of radius 2.5 around G0.570–0.018 (a white dotted circle at the west in figure 13). They fitted all the spectra with the same model of power-law plus three Gaussian lines for the Fe-Kα lines fixing at 6.40, 6.67, and 6.97 keV. The best-fit Fe-Kα line flux (6.40 keV) increased during the period from ASCA (1994) to Chandra (2000) and XMM (2001) by $\sim 2$ times, and then turned to decrease until the XMM-Newton (2004) and Suzaku epoch (2005) by a factor of $\sim 0.7$. The Fe XXV-Heα line flux (6.67 keV) was, on the other hand, almost constant with time.
Table 7. The 6.4 keV clumps near the Sgr B complex.

| Name (l, b)* | N_H (10^{22} cm^{-2}) | EW_{6.4} (keV) | F_X (4–10 keV)^1 | Area* (arcmin^2) | Vari^1 | Instrument^3, reference^1 |
|--------------|------------------------|---------------|-----------------|----------------|--------|-------------------------|
| Sgr B2 (0.66, −0.05) | 83_{−20}^{+25} | 2.9_{−0.9}^{+0.3} | 13 | 28 | — | A, a |
| Sgr B2 (0.66, −0.04) | 88_{−15}^{+20} | 2.1 ± 0.2 | 12 | 11 | — | C, b |
| Sgr B2 (0.7, −0.04) | 40 ± 15 | 2.2 ± 0.1 | 4.5 | 13 | — | B, c |
| Sgr B2 (0.66, −0.03) | 50 ± 13 | 1.2_{−0.3}^{+0.7} | 1.9 ± 0.2 (10–40 keV) | 7 | Y | N+X, j |
| Sgr B2 (0.66−0.03) | 96_{−9}^{+25} | 1.1_{−0.02}^{+0.05} | 11 | 9 | — | S, f |
| M0.74−0.09 | 40_{−11}^{+14} | 1.5_{−0.26}^{+0.37} | 3.0 | 9 | — | |
| Sgr B2 (0.67, −0.02) | 84_{−12}^{+38} | — | 4.3 (5–10 keV)^2 | 9 | Y | S, i |
| Sgr B2 (0.67, −0.02) | 88_{−12}^{+38} | — | 2.1 (5–10 keV)^2 | 9 | Y | |
| M0.74−0.09 | 57±6 | — | 1.7 (5–10 keV)^2 | 7 | Y | |
| M0.74−0.09 | 65±18 | — | 0.9 (5–10 keV)^2 | 7 | Y | |
| G0.66−0.13 | 30_{−9}^{+38} | — | 0.9 ± 0.1 (10–40 keV) | 9 | Y | N+X, j |
| G0.570−0.018 | 13.9_{−3.2}^{+3.3} | — | 1.2–1.5 (2–10 keV) | 20 | Y | C, d, h |
| Sgr B1 (0.51, −0.10) | 15_{−7}^{+5} | 1.4 ± 0.3 | 2.2 (2–10 keV) | 22 | — | S, g |
| Sgr B1+G0.570−0.018 | — | 0.57 ± 0.07 | 9.7 (2–8 keV) | 77 | — | C, e |
| Sgr B2+M0.74−0.06 | — | 1.15 ± 0.15 | 11 (2–8 keV) | 96 | — | |
| +G0.66−0.13 | — | — | — | — | — | |

*Some numerical values in the Name and Area columns may have errors of \( \lesssim 0.01 \) and \( \lesssim 10\% \), respectively, because these are read from the original figures in the References.

1Unabsorbed flux, but reference (f) is absorbed flux.

2With multiple observations, flux variability is found (Y) or not (N).

3Instrument. A: ASCA, C: Chandra, B: BeppoSAX, S: Suzaku, N: NuSTAR, X: XMM-Newton.

4Reference. a: Murakami et al. (2000); b: Murakami, Koyama, and Maeda (2001a); c: Sidoli et al. (2001); d: Senda, Murakami, and Koyama (2002); e: Yusef-Zadeh et al. (2007); f: Koyama et al. (2007a); g: Nobukawa et al. (2008); h: Inui et al. (2009); i: Nobukawa et al. (2011); j: Zhang et al. (2015).

52005 observation.

**2009 observation.

With XMM-Newton, Ponti et al. (2015) found an SNR candidate G0.570−0.001 in the close vicinity of G0.570−0.018. Since the area of Inui et al. (2009) included both G0.570−0.001 and G0.570−0.018, one possibility was that G0.570−0.018 is a time-variable Fe-Kα source (XRN, see table 7), and G0.570−0.001 is an Fe XXV-Heα line-emitting SNR candidate. However, it is still a puzzle whether G0.570−0.001 is an Fe XXV-Heα line-emitting hard X-ray source or a soft source with no Fe XXV-Heα line, because Ponti et al. (2015) detected G0.570−0.001 in the soft X-ray band (2–4.5 keV) only.

4.1.4 G359.942–0.03 and J174400–2913

With the Chandra survey observations, many small diffuse spots of \( \lesssim 10^\circ \) size are found (e.g., Muno et al. 2008; Lu et al. 2008; Johnson et al. 2009; see section 6). Most of them are featureless non-thermal emissions, but a few sources exhibit strong Fe-Kα lines. Johnson, Dong, and Wang (2009) found a Fe XXV-Heα line source, named G359.942–0.03. The spectrum was fitted with a thin thermal plasma model with a \( \sim 7 \) keV temperature and an absorption of \( \sim 2 \times 10^{23} \) cm\(^{-2} \). The \( EW_{6.7} \) was \( \sim 0.8 \) keV. These are similar to the HTP. The detection of the Fe XXV-Heα line from G359.942–0.03 is, however, confusing, possibly due to the limited statistics, because Muno et al. (2008) reported no significant Fe-Kα line \(( EW_{FeK} \lesssim 180 \) eV) from possibly the same source, named G359.941–0.029 (see table 12).

Yamauchi et al. (2014) found another Fe XXV-Heα line source, named Suzaku J174400–2913. The spectrum was fitted with a CIE plasma of \( \sim 4 \) keV temperature and \( \sim 0.6 \) solar abundance. The position coincides with a narrow X-ray filament (\( \sim 10^\circ \)) of G359.55+0.16 (Johnson et al. 2009). This source would be aligned with the radio non-thermal filament G359.54+0.18 (Yusef-Zadeh et al. 1997; Wang et al. 2002a; Lu et al. 2003). The strong Fe XXV-Heα line from G359.55+0.16 was confusing for a bit, because no Fe XXV-Heα line had been reported (Wang et al. 2002a; Lu et al. 2003; Johnson et al. 2009). However, the statistics of Yamauchi et al. (2014) were the highest, high enough to conclude that the Fe XXV-Heα line from Suzaku J174400–2913 is a robust result.

The strong Fe XXV-Heα lines of these sources are similar to young SNRs. However, the filament-like morpholo-
gies with small sizes ($\lesssim 10''$), and the X-ray luminosity of $\sim 2 \times 10^{31}\text{erg s}^{-1}$ (2–10 keV) one or two orders of magnitude smaller than usual for young SNRs, mean these sources would be either small fragments of young SNRs, or have other origins such as a filament produced by magnetic field reconnection and confined by the magnetic field, or a ram-pressure-confined stellar wind bubble generated by a massive star (Johnson et al. 2009). Since these X-ray filaments are very faint ($\sim 10^{31}\text{erg s}^{-1}$), contributions to the HTP flux in the GCXE would be negligible.

4.1.5 Sgr B2 star cluster

Sagittarius B2 (Sgr B2) is a giant MC complex, located at a projected distance of $\sim 100\text{pc}$ from the Galactic center Sgr A*, and is one of the richest star-forming regions (SFRs) in our Galaxy. It contains many compact H II regions (e.g., Benson & Johnston 1984). Thus, Sgr B2 harbors many clusters of very young high-mass stellar objects (YSOs).

With Chandra, Murakami, Koyama, and Maeda (2001a) and Takagi, Murakami, and Koyama (2002) found about one and a half dozen compact sources in the Sgr B2 region in a $3' \times 3.5'$ area. These sources are likely YSOs. The two brightest sources in the compact H II region, Sgr B2 Main, are slightly extended with radii of 3'' and 5''. Their spectra were fitted with a CIE plasma of $\sim 1$ solar abundance. The best-fit temperature and luminosity were in the range of $\sim 5$–$10\text{keV}$ and $\sim 10^{33}\text{erg s}^{-1}$ (2–10 keV), respectively. Another bright source at the position of Sgr B2 North, 25'' $\times$ 21'' in size, had a luminosity of $\sim 10^{33}\text{erg s}^{-1}$. From their extended nature and large luminosity, these three sources are likely to be clusters of YSOs.

The combined spectrum of the other point sources was fitted with a CIE plasma model. The best-fit temperature was $\sim 10\text{keV}$. The individual luminosities were in the range of $\sim 2 \times 10^{31}–10^{32}\text{erg s}^{-1}$. The temperature is higher, but the luminosity is typical of the YSO. Since neither IR nor radio counterpart was found, an alternative idea for these thermal X-ray emissions is isolated white dwarfs powered by Bondi–Hoyle accretion from the dense cloud gas. Whatever their origin, these are surely Fe XXV-Healpha line emitters, which contribute to the HTP of the GCXE. The total luminosity is $\sim 5 \times 10^{33}\text{erg s}^{-1}$ (2–10 keV), which is $\sim 5\%$ of the total X-ray flux of the Sgr B complex. The major X-ray fraction of the Sgr B complex is a diffuse non-thermal emission with prominent FeI-Kalpha lines (the XRN, sub-subsection 5.2.1).

4.1.6 Arches star cluster

The Arches cluster is one of the most massive star clusters near the GC. It has a total mass of $\sim 10^5M_{\odot}$ within a compact size of $\sim 0.5$–1 pc diameter. Yusef-Zadeh et al. (2002b) and Law and Yusef-Zadeh (2004) detected two compact X-ray sources (A2, A1 N/S) in addition to the diffuse emission from the central region using Chandra.

Wang, Dong, and Lang (2006a) reported that the two sources could be separated into three point sources (A1N, A1S, and A2), which exhibited bright Fe XXV-Healpha lines with temperatures of $\sim 1.8\text{keV}$, $\sim 2.2\text{keV}$, and $\sim 2.5\text{keV}$, respectively. Diffuse thermal emission with a strong Fe XXV-Healpha line was also found near the cluster center, at $\lesssim 15''$ radius. The luminosity was $\sim 4 \times 10^{33}\text{erg s}^{-1}$ (2–8 keV), about 20% of the total of A1N, A1S, and A2. The total luminosity of the thermal plasma of A1N, A1S, A2, and the central diffuse source was $\sim 3 \times 10^{34}\text{erg s}^{-1}$ (0.3–8 keV), $\sim 2\%$ of the GCXE.

The Suzaku spectrum of the whole cluster region was fitted with a two-component model, a CIE plasma of $\sim 1$ solar abundance, and a power-law component with an FeI-Kalpha line (Tsujimoto et al. 2007). The best-fit temperature of the CIE plasma was $\sim 2\text{keV}$, and hence it exhibits strong Fe XXV-Healpha lines. The luminosity of the CIE plasma was $\sim 10^{34}\text{erg s}^{-1}$ (3–10 keV). About half of the X-rays were largely extended diffuse emission of power-law spectrum with strong FeI-Kalpha lines (sub-subsection 5.2.1).

Capelli et al. (2011a) examined long-term X-ray emissions observed with XMM-Newton in the period 2002–2009. They found a clear flare with a flux increase of $\sim 70\%$ above the quiescent level. The spectrum in the quiescent state showed both Fe XXV-Healpha and FeI-Kalpha lines, and hence the spectrum was a combination of thermal plasma (Fe XXV-Healpha line) and a non-thermal component (FeI-Kalpha line). The best-fit temperature of the thermal plasma was $\sim 1.7\text{keV}$, in good agreement with those of Suzaku (Tsujimoto et al. 2007) and Chandra (Wang et al. 2006a). The total luminosity (2–10keV) was $\sim 1.5 \times 10^{34}\text{erg s}^{-1}$. The luminosity ratio between the thermal plasma and non-thermal component was 0.85 : 0.15, which seems inconsistent with those of Suzaku (Tsujimoto et al. 2007) and Chandra (Wang et al. 2006a). The total luminosity (2–10keV) was $\sim 1.5 \times 10^{34}\text{erg s}^{-1}$. The luminosity ratio between the thermal plasma and non-thermal component was 0.85 : 0.15, which seems inconsistent with those of Suzaku (Tsujimoto et al. 2007) and Chandra (Wang et al. 2006a). The total luminosity (2–10keV) was $\sim 1.5 \times 10^{34}\text{erg s}^{-1}$. The luminosity ratio between the thermal plasma and non-thermal component was 0.85 : 0.15, which seems inconsistent with those of Suzaku (Tsujimoto et al. 2007) and Chandra (Wang et al. 2006a). However, taking account of the diffuse nature of the FeI-Kalpha line and larger correction area of Tsujimoto, Hyodo, and Koyama (2007), the flux ratios may be consistent with each other. The flare spectrum showed no significant emission of the FeI-Kalpha line, in contrast to the quiescent spectrum. This also supports that the origin of the FeI-Kalpha line is different from that of the higher-ionization Fe XXV-Healpha line. The flare spectrum described well by a CIE plasma of $\sim 1.8\text{keV}$ temperature. The total luminosity was $\sim 3 \times 10^{33}\text{erg s}^{-1}$, one of the largest flares from YSOs.

4.1.7 Other young star clusters

Baganoff et al. (2003) found a central diffuse emission of 10'' radius in the immediate vicinity of Sgr A*, where the central star cluster (CSC) is included. The spectrum was
fitted with a thermal plasma of $\sim 1.3\text{–}1.6$ keV temperature. The luminosity was $\sim 2 \times 10^{34}$ erg s$^{-1}$ (2–10 keV). The spectrum had an Fe-Kα line at $6.5^{+0.1}_{-0.2}$ keV, the energy between the Fe-Kα and Fe XXV-He lines. They suggested that the line energy lower than 6.7 keV was due to ionizing hot plasma (IP). A more plausible idea is that the Fe-Kα line was a mixture of Fe-Kα (CG) and Fe XXV-He (HTP). The luminosity of the hot plasma was significantly higher than that of a single YSO, and hence a likely origin would be a cluster of YSOs, including colliding winds of OBs and Wolf–Rayet stars.

The Sgr D complex is composed of Sgr D H II or G1.13$-0.10$, and an SNR, Sgr D SNR or G1.0$-0.1$ (Downes & Maxwell 1966; Downes et al. 1979). Sawada et al. (2009) found a hard diffuse X-ray spot (Diffuse Source 2: DS2) in the radio shell of Sgr D H II. The spectrum of DS2 was a high-temperature plasma of $\sim 4$ keV, accompanied by an Fe XXV-He line; possibly a cluster of YSOs in the non-thermal radio shell.

M. Nobukawa (in preparation) found faint hard X-ray emissions from the Sgr D SNR region. This remarkable discovery is an extremely high Ni abundance of $\sim 30$ solar from the northeastern shell of the SNR. Such a large Ni abundance has not been predicted by any model of normal SNR. This anomalous structure must be due to some extreme circumstellar conditions in the GCXE region. One possible scenario is that Sgr D SNR is a CC-SN, and the SN explosion highly asymmetric so that part of the neutron-rich (Ni) inner core region is ejected perpendicularly to the northeastern shell of the SNR.

Sgr C is also an MC complex, and hence could be Fe XXV-He line sources like Sgr B, Arches, and Sgr D. However, no hot plasma with an Fe XXV-He line has been found, except for lower-temperature plasmas with an S XV-He line (subsubsection 4.2.7), and hence Sgr C would not contribute to the HTP in the GCXE.

Sgr A is another MC complex, which is associated with many XRNe (table 9). Although no compact point source with an Fe XXV-He line has been found from the Sgr A complex due to the very crowded region, some fractions of HTP may come from this region, possibly the activities of YSOs.

Law and Yusef-Zadeh (2004) found four X-ray point sources and diffuse emission from the Quintuplet cluster with a luminosity of $\sim 10^{34}\text{–}10^{35}$ erg s$^{-1}$. Wang, Dong, and Lang (2006a) found eight X-ray sources in the Quintuplet region. Since the X-ray properties were largely different, they combined three bright sources with similar properties (QX2, QX3, and QX4), and fitted the spectrum with a CIE model. The best-fit $kT$ and $N_{\text{H}}$ were $\sim 8$ keV and $\sim 6 \times 10^{22}$ cm$^{-2}$, respectively. The total luminosity was $\sim 8 \times 10^{32}$ erg s$^{-1}$. An extended emission was also found with $\sim 3 \times 10^{33}$ erg s$^{-1}$ luminosity and $\sim 10$ keV temperature.

In summary, the total luminosity of the young star clusters with Fe XXV-He lines is larger than that of the other diffuse hot plasma, excluding Sgr A East. The sum of the luminosity of all the young clusters (both point sources and diffuse plasma) in the GC would not exceed $\sim 5\%$ of the GCXE, even if contributions of undetected X-ray faint young star clusters are taken into account.

### 4.2 S XV-He $\alpha$ sources (LTP)

Soft X-ray plasmas with a size of $\lesssim 10'$ are given in this section. Most of them exhibit strong Si XVIII-He $\alpha$ and S XV-He $\alpha$ lines with a moderate temperature of $\sim 1$ keV, and hence these are likely intermediate-old SNRs. However, some of them show structures that are unusual for SNRs, either in morphology or in spectrum. This would be closely related with the extreme ISM environment near the GC. These soft X-ray plasmas may contribute significant fractions to the LTP flux, but the contribution to the HTP would be ignored.

#### 4.2.1 G0.42$-0.04$ (G0.40$-0.02$), G1.2$-0.0$,
and G0.13$-0.12$

In the soft X-ray band map of Suzaku, Nobukawa et al. (2008) found an excess spot with the elliptical shape of $\sim 1.8\times 2.4$ at $(l, b) = (0.42, --0.04)$, hence named G0.42$-0.04$ (Suzaku J1746.4–2835.4). The source had an S XV-He line at $\sim 2.45$ keV, a cut-off below $\sim 2$ keV, and a steep slope above $\sim 4$ keV. The spectrum was fitted with a CIE plasma model with a temperature of $\sim 0.7$ keV, and abundances $\sim 0.9$ solar. The absorption column of $\sim 8 \times 10^{22}$ cm$^{-2}$ was consistent with the GC distance of $8$ kpc. Then, the physical size of the ellipse was $\sim 5.6$ pc $\times$ $4.2$ pc. The X-ray luminosity was estimated to be $\sim 6 \times 10^{33}$ erg s$^{-1}$ (2–10 keV). These values are consistent with an intermediate-aged SNR.

Ponti et al. (2015) found a larger ellipse at $(l, b) = (0.40, --0.02)$, named G0.40$-0.02$, with a size of $\sim 4.7 \times 7.4$. The spectrum was fitted with a CIE plasma with a temperature of $\sim 0.55$ keV and an absorption column of $\sim 8 \times 10^{22}$ cm$^{-2}$; both values are similar to those of G0.42$-0.04$. Therefore, G0.40$-0.02$ and G0.42$-0.04$ must be the same object with a distance of $8$ kpc. Then, the physical size of G0.40$-0.02$ was $\sim 11$ pc $\times$ $17$ pc. The authors estimated that the dynamical age and thermal energy of G0.40$-0.02$ were $\sim 3700$ yr and $\sim 1.9 \times 10^{50}$ erg, respectively.

From the radio SNR candidate G1.0$-0.1$ in the Sgr D complex (Downes et al. 1979), Sidoli et al. (2001) found a faint diffuse soft X-ray with BeppoSAX, but Suzaku found
no soft X-ray from G1.0–0.1 (Sawada et al. 2009). Instead, Sawada et al. (2009) found an elliptical X-ray spot (Diffuse Source 1: DS1) with a size of \(~4' \times 7'\) at the northeast of the radio shell Sgr D H\ II. From the position, the spot DS1 was named G1.2–0.0. The spectrum of G1.2–0.0 had He\(\alpha\) lines of S, Ar, and Ca, and hence was fitted with a CIE plasma of \(~0.9\) keV temperature. The abundances of S, Ar, and Ca were \(~1.6\), \(~1.8\), and \(~1.8\) solar, respectively. The X-ray absorption was \(~8.5 \times 10^{22}\) cm\(^{-2}\), possibly in or behind the Sgr D MC complex. Assuming the distance to be 8 kpc, the size was estimated to be \(~8\) pc \(\times\) 16 pc. The plasma temperature, abundances, and size suggest that G1.2–0.0 is an intermediate-aged SNR. The authors reported that the unabsorbed luminosity in the 0.7–8 keV band was \(1.4 \times 10^{35}\) erg s\(^{-1}\). However, this luminosity would be the subject of considerable ambiguity due to the large N\(_{\rm{HI}}\) for the soft spectrum.

In the XMM-Newton image, Heard and Warwick (2013b) discovered a diffuse soft X-ray circular spot of radius 1.5 near the X-ray filament G0.13–0.11 (section 6). From the position, this source was named G0.13–0.12. The X-ray spectrum was fitted with a CIE plasma of \(~1.1\) keV temperature. The absorption was \(~5.6 \times 10^{23}\) cm\(^{-2}\), consistent with being a GC source. Then, the X-ray luminosity was \(~2.2 \times 10^{34}\) erg s\(^{-1}\) (2–10 keV). The abundances of Si, S, and Ar were \(~1.4\), \(~2.0\), and \(~3.4\) solar, respectively. These values are consistent with G0.13–0.12 being an intermediate-aged SNR. Since the massive MC G0.13–0.13 is present in this region, an alternative idea is hot interstellar medium (ISM) or circumstellar medium (CSM) plasmas heated by powerful stellar winds.

### 4.2.2 G359.79–0.26 and G359.77–0.09

Mori et al. (2008, 2009) found two bright diffuse spots, G359.79–0.26 and G359.77–0.09, in the Suzaku SXV-He\(\alpha\) line image near the GC (figure 9). The sizes were \(~4.0' \times 2.6'\) and \(~4.9' \times 2.4'\), respectively. They reported that the X-ray spectra of G359.79–0.09 and G359.79–0.26 were fitted with a CIE plasma model, with temperatures of \(~0.7\) and \(~1.0\) keV, respectively. The diffuse source G359.77–0.09 exhibited clear He\(\alpha\) lines of Si, S, and Ar with abundances of \(~0.9\) solar, \(~0.7\) solar, and \(~0.9\) solar, respectively. The other diffuse source G359.79–0.26 exhibited He\(\alpha\) lines of Mg, S, S, Ar, and Ca with abundances of \(~1.3\), \(~1.1\), \(~1.4\), \(~1.7\), and \(~1.4\) solar, respectively. The absorption column densities of G359.79–0.26 and G359.77–0.09 were \(~5 \times 10^{22}\) cm\(^{-2}\) and \(~7 \times 10^{22}\) cm\(^{-2}\), consistent with GC sources at 8.0 kpc, and hence the sizes of G359.79–0.26 and G359.77–0.09 were \(~9.3\) pc \(\times\) 6 pc and \(~11.4\) pc \(\times\) 5.6 pc, respectively. The luminosity was in the range of \(~(4–6) \times 10^{33}\) erg s\(^{-1}\).

In the XMM-Newton image, Heard and Warwick (2013b) and Ponti et al. (2015) confirmed the soft X-ray sources G359.79–0.26 and G359.77–0.09. The plasma temperatures, absorptions, abundances, and luminosities were all consistent with Mori et al. (2008, 2009).

Although the two SNR candidates, G359.79–0.26 and G359.77–0.09, were spatially separated by \(~0.2\) pc, all the physical parameters were nearly the same. These sources made up a single elliptical ring with \(~20' \times 16'\) diameter and \(~6'–9'\) width (figure 9). The X-ray spectrum from the ring was fitted with a CIE plasma model of \(~0.9\) keV temperature and Si, S, and Ar abundances of \(~1.0\), \(~1.2\), and \(~1.4\) solar, respectively. The thermal energy of the ring was \(~10^{31}\) erg. Therefore, the ring and the two sources, G359.79–0.26 and G359.77–0.09, must be comprised of a single source, a super bubble (SB) with diameter and width of \(~40–50\) pc and \(~15–20\) pc, respectively. Since the shape of the ring was nearly symmetrical with respect to the center point at \((l, b) = (359.83, -0.14)\), an alternative idea would be that the ring is a hypernova remnant (Mori et al. 2009; Heard & Warwick 2013b).

#### 4.2.3 Diffuse soft sources near Sgr A\(^\ast\) (NW, SE, and E)

In the Chandra image near Sgr A\(^\ast\), Baganoff et al. (2003) found diffuse sources named NW and SE. Since these were bright in the 1.5–6 keV band image but weak in the 6–7 keV, these were soft X-ray sources, unrelated to the Sgr A East SNR. Instead, the authors proposed that these were bipolar flows from Sgr A\(^\ast\), although no spectral information was available. In the XMM-Newton X-ray image near Sgr A\(^\ast\), Heard and Warwick (2013b) found three diffuse sources with sizes of \(~1' \times 0.7'\), \(~1.7' \times 1'\), and \(~1' \times 1'\), named...
NW, SE, and E. The sources NW and SE were the same sources as from Baganoff et al. (2003).

The spectra of NW, SE, and E were fitted with a CIE plasma of \(\sim 0.9 \text{ keV}, \sim 1.1 \text{ keV}, \text{ and } \sim 1.0 \text{ keV} \) temperatures. The Si, S, and Ar abundances were in the ranges of \(\sim 1.0-0.6\), \(\sim 0.6-0.9\), and \(\sim 0.7-1.5 \) solar, respectively. The absorptions of NW, SE, and E were \(\sim 8 \times 10^{22}, \sim 6 \times 10^{22}, \text{ and } \sim 6 \times 10^{22} \text{ cm}^{-2}\), respectively, consistent with the GC distance of 8 kpc. Then, the sizes of NW, SE, and E were estimated to be \(\sim 2.3 \times 1.6\), \(\sim 4.0 \times 2.3\), and \(\sim 2.3 \times 2.3 \text{ pc}^2\), respectively, while the luminosity (2–10 keV) was \(\sim (1.5-2.7) \times 10^{34} \text{ erg s}^{-1}\). The temperatures, abundances, and luminosities were similar to, but the sizes significantly smaller than, those of intermediate-aged SNRs. Heard and Warwick (2013b) estimated the electron densities of NW, SE, and E to be \(\sim 4.6-9.9 \text{ cm}^{-3}\), significantly higher than that of ISM or CSM. The small size of the elongated shape pointing to Sgr A*, the high density, and the closeness to Sgr A* led to an alternative scenario that NW, SE, and E are outflows from Sgr A* (subsection 7.3).

### 4.2.4 G359.1–0.5: A recombining plasma

G359.1–0.5 is a shell-like radio SNR with a radius of \(\sim 10^\prime\) (Downes et al. 1979). Center-filled thermal X-rays were found with ASCA (Bamba et al. 2000), and hence G359.1–0.5 is an MM-SNR. The X-ray spectrum has prominent Si XIX-He\(\alpha\) and SXV-Ly\(\alpha\) lines. This is very peculiar, because S is more highly ionized (H-like) than the lighter element Si (He-like).

Ohnishi et al. (2011) observed G359.1–0.5 with Suzaku. They made a high-quality spectrum, as shown in figure 10. The problem of the peculiar spectrum of ASCA was solved by adding radiative recombination continuum (RRC), a sawtooth continuum shape made by transition of free electrons to the K-shell of Si XIX and SXV. The strong RRC structures indicate that the plasma is in over-ionization (recombining plasma: RP). In fact, the observed spectrum was fitted well with an RP model.

The best-fit \(N_{\text{H}}\) of \(\sim 2 \times 10^{22} \text{ cm}^{-2}\) seems smaller than that of the GCXE. However, taking account of the small e-folding latitude of \(\sim 0.25\) of the GCXE (tables 3 and 4), this value is consistent with G359.1–0.5 being located near the boundary of the GCXE.

TeV gamma ray emission (HESS J1745–303) and a hint of the Fe K\(\alpha\) line were found near this SNR (Aharonian et al. 2008; Bamba et al. 2009). Since the Fe K\(\alpha\) line is hardly produced in this low-temperature SNR, this would be due to a bombardment of low-energy cosmic rays (LECR) on surrounding cool MCs. These LECRs would preferentially ionize Si and S, and would make an RP. Other ideas for making an RP are cooling of electrons by thermal conduction to adjacent MCs, or adiabatic expansion when the shock breaks through a surrounding dense MC gas to a tenuous ISM. These MCs should be more numerous in the GC region compared to the other regions of the Galaxy. The ratio of the ionization temperature (\(\sim 0.8 \text{ keV}\)) to the electron temperature (\(\sim 0.3 \text{ keV}\)) of G359.1–0.5 is the largest among the known \(\sim 10\) RP-SNRs (e.g., Koyama 2014; Sato et al. 2014; Washino et al. 2016), suggesting that some extreme MC, ISM, or CSM conditions are presented in the GC, or near G359.1–0.5.

### 4.2.5 G359.41–0.12 and Chimney

Tsuru et al. (2009) found an ellipse and a chimney-like structure in the SXV-He\(\alpha\) line image of Suzaku near the Sgr C complex region. These were named G359.41–0.12 and Chimney. The morphology of Chimney is similar to a PWN with NS moving in one direction. However, no NS candidate was found at the head region. Furthermore, the spectrum was fitted with a CIE plasma model with \(\sim 1.2 \text{ keV} \) temperature. The spectrum of G359.41–0.12 was also fitted with a CIE plasma model of \(\sim 0.9 \text{ keV} \) temperature. The absorption columns of G359.41–0.12 and Chimney were very large and nearly the same at \(\sim 1.2 \times 10^{23} \) and \(\sim 1.0 \times 10^{23} \text{ cm}^{-2}\), respectively. The abundances of S and Ar were both \(\sim 1.7\) solar. These indicate that G359.41–0.12 and Chimney originated in the same region located at the same distance on the same line of sight, possibly just behind a dense MC in the Sgr C complex at 8 kpc. Then, the X-ray luminosities (\(1.5-8 \text{ keV}\)) of G359.41–0.12 and Chimney were estimated to be \(\sim (2-4) \times 10^{33} \text{ erg s}^{-1}\).

The sum of the thermal energies of G359.41–0.12 and Chimney was estimated to be \(\sim 1.4 \times 10^{50} \text{ erg}\). The dynamical time scales of G359.41–0.12 and Chimney were \(\sim 2.5 \times 10^4 \) and \(\sim 4 \times 10^4 \text{ yr}\), respectively. These values are typical of a single Galactic SNR. Tsuru et al. (2009)
proposed that Chimney is an outflow plasma, extending about 30 pc from an SNR candidate G359.41−0.12. However, the highly collimated outflow of ∼5 pc width and ∼30 pc length emanating from G359.41−0.12 is very unusual for the result of a single SN. One possibility is that many MCs in the Sgr C complex deformed a spherical SN expansion to the outflow-like expansion. Still, to make a highly collimated unipolar structure would be difficult. Some other extreme conditions of ISM in the GCXE or near the Sgr C complex must be responsible for the outflow-like morphology of Chimney.

4.2.6 Diffuse plasma near 1E 1740.7−2942
1E 1740.7−2942 is the brightest XB near the GC region. Since the time variability and spectral behavior are similar to those of the low state of Cygnus X-1, the archetypal BH candidate, 1E 1740.7−2942 must be another BH candidate. It is named the Great Annihilator (GA), because a hint of the electron–positron annihilation line at 511 keV was found (e.g., Sunyaev et al. 1991). Although no further evidence for the annihilation line has been found so far with other instruments, this source has drawn great attention because a thermal plasma source, G359.12−0.05, near the position of the radio SNR G359.07−0.02 (LaRosa et al. 2000). The spectrum of G359.12−0.05 was fitted with a CIE plasma model of ∼0.9 keV temperature and an absorption column of ∼7 × 10^{22} cm^{-2}. The abundances of Si, S, and Ar were ∼1.2, ∼1.4, and ∼1.5 solar, respectively.

The N_{H} is a typical column density for the GC region of ∼6 × 10^{22} cm^{-2}, and hence G359.12−0.05 is a GC source at 8 kpc. From the ∼0.9 keV temperature, radius of ∼12', and flux of ∼6.3 × 10^{-4} photons s^{-1} cm^{-2}, the luminosity and dynamical age were estimated to be ∼5 × 10^{31} erg s^{-1} (1−10 keV, absorbed flux) and ∼6 × 10^4 yr, respectively. These values are consistent with an intermediate-aged SNR, and hence G359.12−0.05 comprises a unique system, an SNR associated with the black hole candidate, microquasar or the GA.

4.2.7 Other SNR candidates with soft X-rays
Ponti et al. (2015) found three diffuse soft X-ray sources, named G0.52−0.046, G0.570−0.001, and G0.224−0.032, while making the deep survey of XMM-Newton. The soft source G0.570−0.001 was located in the close vicinity of the hard X-ray source G0.570−0.018 (sub-subsection 4.1.3), but these are two separate sources. The spectra of G0.52−0.046, G0.570−0.001, and G0.224−0.032 were fitted with thermal plasmas of temperatures ∼0.8, 0.6 (fixed), and ∼0.5 keV, and with absorption columns (N_{H}) of ∼8 × 10^{22}, ∼1 × 10^{23}, and ∼7 × 10^{22} cm^{-2}, respectively, and hence these are likely located near the GC. At the GC distance of 8 kpc, their plasma sizes are ∼6 × 12 pc^{2}, ∼4 × 7 pc^{2}, and ∼5 × 11 pc^{2}, respectively. Their dynamical ages are ∼1700, ∼1600, and ∼1800 yr, and their total thermal energies ∼5 × 10^{49}, ∼3 × 10^{49}, and ∼3 × 10^{49} erg, respectively. As noted in sub-subsection 4.1.3, the possibility that G0.570−0.001 is an Fe xxv-Heα-line-emitting hard X-ray source is not fully excluded.

5 The Fe I-Kα clumps
The Fe I-Kα line distribution in the GCXE is not uniform but clumpy, as shown in figure 11. The Fe I-Kα flux from these clumps occupies nearly half of that in the GCXE. This
section reviews the local diffuse sources, which emit strong Fe I-Kα lines (Fe I-Kα clumps). The mechanisms of the Fe I-Kα emission and results of the $EW_{6.4}$ values are given in subsection 5.1. The Fe I-Kα clumps with origins of past big flares of Sgr A* are described in subsection 5.2, while Fe I-Kα clumps with some origin other than Sgr A* flares are discussed in subsection 5.3.

### 5.1 Mechanisms of Fe I-Kα emission and $EW_{6.4}$

When an X-ray or a low-energy cosmic ray (LECR) hits a neutral Fe atom in a cold cloud, an electron hole is made in the K-shell of the neutral Fe (K-shell ionization). Then another electron in the L-shell falls to the hole, and re-emits a characteristic X-ray at 6.4 keV. This process produces an Fe I-Kα line. If the K-shell ionization source is an X-ray of a power-law spectrum with photon index $\Gamma$, $I(E) \propto E^{-\Gamma}$, the $EW_{6.4}$ is given by

$$EW_{6.4} = 4 \left( \frac{\Gamma + 2}{7.1} \right) \left( \frac{6.4}{7.1} \right)^{\Gamma} \left( \frac{1}{1 + \cos^2 \theta} \right) \text{keV},$$

(4)

where the fluorescent yield ($Y_{6.4}$), the density ratio of iron to electron ($n_{Fe}/n_e$), the differential Thomson scattering cross section ($da_t/d\Omega$), and the photoabsorption cross section by Fe atoms ($\sigma_T$) are $\sim 0.34$, $\sim 4 \times 10^{-5}$, $\sim 4.0 \times 10^{-26}(1 + \cos^2 \theta) \text{cm}^2$, and $2 \times 10^{-20}(E/7.1 \text{keV})^{-3} \text{cm}^2$, respectively. For a typical value of $\Gamma = 1.5$ and a scattering angle of $\theta = 90^\circ$, the $EW_{6.4}$ is $\sim 1$ keV. The Fe I-Kα line flux is proportional to $N_{\text{H}I}$ when the target cold gas is optically thin or $N_{\text{H}I}$ is $\lesssim 10^{24} \text{cm}^{-2}$. Therefore, in order to produce detectable Fe I-Kα line flux as shown in figure 11, the absorption K-edge of the neutral Fe at 7.1 keV should be large enough, and $N_{\text{H}I} \gtrsim 10^{23} \text{cm}^{-2}$.

If the K-shell ionization source is a charged particle with the number distribution a power-law function of $N(E) \propto E^{-\Gamma}$, the $EW_{6.4}$ is given as a function of the spectral index $\Gamma$ (Dogiel et al. 2011). The result is shown in figure 12. In the case of an electron, the $EW_{6.4}$ is $\sim 250$–$400 \text{eV}$, almost independent of $\Gamma$. In the case of protons, the $EW_{6.4}$ depends largely on $\Gamma$. In the normal case where $\Gamma$ is $\gtrsim 1$, the $EW_{6.4}$ is $\gtrsim 1$ keV.

The largest cross sections of K-shell ionization of protons and electrons are around the energy of a few 10 MeV and a few 10 keV, respectively (Tatischeff et al. 2012). A particle with these energies is called either a low-energy cosmic-ray proton (LECRp) or a low-energy cosmic-ray electron (LECRE). Both LECRp and the LECRe can penetrate only $N_{\text{H}I} \lesssim 10^{22} \text{cm}^{-2}$. Therefore, if the absorption depth of the iron K-edge at 7.1 keV is shallow and $N_{\text{H}I} \lesssim 10^{22} \text{cm}^{-2}$, the ionization source is likely to be an electron or proton.

### 5.2 X-ray reflection nebulae

Bright Fe I-Kα clumps are found in the MC complexes of Sgr A, B, C, D, and E in the Central Molecular Zone (CMZ)—see figure 11. The spectra have a mean $EW_{6.4}$ of $\sim 1$ keV and a pronounced edge structure at 7.1 keV of $N_{\text{H}I} \sim 10^{23}$–$10^{24} \text{cm}^{-2}$. Thus, the origin of the bright Fe I-Kα clumps must be X-ray irradiation. The flux and morphology are often variable on the time scale of a few–10 yr. This section gives an overview of the bright Fe I-Kα line clumps, named X-ray reflection nebulae (XRNe), and we discuss their nature, structure, and origin.

#### 5.2.1 Sgr B: A prototype for the X-ray reflection nebulae

As noted in subsection 2.2, the XRN scenario of the Fe I-Kα line from the Sgr B2 clouds was proposed by Koyama et al. (1996) and Murakami et al. (2000) with the ASCA observation. BeppoSAX found hard X-ray emission from the Sgr B2 cloud (Sidoli et al. 2001), but the line center energy of $6.5 \pm 0.07 \text{keV}$ was higher than those from Koyama et al. (1996) and Murakami et al. (2000), and any other later observations with instruments with better energy resolution (see table 7). With Chandra, Murakami, Koyama, and Maeda (2001a) found a diffuse emission of nearly one order of magnitude brighter than those of the X-ray-emitting young stars in the Sgr B regions (sub-subsection 4.1.5). The morphology was a convex shape of $\sim 2' \times 4'$ size facing Sgr A*. The X-ray peak was shifted from the core of the MC toward Sgr A* by $\sim 1'$. The X-ray spectrum exhibited pronounced Fe I-Kα, Fe I-Kβ lines, a deep Fe I K-edge at 7.1 keV, and large photoelectric absorption at the low energy. The absorption-corrected X-ray luminosity was $\sim 10^{33} \text{ergs}^{-1}$. These were nearly the same as the ASCA results. Using the best-fit spectral parameters and the geometry of the MC,
Murakami, Koyama, and Maeda (2001a) simulated the X-ray properties with the XRN scenario in the case where \( N_{\text{H}} \) is larger than \( 10^{24} \text{ cm}^{-2} \). Their simulation successfully reproduced the convex morphology and the peak shift of \( \sim 1' \) toward the GC or Sgr A*. Thus, the X-ray morphology and spectrum are all explained well by the XRN scenario, where the irradiation source is located toward the GC, or Sgr A* itself.

The Suzaku observations by Koyama et al. (2007a) provided separate maps of the Fe I-K\( \alpha \) and Fe XXV-He\( \alpha \) lines. Although the Fe XXV-He\( \alpha \) line was smoothly distributed over the Sgr B region, except for a faint clump for the SNR candidate G0.61\( -0.01 \) (sub-subsection 4.1.2), the Fe I-K\( \alpha \) line image was more clumpy with local excesses at the positions of the Sgr B2 cloud and at \((l, b) = (0.74, -0.09)\). The latter clump is called M0.74\( -0.09 \) (see figure 11).

The Fe XXV-He\( \alpha \) line flux is constant with time in all the regions, including the vicinity of the Sgr B complex. On the other hand, a time variability of the Fe I-K\( \alpha \) line in the Sgr B complex regions was discovered for the first time by Koyama et al. (2008) between the Chandra and Suzaku observations separated by 5 yr. The time variability was confirmed by the more extended data sets from ASCA, Chandra, XMM-Newton, and Suzaku over a time span of more than 10 yr (Inui et al. 2009). The long-term time variability of the Fe I-K\( \alpha \) line in the giant MC Sgr B2 is shown in figures 13 and 14. The Fe I-K\( \alpha \) line flux of ASCA and Chandra in the observations of 1994 and 2000 was 1.4 times stronger than those of the XMM-Newton and Suzaku observations of 2004–2005.

The fluorescent Fe I-K\( \alpha \) lines should be accompanied by Compton-scattered hard X-rays from the cloud. Indeed, the INTEGRAL satellite found a diffuse hard X-ray source, named IGR J17475–2822, at the position of the Sgr B2 cloud (Revnivtsev et al. 2004). With more than 40 Ms of INTEGRAL observations during the period from 2003 to 2009, Terrier et al. (2010) found that the flux of IGR J17475–2822 decreased on a time scale of \( 8.2 \pm 1.7 \text{ yr} \).

Nobukawa et al. (2011) made an additional Suzaku observation in 2009. They compared the two Sgr B2 spectra observed in 2005 and 2009—see figure 15. This figure includes all the essentials of the XRN scenario: the rapid and correlated time variability of the Fe I-K\( \alpha \) line and the continuum fluxes, the large \( EW_{6.4} \), and the deep K-edge absorption. The X-ray flux of the Fe I-K\( \alpha \) line decreased in correlation with the hard-continuum flux by a factor of 0.4–0.5 in 4 yr, almost equal to the light traveling time across the Sgr B2 cloud. The same flux decrease during the years 2005–2009 was also found for the other Fe I-K\( \alpha \) line clump in the Sgr B complex, M0.74–0.009.

Zhang et al. (2015) detected hard X-rays up to 20 keV with NuSTAR from the Sgr B region. The photon index was determined to be \( \Gamma \sim 2 \), similar to typical AGNs. They also reported the time variability of the Sgr B2 cloud using XMM-Newton: the Fe I-K\( \alpha \) flux showed a continuous decrease from 2001 to 2012–2013. This was a smooth extension of the decreasing trend in 2000–2009. NuSTAR showed a hint that the flux became constant from 2013 to 2014 at a level of 20% of that in 2001.

Zhang et al. (2015) found a new Fe I-K\( \alpha \) cloud in the Sgr B complex, named G0.66–0.13. This source is time
variable with increasing Fe\,i-Kα flux during the years 2001–2013. In 2013, the flux was brighter than the Sgr B2 cloud, but in 2014 it fell below the detection limit. The 8–12 keV band flux of NuSTAR in the non-thermal continuum emission dropped by 50% in 2013 from that measured with XMM-Newton in 2012. Due to the faintness, however, no detailed spectral information was available for G0.66−0.13.

Another Fe\,i-Kα clump, named M0.51−0.10, was found at the position of the Sgr B1 cloud (Yusef-Zadeh et al. 2007; see figure 11). With Suzaku, Nobukawa et al. (2008) examined the location in detail and found that the $EW_{6.4}$ and $N_{H}$ were $\sim 1.4$ keV and $\sim 1.5 \times 10^{23}$ cm$^{-2}$, respectively. Therefore, M0.51−0.10 (Sgr B1) was likely to be another XRN in the Sgr B complex.

As noted in sub-subsection 4.1.3, the young SNR candidate G0.570−0.018 was discovered with Chandra and then confirmed with ASCA (Senda et al. 2002). Inui et al. (2009), however, found a time variability of the Fe\,i-Kα line from this source in the ASCA, Chandra, XMM-Newton, and Suzaku observations (dotted circles in figure 13). The Fe\,i-Kα line flux changed by a factor of $\sim 0.5$, but the Fe\,XXV-Heα line was constant with time. Thus, G0.570−0.018 is an XRN, but the X-ray is contaminated by the nearby SNR, G0.570−0.001, which may emit Fe\,XXV-Heα and Fe\,XXVI-Lyα lines (sub-subsection 4.1.3).

All the Fe\,i-Kα clumps (candidates for XRNes) near the Sgr B complex are listed in table 7. In this table, the $EW_{6.4}$ in Sgr B1+G0.57−0.018 (Yusef-Zadeh et al. 2007) is exceptionally small compared to those of other regions and other authors. Since Yusef-Zadeh et al. (2007) used larger photon collecting areas than the other authors, the value of $EW_{6.4}$ could be affected by the local background of the GCXE with small $EW_{6.4}$, and hence their value gives smaller $EW_{6.4}$ than the other authors using the smaller photon collecting areas. On the other hand, the Sgr B2 + M0.7−0.09 + G0.66−0.13 clouds (Yusef-Zadeh et al. 2007) have a large XRN area, and hence the observed $EW_{6.4}$ should be normal. From the Sgr B2 cloud, an unusually large $EW_{6.4}$ of $\sim 2–3$ keV was reported by Murakami et al. (2000), Murakami, Koyama, and Maeda (2001a), and Sidoli et al. (2001). These would be due to the limited spectral resolution and statistics of ASCA and BeppoSAX compared to the other later observations with Suzaku, Chandra, and XMM-Newton.

The X-ray spectra and time variability in the flux and morphology of the Fe\,i-Kα clumps in the Sgr B complex strongly support the XRN scenario. The Fe\,i-Kα line and its associated power-law continuum are due to “an X-ray echo,” or X-ray fluorescence (Fe\,i-Kα) and Thomson scattering (power-law) of an external X-ray source. The required flux of the external X-ray source depends on the distance to the Fe\,i-Kα clump. Even in the minimum case where the external X-ray source is inside the Fe\,i-Kα clump of $\sim 1$ pc size, the flux should be larger than $10^{37}$ erg s$^{-1}$. Furthermore, this high flux should be an averaged value in more than $\sim 1$ yr. Since no Galactic X-ray source has been found near the Sgr B complex, a unique candidate for the irradiating X-ray source is the SMBH, Sgr A*. One plausible scenario is that Sgr A* exhibited large flares with luminosity of more than $\sim 10^{39}$ erg s$^{-1}$ (on average in $\gtrsim 1$ yr). The fluorescent Thomson-scattered X-rays from the Sgr B clouds have now arrived at Earth after traveling for an extra time between the direct pass from Sgr A* and the pass via the Sgr B clouds, which is a few hundred light-years. From all the observational results, the Sgr B Fe\,i-Kα clumps are regarded as the most secure example of XRNes, and hence may be called a prototype for the XRNes.

Sunyaev and Churazov (1998) and Odaka et al. (2011) proposed that the morphologies, spectra, and time variations of scattered and fluorescent X-rays are useful diagnostics for the study of the XRN scenario. A detailed simulation was made by Odaka et al. (2011). In order to compare the observations to this simulation, very fine and complicated observational results are required, which is a subject of future study.

5.2.2 The northeastern region from Sgr A*: The Sgr A XRN complex

The Fe\,i-Kα line clumps in the Sgr A complex located at the northeast of Sgr A* were found for the first time with ASCA (Koyama et al. 1996). However, unlike the Sgr B complex, no detailed study was made due to its highly complex structure. With Chandra, Koyama, Senda, and Murakami (2004) found Fe\,i-Kα line clumps in the MC at $(l, b) \sim (0.12, -0.12)$ (Tsuboi et al. 1997; Oka et al. 2001), and proposed that these were XRN candidates. Park et al. (2004) found at least three Fe\,i-Kα clumps (Nos. 1, 2, and 3 in table 9) with a large $EW_{6.4}$ of $\sim 1$ keV from this region. Munu et al.
the superluminal motion suggested by Ponti et al. (2010). They divided the Fe I-\(\alpha\) flux in MC1 into MC1a–MC1f with a size of 26'' × 61'', and found increases of the Fe I-\(\alpha\) flux in MC1c–MC1f, and decreases in MC1a and MC1b. They further selected 13 small bright spots in the 4–8 keV band from Bridges 1 and 2, G0.11–0.11, MC1, and MC2, with a 15'' square, and found the time variability in the light curves of the 4–8 keV band. The fluxes of the spots Br1p, Br1m, Br2o, G0.11s, and MC1j were increasing. From the former three spots, short flares of a time scale of a few years were observed. The fluxes of the spots G0.11u, G0.11r, MC1k, and MC2n were decreasing during the time span of 10 yr. The fluxes of the other four spots were constant with time.

Nobukawa et al. (2010) made a high-quality spectrum with Suzaku from the brightest \(\alpha\) source near the GC (subsection 6.1). Some of them exhibited a large \(\Delta W_{6,4}\). Therefore these would be bright fragments of normal XRNe in the XRN complex region. This unusual morphology, on the other hand, leads one to suspect different origins from XRNe. One plausible idea is that the filament-like Fe I-\(\alpha\) line source is due to the bombardment of LECRp on low-temperature gas confined by strong magnetic fields.

Lu et al. (2008) discovered \(\alpha\) sources near the radio and X-ray filament F10 (table 12). These sources were named East and West, and were the same sources as No. 1 and No. 2, respectively. Although they suggested the electron origin, the discovery of time variability by Muno et al. (2007) strongly supports an X-ray irradiation scenario.

Muno et al. (2008) listed small-sized (≤0.1') filament-like sources near the GC (subsection 6.1). Some of them exhibited a large \(\Delta W_{6,4}\). Therefore these would be bright fragments of normal XRNe in the XRN complex region. This unusual morphology, on the other hand, leads one to suspect different origins from XRNe. One plausible idea is that the filament-like Fe I-\(\alpha\) line source is due to the bombardment of LECRp on low-temperature gas confined by strong magnetic fields.

Capelli et al. (2012), on the other hand, divided the XMM-Newton image of the Fe I-\(\alpha\) line complex into nine regions, and found flux-increasing clumps (B2, C, and D) and flux-decreasing clumps (B1 and F). The fluxes in clumps A, E, DS1, and DS2 were constant with time.

Using the Chandra data, Clavel et al. (2013) examined the details of the time variability and the spatial structure of the Fe I-\(\alpha\) clumps in the regions of Ponti et al. (2010). They divided Bridge 1 into Br1a–Br1e with a size of 26'' × 61'', and selected the same small bright spot Br2f from Bridge 2. They found short flares of the Fe I-\(\alpha\) line in the 10 yr light curves from Br1a–Br2f. The peak position moved in the order of the look-back time in the light curve of Br1a–Br2f during the years 2005–2012. This confirmed the superluminal motion suggested by Ponti et al. (2010). Since the flare peak was ~10 times brighter than the quiescent level, they proposed that the past flare of Sgr A* was not single but was composed of multiple flares with peak luminosity \(\sim 10^{39}\) erg s\(^{-1}\). They also divided the clump MC1 into MC1a–MC1f with a size of 26'' × 61'', and found increases of the Fe I-\(\alpha\) flux in MC1c–MC1f, and decreases in MC1a and MC1b. They further selected 13 small bright spots in the 4–8 keV band from Bridges 1 and 2, G0.11–0.11, MC1, and MC2, with a 15'' square, and found the time variability in the light curves of the 4–8 keV band. The fluxes of the spots Br1p, Br1m, Br2o, G0.11s, and MC1j were increasing. From the former three spots, short flares of a time scale of a few years were observed. The fluxes of the spots G0.11u, G0.11r, MC1k, and MC2n were decreasing during the time span of 10 yr. The fluxes of the other four spots were constant with time.

Nobukawa et al. (2010) made a high-quality spectrum with Suzaku from the brightest \(\alpha\) region at the northeast of Sgr A* (figure 16, left). The spectrum of this region is shown in figure 16 (right). They fitted the spectrum with a combined model, two CIE plasmas and a power-law continuum with many Gaussian lines. The CIE plasmas represented the background spectrum (GCXE) in these clumps. They discovered \(\alpha\) lines from neutral Ar, Ca, chrome (Cr), and manganese (Mn), in addition to the already known K-shell lines from the neutral Fe and Ni (Gaussians in figure 16, right). The best-fit parameters of the Gaussian lines are given in table 8. They determined the Fe abundance in the GCXE around these XRNe to be \(\sim 1.1–1.2\) solar. Assuming a scattering angle of \(\theta = 90^\circ\), the \(\Delta W_{6,4}\) of 1150 ± 90 eV in these XRNe was converted to the Fe abundance of 1.2 ± 0.1 solar. Thus, the Fe abundances in the GC region, estimated by using the Fe I-\(\alpha\) line in the XRN and the Fe XXV-He\(\alpha\) line in the GCXE, were almost the same at \(\sim 1.1–1.2\) solar, consistent with those of Koyama et al. (2007b), Uchiyama et al. (2013), and Muno et al. (2004a). The \(\Delta W\) values of the \(\alpha\) lines of Ar I, Ca I, Cr I, and Ni I were roughly consistent with the solar abundances (table 8).

NuSTAR detected non-thermal continuum X-rays (Mori et al. 2015) spatially correlated with the Fe I-\(\alpha\) fluorescence line from the two Fe I-\(\alpha\) clumps MC1 and Bridge. Mori et al. (2015) made a Monte Carlo simulation with the XRN model for the broad-band X-ray spectrum. Then, they determined the intrinsic column density to be \(\sim 10^{23}\) cm\(^{-2}\), and determined that the primary X-ray spectrum of the power-law model had photon index (\(\Gamma\)) of ~2 and that the flare luminosity of Sgr A* was \(\geq 10^{38}\) erg s\(^{-1}\).

Lu et al. (2008) found a faint source at the east of the southernmost extension of the Radio Arc
Fig. 16. Left: Suzaku X-ray map of the northeast of the Sgr A region (near the Radio Arc). Right: X-ray spectrum. The red solid histograms are the best-fit plasma models of the GCXE. The blue histogram is the best-fit power-law model associated with the Kα lines of neutral Ar, Ca, Cr, Mn, Fe, and Ni (blue Gaussians). The Heα lines of Cr and Mn are also added (from Nobukawa et al. 2010). (Color online)

Table 8. K-shell lines from heavy elements from the Radio Arc region (after Nobukawa et al. 2010).

| Line     | Energy (keV) | Intensity* | EW (eV) |
|----------|--------------|------------|---------|
| Ar I-Kα  | 2.94 ± 0.02  | 170±60     | 140 ± 40 |
| Ca I-Kα  | 3.69 ± 0.02  | 54±14      | 83 ± 13  |
| Cr I-Kα  | 5.41 ± 0.04  | 9.5 ± 2.5  | 24 ± 7   |
| Mn I-Kα  | 5.94 ± 0.03  | 7.4 ± 2.2  | 22 ± 7   |
| Fe I-Kα  | 6.404 ± 0.002| 340 ± 10   | 1150 ± 90|
| Fe I-Kβ  | 7.06 (fixed) | 40 ± 3     | 160 ± 20 |
| Ni I-Kα  | 7.48 ± 0.02  | 18 ± 3     | 83 ± 13  |

*In units of 10^{-6} photons s^{-1} cm^{-2}.

Fig. 17. Spectrum of G0.174−0.233. The data and the best-fit model are shown by the crosses and the solid line, respectively (from Fukuoka et al. 2009).

The spectrum exhibited bright Fe I-Kα and Ca I-Kα lines and a hint of the Ar I-Kα line. Their EW_{6.4} was ~0.95 keV, typical of XRNes. The detection of the Ca I-Kα and Ar I-Kα lines from G0.174−0.233 (Fukuoka et al. 2009) was the second case after the Sgr A XRN (Nobukawa et al. 2010).

The physical parameters of the XRNes in the Sgr A complex are summarized in table 9. Since the Sgr A region is very crowded with many XRNes, some XRNes overlap with ones reported by other authors. The most important parameter, EW_{6.4}, should be time constant, regardless of the time-variable flare fluxes of Sgr A*, and should be free from the observed ambiguity of the N_{HI} values. If the iron abundances and the scattering angle θ are the same among the XRNes, the EW_{6.4} should be the same in all the XRNes [equation (4)]. Nevertheless, the reported EW_{6.4} show apparent and systematic variations among the authors and instruments, and among individual XRNes. For example, No. 3 (Park et al. 2004), G0.11−0.11 (Ponti et al. 2010), and F (Capelli et al. 2012) are the same XRN in position with a similar collecting area. However, their observed EW_{6.4} values are largely different at ~1.3, ~1.0, and ~1.7 keV, respectively.
Table 9. The 6.4 keV clumps near the Radio Arc region.*

| Name (i, b) | $N_{\text{H}}$ (10$^{22}$ cm$^{-2}$) | EW$_{6.4}$ (keV) | $F_X$ (2–10 keV) (10$^{-12}$ erg s$^{-1}$ cm$^{-2}$) | Var$^1$ | Area (arcmin$^2$) | Instrument$^1$, reference$^6$ |
|-------------|-------------------------------|----------------|---------------------------------|---------|------------------|------------------------------|
| No. 1 (0.023, −0.053) | $32.9_{-4.2}^{+4.0}$ | $1.19 \pm 0.10$ | $1.7$ | — | 0.5 | C, a |
| No. 2 (0.045, −0.081) | $36.8_{-13.8}^{+9.6}$ | $1.03_{-0.23}^{+0.37}$ | 3.1 | — | 1.5 | |
| No. 3 (0.121, −0.137) | $15.8_{-2.6}^{+4.1}$ | $1.29 \pm 0.10$ | 2.0 | — | 1.3 | |
| All (0.08, −0.08) | — | $0.67 \pm 0.05$ | 56 | — | 123 | C, b |
| All (0.08, −0.08) | $12.0 \pm 1.1$ | $1.15 \pm 0.09$ | — | — | 45 | S, h |
| Feature 1 (0.023, −0.053) | $36_{-3}^{+5}$ | $1.00_{-0.09}^{+0.24}$ | 0.52$^{-0.03}_{+0.02}$ (4–8 keV)$^*$ | N | 0.9 | C, c |
| Feature 1 (0.023, −0.053) | $34_{-3}^{+5}$ | $1.01_{-0.09}^{+0.19}$ | $0.49_{-0.03}^{+0.02}$ (4–8 keV)$^†$ | N | 0.9 | |
| Feature 2 (0.045, −0.081) | $40_{-6}^{+20}$ | $0.93_{-0.16}^{+0.16}$ | $0.77_{-0.03}^{+0.03}$ (4–8 keV)$^*$ | Y | 2 | |
| Feature 2 (0.045, −0.081) | $75_{-18}^{+26}$ | $0.69_{-0.22}^{+0.22}$ | $0.55_{-0.03}^{+0.03}$ (4–8 keV)$^†$ | Y | 2 | |
| East clump (0.023, −0.053) | $14 \pm 0.2$ | $0.75_{-0.07}^{+0.08}$ | 1.1 | — | 0.9 | C, d |
| West clump (0.045, −0.081) | $23_{-7}^{+6}$ | $1.07_{-0.13}^{+0.16}$ | 1.1 | — | 2 | |
| G0.014−0.054 | — | $0.85_{-0.38}^{+0.45}$ | 0.08 (2–8 keV) | — | 0.072 | C, c |
| G0.021−0.051 | — | $1.0_{-0.47}^{+0.57}$ | 0.07 (2–8 keV) | — | 0.052 | |
| G0.039−0.077 | — | $0.66_{-0.27}^{+0.15}$ | 0.11 (2–8 keV) | — | 0.093 | |
| G0.062+0.010 | — | $1.58_{-1.35}^{+1.38}$ | 0.06 (2–8 keV) | — | 0.33 | |
| G0.097−0.131 | — | $1.19_{-0.35}^{+0.42}$ | 0.48 (2–8 keV) | — | 1.2 | |
| G0.017−0.044 | — | $0.62_{-0.34}^{+0.58}$ | 0.04 | — | 0.01 | C, f |
| G0.174−0.233 | $7.5_{-1.7}^{+2.0}$ | $0.95_{-0.19}^{+0.18}$ | 0.48 | — | 3 | S, g |
| Bridge$^3$ (0.09, −0.08) | $4 \pm 3$ | $0.75_{-0.03}^{+0.051}$ | — | Y/N | 7.4 | X, i; C, k |
| G0.11−0.11 | $7 \pm 4$ | $0.96 \pm 0.06$ | — | Y | 14 | |
| MC1 (0.020, −0.052) | $10_{-2}^{+1}$ | $0.68_{-0.02}^{+0.071}$ | — | N | 2.1 | |
| MC2 (0.035, −0.096) | $5_{-4}^{+5}$ | $0.73_{-0.02}^{+0.12}$ | — | N | 1.8 | |
| A (0.022, −0.052) | $18.4_{-2.7}^{+1.5}$ | $0.9 \pm 0.1$ | — | N | 2.2 | X, j |
| B1 (0.028, −0.077) | $10.2_{-2.0}^{+2.2}$ | $0.9 \pm 0.1$ | — | Y | 2.6 | |
| B2 (0.055, −0.083) | $12.3_{-2.7}^{+3.0}$ | $1.5_{-0.3}^{+0.4}$ | — | Y | 1.9 | |
| C (0.048, −0.053) | $5.8_{-1.9}^{+2.3}$ | $1.0_{-0.1}^{+0.2}$ | — | Y | 2.0 | |
| D (0.072, −0.072) | $13.2_{-5.0}^{+4.7}$ | $1.3_{-0.3}^{+0.4}$ | — | Y | 1.8 | |
| E (0.090, −0.087) | $9.6_{-1.4}^{+1.7}$ | $1.4 \pm 0.2$ | — | N | 2.9 | |
| F (0.125, −0.115) | $9.2_{-2.3}^{+2.7}$ | $1.7 \pm 0.2$ | — | Y | 15 | |
| DS1 (0.065, −0.020) | $15.5_{-3.3}^{+3.7}$ | $0.9 \pm 0.2$ | — | N | 3.7 | |
| DS2 (0.025, −0.012) | $14.5 \pm 2.3$ | $0.9 \pm 0.1$ | — | N | 6.5 | |

* Same as table 7, but for the XRNe in the Sgr A complex.

† With multiple observations, flux variability is found (Y) or not (N).

$^1$ Instruments: A: ASCA; C: Chandra; B: BeppoSAX; S: Suzaku; N: NuSTAR; X: XMM-Newton.

$^2$ References: a: Park et al. (2004); b: Yusef-Zadeh et al. (2007); c: Muno et al. (2007); d: Lu, Yuan, and Lou (2008); e: Muno et al. (2008); f: Johnson, Dong, and Wang (2009); g: Fukuoka et al. (2009); h: Nobukawa et al. (2010); i: Ponti et al. (2010); j: Capelli et al. (2012); k: Clavel et al. (2013).

$^3$ Errors are estimated from the flux errors of the Fe Kα line.

$^4$ This region is separated into subgroups, Bridge 1–7.

** Observed in 2002.

*** Observed in 2004–2005.
The Sgr C complex is a unique star-forming region in the west of the CMZ, located at the mirror point of the Sgr B complex with respect to Sgr A* complex (Murakami et al. 2001b). The X-ray spectrum was characterized by a large EW_{6.4} of \( \sim 1 \) keV and a large absorption column of \( \sim 10^{23} \) cm\(^{-2}\), suggesting that the X-rays are due to fluorescence and scattering of external X-rays. A source in the immediate vicinity of the Sgr C complex bright enough to account for the fluorescence flux was not found. Thus, for the same reason as the Sgr B complex, the irradiating X-ray source must be a past bright flare of Sgr A*; therefore, the Sgr C complex is the second XRN discovered after the Sgr B complex.

With Chandra, Yusef-Zadeh et al. (2007) found five X-ray spots from the Sgr C complex in the 2–6 keV band image. Two of them, G359.45–0.07 and G359.42–0.07, were diffuse sources of size \( \lesssim 4' \). Yusef-Zadeh et al. (2007) made an X-ray spectrum from the region including these two diffuse sources; the mean EW_{6.4} was \( \sim 470 \) eV.

Suzaku found four diffuse clumps near the Sgr C region (Nakajima et al. 2009), named M359.47–0.15, M359.43–0.076, M359.38–0.07, and M359.42–0.07. Two of them, M359.47–0.15 and M359.43–0.07, were prominent in the Fe I-K\( ^\alpha \) line image. The EW_{6.4} values were very large at \( \sim 2.0–2.2 \) keV, nearly twice as large as those of the normal XRN in the Sgr B and Sgr A complexes. This is puzzling, but possibly some systematic errors were involved. The absorptions (\( N_{\text{HI}} \)) were \( \sim 10^{23} \) cm\(^{-2}\), consistent with the sources in the MCs of the Sgr C complex.

Ryu et al. (2013) reanalyzed the same region, and found three Fe I-K\( ^\alpha \) diffuse sources, named C1, C2, and C3, where the positions of C1 and C2 coincided with those of M359.47–0.15 and M359.43–0.07, respectively. These sources had a reasonable EW_{6.4} of \( \sim 1.1–1.6 \) keV. The Fe I-K\( ^\alpha \) line of C1 increased by 8% (2.9 \( \sigma \) confidence) from the 2006–2010 observations. The time variability of C1 and the large EW_{6.4} of 1–1.6 keV of C1, C2, and C3 favor the X-ray irradiation scenario (XRN).

### Table 10. The 6.4 keV clumps near the Sgr C complex.\(^a\)

| Name (l, b) | \( N_{\text{HI}} \) (10\(^{22} \) cm\(^{-2}\)) | \( EW_{6.4} \) (keV) | \( F_X \) (3–10 keV)\(^{1} \) (10\(^{-12} \) erg s\(^{-1}\) cm\(^{-2}\)) | Area (arcmin\(^2\)) | Instrument\(^b\), reference\(^c\) |
|------------|----------------------|------------------|----------------------------------|-----------------|-----------------|
| Sgr C (359.42, −0.04) | 12.6±1.5 | 0.8±0.2 | 6 (4–10 keV) | 23 | A, a |
| G359.43+G359.42 | — | 0.47±0.10 | 12 (2–8 keV) | 77 | C, b |
| M359.43−0.076 | 9.2±1.5 | 2.2±0.1 | 0.27 | 7.1 | S, c |
| M359.47−0.15 | 8.2±1.5 | 2.0±0.1 | 0.41 | 6.9 | |
| C1 (359.43, −0.076) | 11.6±1.5 | 1.1−1.5 | — | 13 | S, d |
| C2 (359.47, −0.15) | 17.9±1.5 | 1.1−1.6 | — | 13 | |
| C3 (359.58, −0.13) | 13.7±0.7 | 0.7−1.3 | — | 31 | |

\(^a\)As table 7, but for the XRN in the Sgr C complex.

\(^b\)Unabsorbed flux, but reference c is absorbed flux. Two separate observations of C1 made in 2006 and 2010 show a time variability.

\(^c\)Instruments: A: ASCA; C: Chandra; B: BeppoSAX; S: Suzaku; N: NuSTAR; X: XMM-Newton.

\(^d\)References. a: Murakami et al. (2001b); b: Yusef-Zadeh et al. (2007); c: Nakajima et al. (2009); d: Ryu et al. (2013).
A summary of the Fe-I-Kα sources in the Sgr C complex is given in table 10. The small $EW_{6.4}$ value of $\sim$470 eV from Yusef-Zadeh et al. (2007) is marginal as to whether the origin was LECR electron or X-ray irradiation (XRN). However, the small $EW_{6.4}$ value could be due to the larger collecting area of 77 arcmin$^2$ than Nakajima et al. (2009) and Ryu et al. (2013), and hence the spectrum would be contaminated by the nearby GCXE (see sub-subsection 5.2.2). In fact, Nakajima et al. (2009) observed the $EW_{6.4}$ value from nearly the same area as Yusef-Zadeh et al. (2007) with Suzaku, and found that the $EW_{6.4}$ was 460 eV.

The extensive Suzaku observations near the edge of the GCXE revealed strong Fe-I-Kα lines from the Sgr D and Sgr E complexes (see figure 11). Although no detailed follow-up analysis of these complexes has been made, the similarity in spectrum and morphology to those of the Sgr B, Sgr A, and Sgr C complexes suggests that the Sgr D and Sgr E complexes also contain XRNe.

### 5.3 Fe-I-Kα clumps other than XRNe

This subsection reviews Fe-I-Kα clumps other than those in subsection 5.2. The origin may not be X-ray irradiation from Sgr A*, but irradiation sources would be either local nearby bright X-ray stars, LECRe, or LECRp.

#### 5.3.1 Arches cluster

In addition to the thermal hot plasma (sub-subsection 4.1.6) in the central region, Yusef-Zadeh et al. (2002b) and Law and Yusef-Zadeh (2004) found extended emission, named A3, southeast of the core of the Arches cluster with Chandra. The source A3 had a power-law spectrum with possible Fe-I-Kα lines. However, no detail of the spectrum was reported. Later, Yusef-Zadeh et al. (2007) reported on Fe-I-Kα line emission with $EW_{6.4}$ of $\sim$0.8 keV. A long-exposure Chandra observation by Wang, Dong, and Lang (2006a) found that the thermal plasma mainly comes from the center region of the cluster, but a strong Fe-I-Kα line with power-law continuum emission originates from the southeastern region of the star cluster, named the SE extension. Since the $EW_{6.4}$ is $\sim$1.4 keV, its origin is most likely the bombardment of molecular gas by X-ray photons or low-energy protons.

Tsujimoto, Hyodo, and Koyama (2007) produced the Suzaku spectrum for the whole region of the Arches cluster, because Suzaku did not have good spatial resolution. The spectrum was fitted with a model of a CIE plasma plus a power-law continuum with two Gaussian lines at 6.4 keV (Fe-I-Kα) and 7.05 keV (Fe-I-Kβ). Then, the power-law spectrum had a photon index of $\sim$0.7, but no pronounced iron K-edge feature at 7.1 keV was found. Since the narrow-band image of 7.5–10.0 keV showed a similar distribution to that of the Fe-I-Kα line flux, the Fe-I-Kα and Fe-I-Kβ lines were associated with the power-law component with an $EW_{6.4}$ of $\sim$1.42 keV. They also examined the Chandra spectra, and found that the power-law index and $EW_{6.4}$ were $\sim$1.2 and $\sim$1.25 keV, respectively.

XMM-Newton found a big loop-like annular structure in the Fe-I-Kα band with a diameter of $\sim$ 3′ and width of $\sim$ 1′ around the star cluster, named the Loop (Sakano et al. 2006). Sakano, Warwick, and Decourchelle made an X-ray spectrum from the brightest part of Loop at the southeast of the cluster center, and fitted it with a model of a power law plus a Gaussian line. The best-fit absorption column and photon index were ($7.2 \pm 1.4$) $\times$ 10$^{22}$ cm$^{-2}$ and 1.4 $\pm$ 0.6, respectively. The $EW_{6.4}$ was 1.0 $\pm$ 0.25 keV. Capelli et al. (2011b) found three Fe-I-Kα clumps: N, S, and SN. These comprised part of the loop-like structure of Sakano, Warwick, and Decourchelle (2006). The $EW_{6.4}$ were all within the range of 0.9–1.1 keV. They interpreted this as N, S, and SN being explained by the MC bombardment of LECRs from the Arches cluster stars. Tatischeff, Decourchelle, and Maurin (2012) found a strong Fe-I-Kα line from nearly the same regions as N and S, with $EW_{6.4}$ of $\sim$1.2 keV. Since no time variability of the Fe-I-Kα line has been found during 2000–2010, they claimed that the origin would be LECRp. A possible supersonic collision between the stellar wind from star clusters and MCs would make a strong shock and hence would become efficient particle acceleration, which would make enough LECR to produce the Fe-I-Kα line and power-law flux. Although it is not clear whether the origin is X-rays or protons, the candidate source would be related to high-mass stars in the Arches cluster.

Krivonos et al. (2014) detected diffuse X-rays up to $\sim$30 keV with NuSTAR. The emitting region was an ellipse of northwest–southeast major axis, nearly the same regions as the N and S of Capelli et al. (2011b). Krivonos et al. (2014) determined that the $EW_{6.4}$ was $\sim$1.1 keV. The wide-band X-ray spectrum was in broad agreement with an LECR origin. Using the XMM-Newton data during the period from 2000 to 2013, Clavel et al. (2014) examined the long-term time variability of the power-law emission in the same eclipse as in Krivonos et al. (2014). The $EW_{6.4}$ was $\sim$0.9 keV. They found a flux drop of 30% in 2012, and hence a constant-flux hypothesis is rejected with more than 4σ confidence. From this time variability, they suggested that the power-law emission is due to the reflection of an X-ray transient source in the Arches cluster.

Most of the authors suggested that the irradiation source for the Fe-I-Kα emission is active stars in the core of the Arches cluster, because of extreme activity of the embedded stars compared with other star clusters. If the irradiation sources are the cluster stars in the core, with the mean...
distance of $\sim 1$ pc from the Fe I-$\alpha$ diffuse sources, the X-ray luminosity should be $> 100$ times brighter than any of the observed results of $\sim 4 \times 10^{35}$ erg s$^{-1}$ (Capelli et al. 2011a). Therefore, for the same reason as the other XRN candidates (subsection 5.1), it is also possible that the Fe I-$\alpha$ emission from the Arches cluster is due to the past flare of Sgr A$^*$. The luminosity and epoch of the flare are not largely different from those of the Sgr A XRNe because the flare positions, Fe I-$\alpha$ fluxes, and luminosity are not largely different from those estimated from the XRNe in the Sgr A complex, if possible systematic errors and time variability are taken into account. The combination of M359.23$-$0.04 and 1E 1740.7$-$2942 is a rare case of the association of the diffuse Fe I-$\alpha$ line with a bright binary X-ray source.

5.3.3 G0.162$-$0.217

From the Radio Arc region, a small occurrence of the Fe I-$\alpha$ line was found at $(l, b) = (0.162, -0.217)$ with Suzaku and named G0.162$-$0.217 (Fukuoka et al. 2009). This source is located adjacent to the southern end of the Radio Arc (LaRosa et al. 2000; Yusef-Zadeh et al. 2004). The Radio Arc is a site of relativistic electrons, which may include LECRe along the magnetic field line of the Radio Arc. Thus, G0.162$-$0.217 would be made by the LECRe. The observed $E_{\text{W_{Fe I-$\alpha$}}} \sim 0.2$ keV, consistent with the LECRe bombardment scenario (figure 12). This type of faint Fe I-$\alpha$ line emitter would be more numerous in the

Table 11. The 6.4 keV clumps near the Arches cluster.

| Name $(l, b)$ | $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $E_{\text{W_{6.4}}}$ (keV) | $F_X$ (2–8 keV) ($10^{-12}$ erg s$^{-1}$ cm$^{-2}$) | Area (arcmin$^2$) | Instrument$^1$, reference$^1$ |
|---------------|-----------------|-----------------|-----------------|----------------|-----------------|
| SE extension $(0.1, 0.02)$ | $6.2^{+2.7}_{-3.6}$ | $1.4^{+1.0}_{-0.5}$ | 0.54 | 0.5 | C, a |
| Loop $(0.1, 0.05)$ | $7.2 \pm 1.4$ | $1.00 \pm 0.25$ | — | — | X, b |
| Arches $(0.1, 0.03)$ | — | $0.81 \pm 0.2$ | 1.2 | 1.6 | C, c |
| Arches $(0.01, 0.03)$ | $14 \pm 5$ | $\sim 1.25$ | 11.1 (3–10 keV) | 6.2 | C, S, d |
| N $(0.13, 0.02)$ | $9.5 \pm 1.5$ | $1.0 \pm 0.4$ | — | — | X, e |
| S $(0.12, 0.01)$ | $10.1 \pm 0.7$ | $0.9 \pm 0.2$ | — | — | 0.5 |
| SN $(0.10, 0.01)$ | $8.5^{+4.0}_{-3.4}$ | $1.1 \pm 0.4$ | — | 0.9 |
| DX $(0.10, 0.05)$ | 6 (fixed) | $2.6^{+2.1}_{-1.1}$ | — | 0.8 |
| Cloud region $(0.12, 0.02)$ | $11.3^{+1.9}_{-1.3}$ | $1.2 \pm 0.2$ | — | 1.1 | X, f |
| Cloud region $(0.12, 0.02)$ | 9.5 (fixed) | $1.1^{+0.7}_{-0.5}$ | 1.5 (3–20 keV) | 1.1 | N, g |
| Cloud region $(0.12, 0.02)$ | $6.0 \pm 0.3$ | $0.9 \pm 0.1$ | — | 1.1 | X, h |

*a As table 7, but for the Fe I-$\alpha$ clumps in the Arches cluster.

1Instruments: A: ASCA; C: Chandra; B: BeppoSAX; S: Suzaku; N: NuSTAR; X: XMM-Newton.

References: a: Wang, Dong, and Lang (2006a); b: Sakano, Warwick, and Decourchelle (2006); c: Yusef-Zadeh et al. (2007); d: Tatischeff, Decourchelle, and Maurin (2012); e: Capelli et al. (2011b); f: Tatischeff, Decourchelle, and Maurin (2012); g: Krivonos et al. (2014); h: Clavel et al. (2014).
GCXE (section 6), and may contribute to a significant fraction of Fe-Kα flux in the GCXE (subsection 9.3). However, the limited statistics of the current instruments do not allow us to make a further search for these potential LECRe sources of the Fe-Kα lines.

6 Small-sized X-ray sources or non-thermal X-ray filaments

This section reviews small-scale diffuse plasmas discovered mainly with Chandra in the central region (subsection 6.1) and the outer region (subsection 6.2) of the GCXE. The shapes of the diffuse plasmas are mostly either filamentary or cometary with non-thermal X-ray spectra. In this section, these sources are called the X-ray filament. The summed luminosity (2–10 keV) of the X-ray filaments is \(\sim 5 \times 10^{34} \text{ erg s}^{-1}\), only \(\sim 4\%\) of the 2–10 keV band luminosity of the GCXE (\(\sim 1.2 \times 10^{36} \text{ erg s}^{-1}\)).

6.1 The central region of the GCXE

Muno et al. (2008) and Lu, Yuan, and Lou (2008) produced a Chandra map in the close vicinity of Sgr A*, the \(\sim 10' \times 10'\) region (within \(\sim 20\) pc of Sgr A*). They found many small-scale diffuse sources, most of them with a filamentary or cometary shape. Figure 18 shows the map of the X-ray filaments near Sgr A*. Table 12 is a summary of the X-ray filaments within \(\sim 20\) pc of Sgr A*, where strong Fe-Kα line filaments in Sgr A East and near the Sgr A complex and the Arches cluster are excluded, because these are discussed separately in sections 4 and 5. All the diffuse sources listed in the upper rows in table 12—their positions (source names), sizes, and luminosity—are taken from Muno et al. (2008), while those in the lower rows are from Lu, Yuan, and Lou (2008).

Diffuse sources have also been found or studied by many other authors. Since the typical morphology is filamentary or cometary with a length and width of \(\sim 20'\) and \(\sim 4'\) (the mean values of Muno et al. 2008 and Lu et al. 2008), the cited positions may have a typical uncertainty of a few 10'. Therefore, if the source positions are within \(\lesssim 20'\) of Muno et al. (2008) or Lu, Yuan, and Lou (2008), these sources are regarded as the same objects as Muno et al. (2008) or Lu, Yuan, and Lou (2008), and the authors’ names are listed in the sixth column of table 12.

Most of the sources have power-law (non-thermal) spectra with photon index of \(\Gamma \sim 1–2\). However, only small fractions of the X-ray filaments are associated with radio NTF. Four X-ray filaments, G359.945–0.044, G359.942–0.045, G359.944–0.052, and G359.950–0.043, are located very close to Sgr A* in the Sgr A West Cavity or on the Mini Spiral, and hence are possibly associated with the CSC, or related to the Sgr A* activity. The other four X-ray filaments, G359.956–0.052, G359.962–0.062, G359.964–0.053, and G359.965–0.056, are in the Sgr A East SNR. Since the \(E_{\text{W}K\alpha}\) of these X-ray filaments is less than \(\sim 70\) eV (Muno et al. 2008), they are not part of the hot plasma of Sgr A East, but are more likely non-thermal filaments due to accelerated particles in SNR Sgr A East.

The X-ray filament G359.945–0.044 (or G359.95–0.04 in Wang et al. 2006b, Le et al. 2008, and Johnson et al. 2009) is one of the brightest filaments and separated by only 0.1 from Sgr A*. It has a bright head and a faint tail structure. The spectrum shows softening from the head to the tail of photon index \(\Gamma\) from \(\sim 1.3\) to \(\sim 3.1\) (Wang et al. 2006b). The total X-ray luminosity is \(\sim 10^{34} \text{ erg s}^{-1}\), with an averaged photon index of \(\sim 1.7–1.9\) (Muno et al. 2008; Lu et al. 2008; Johnson et al. 2009). These values are consistent with a PWN. However, no X-ray pulsar is found at the head. Thus, an alternative scenario is a ram-pressured magnetic tube, which traps TeV electrons accelerated by Sgr A* (e.g., Wang et al. 2006b).

Hard X-rays above 10 keV were detected with NuSTAR in this source (Mori et al. 2015). The 20–40 keV luminosity was \(\sim 7 \times 10^{33} \text{ erg s}^{-1}\).

Hard X-rays above 10 keV were also detected with NuSTAR in the other bright X-ray filaments, G359.983–0.046 (J174545.5–285829: the Cannonball), G359.89–0.08 (Sgr A–E), and G359.97–0.038 (Nynka et al. 2013, 2015; Zhang et al. 2014; Mori et al. 2015). With the wide-band spectra, the X-ray luminosities and photon indexes were determined to be \(\sim 10^{33}–10^{34} \text{ erg s}^{-1}\) and \(\sim 1.3–2.6\), respectively.

![Fig. 18. X-ray filaments near Sgr A* in the central region of 6′5 × 6′5. The dashed line indicates the Galactic plane, and the plus sign denotes the position of Sgr A*. The brightest diffuse emission around Sgr A* is the central star cluster, and the extended emission at the northeast of Sgr A* is the Sgr A East SNR (from Lu et al. 2008).](https://academic.oup.com/pasj/article-abstract/70/1/R1/4564190/70145464189)
Table 12. Non-thermal X-ray filaments within the 17′ region.†

| Name          | Size (arcsec²) | EW_f (eV) | L_X (2–8 keV) (10^32 erg s⁻¹) | Comment       | References‡ |
|---------------|----------------|-----------|-------------------------------|---------------|-------------|
| G359.945−0.044 | 22             | ≤60       | 66                            | In the Cavity, PWN? | a, b, c, d, n |
| G359.942−0.045 | 28             | ≤220      | 16                            | In the Cavity   | a            |
| G359.944−0.052 | 20             | ≤470      | 2                             | Jet, in the Spiral | a, c, j      |
| G359.950−0.043 | 55             | ≤140      | 4                             | In the Spiral   | a            |
| G359.933−0.039 | 15             | —         | —                             | F1             | a, b, c      |
| G359.956−0.052 | 10             | —         | 1                             | In Sgr A East   | a            |
| G359.933−0.037 | 13             | ≤170      | 3                             | a, b           |
| G359.941−0.029 | 17             | ≤180      | 2                             | F2 stellar wind? | a, c         |
| G359.925−0.051 | 19             | ≤2060     | 3                             |                |
| G359.964−0.053 | 76             | ≤70       | 17                            | In Sgr A East, PWN?, F3 | a, b, c, e |
| G359.965−0.056 | 29             | —         | 3                             | In Sgr A East, F4 | a, b         |
| G359.921−0.052 | 12             | —         | —                             |                |
| G359.962−0.062 | 26             | —         | 2                             | In Sgr A East   | a            |
| G359.939−0.027 | 34             | ≤75       | 6                             | knot-1, F5     | a, b, c, f   |
| G359.971−0.038 | 148            | ≤130      | 10                            | PWN?, F6       | a, b, c      |
| G359.969−0.033 | 17             | —         | —                             | PWN?           | a            |
| G359.921−0.030 | 30             | ≤1300     | 3                             | F7             | a, b         |
| G359.915−0.061 | 22             | —         | —                             |                |
| G359.983−0.040 | —              | —         | —                             |                |
| G359.904−0.047 | 32             | —         | 1                             |                |
| G359.977−0.076 | 26             | —         | —                             |                |
| G359.970−0.008 | 30             | ≤110      | 6                             | knot-2 PWN?, F8 | a, b, c, f, m |
| G359.899−0.065 | 30             | —         | 3                             |                |
| G359.897−0.023 | 42             | —         | 2                             |                |
| G359.889−0.081 | 432            | ≤30       | 70                            | Radio, Sgr A-E, PWN? | a, b, c, g, h, l, n, o |
| G0.008−0.015   | 51             | —         | —                             |                |
| G0.032−0.056   | 429            | ≤110      | 10                            |                |
| G0.029−0.080   | 838            | —         | —                             |                |
| G0.116−0.111   | 2257           | —         | —                             |                |
| G0.029−0.06    | 6 × 47         | —         | 11                            | Radio, PWN?, F10 | b            |
| G359.974−0.00  | 4 × 7          | —         | 4                             | knot-3, F9     | b, f         |
| G359.983−0.046 | —              | —         | 31                            | Canonball, PWN? | b, f         |
| G359.90−0.06   | 3 × 6          | —         | 108                           | Radio, Sgr A-F | b, o         |

Total luminosity (2–10 keV) 3.8 × 10^34 erg s⁻¹

†Sources and parameters in the upper rows are taken from Muno et al. (2008) in the order of the angular distance from Sgr A*, while those of the lower rows are from Lu, Yuan, and Lou (2008). The overlapping sources from both Muno et al. (2008) and Lu, Yuan, and Lou (2008) are combined in the first row. Sources observed by other authors with a separation angle of ≲ 0.3′ are treated as the same objects.

‡The authors names are given in the Reference column. a: Muno et al. (2008); b: Lu, Yuan, and Lou (2008); c: Johnson, Dong, and Wang (2009); d: Wang, Lu, and Gotthelf (2006b); e: Baganoff et al. (2003); f: Koyama, Senda, and Murakami (2004); g: Sakano et al. (2003); h: Lu, Wang, and Lang (2003); i: Park et al. (2003); j: Li, Morris, and Baganoff (2013); k: Nynka et al. (2013); l: Nynka et al. (2014); m: Nynka et al. (2015); n: Mori et al. (2015); o: Yusef-Zadeh et al. (2005).

From the star formation rate at the Galactic center, Muno et al. (2008) estimated ≈20 PWNe are expected in the Galactic center. However, only small fractions of the X-ray filaments are suspected to be PWNe (Muno et al. 2008). Therefore, most of the PWNe would have an X-ray luminosity of ≲ 10^{31} erg s⁻¹, below the detection limit of the sources in table 12.

The X-ray filaments G359.959−0.027, G359.970−0.008, and G359.974−0.00 have narrow features associated with the radio filaments, and are roughly aligned on a slightly curved line crossing over Sgr A*. These were named knot-1, -2, and -3 by Koyama, Senda, and Murakami (2004). The other narrow filament, G359.944−0.052, named Jet by Li, Morris, and Baganoff (2013), has a well-collimated structure pointing to Sgr A* located on the other side of the Galactic plane. Detailed discussion of these filaments related to the past high activity of the SMBH Sgr A* is given in subsection 7.3.
In table 12, the X-ray luminosity is available for two thirds of the X-ray filaments, with luminosity of $\sim 10^{32} - 10^{34}$ erg s$^{-1}$ (2–8 keV). The summed luminosity (2–10 keV) is $\sim 3.8 \times 10^{33}$ erg s$^{-1}$. The luminosity of the remaining third is unavailable due to the faintness. Assuming the luminosity of the remaining sources is near the lower limit of the observable luminosity of $\sim 10^{32}$ erg s$^{-1}$, the summed luminosity of all the X-ray filaments is estimated to be $\sim 4 \times 10^{34}$ erg s$^{-1}$, only 3% of the GCXE.

6.2 The outer region of the GCXE

A high spatial resolution survey of the whole GCXE of $\sim 2' \times 0.8$ around Sgr A$^*$ was first made by Wang, Gotthelf, and Lang (2002a) with Chandra. Although eight bright radio non-thermal filaments are included in this region, only one source, G359.54+0.18 (Yusef-Zadeh et al. 1997), is found to be an X-ray filament, named the X-ray Thread. With a deeper Chandra survey of 1:1 × 0.57 around Sgr A*, Johnson, Dong, and Wang (2009) found 17 X-ray filaments, and a dozen of them are located in the inner GCXE region of $\sim 10' \times 10'$; these are listed in table 12. A source list for the whole GCXE of 1:1 × 0.57 excluding the inner region is given in table 13.

Ponti et al. (2015) surveyed nearly the same region with XMM-Newton. Since most of them except G0.17–0.42 overlapped with Johnson, Dong, and Wang (2009), the sources listed in table 13 are mainly due to the Chandra observations. The References column in table 13 indicates the other authors who observed the relevant sources.

The X-ray filament G0.13–0.11 is the one of brightest and the most studied X-ray filaments in this region. This name and its features are confusing, because other nearby objects with a similar name but different nature are present. The radio MC G0.13–0.13 was found to be an Fe-Kα line source (Yusef-Zadeh et al. 2002a, 2002b), and it was claimed that the Fe-Kα line is due to LECRe. However, the selected area was rather large ($4' \times 3'$), and hence was contaminated by a nearby X-ray source, G0.11–0.11 (table 9). The diffuse soft X-ray source G0.13–0.12, a candidate for an intermediate-aged SNR, is near the filament G0.13–0.11 (sub-section 4.2.1).

Wang, Lu, and Lang (2002b) found that the X-ray spectrum of G0.13–0.11 was a simple power law with a luminosity of $\sim 3 \times 10^{33}$ erg s$^{-1}$. At the head of G0.13–0.11, a point source, CXOGCS J174621.5–285256, was found with a power-law photon index of $0.9^{+0.9}_{-0.7}$ and 2–10 keV-band luminosity of $\sim 8 \times 10^{32}$ erg s$^{-1}$. This luminosity was $\sim 30\%$ of the whole of G0.13–0.11. The morphology, spectrum, and luminosity indicate that G0.13–0.11 is the leading edge of a PWN, produced by a pulsar CXOGCS J174621.5–285256 moving in a strong magnetic field environment. The main body of this PWN is likely traced by a bow-shaped radio feature, which is apparently bordered by G0.13–0.11, and is possibly associated with the prominent non-thermal radio filament. The origin may be due to synchrotron radiation, or inverse Compton scattering of far-infrared photons from dust by the relativistic electrons responsible for the radio synchrotron emission. The magnetic field strength was estimated to be 0.08 mG within the radio NTF (Yusef-Zadeh et al. 2005).

The source density in the outer region (table 13) is far smaller than in the area of the inner region (table 12). This is, at least partly, due to the higher detection threshold luminosity in the larger area of the outer region than that of the inner region. In fact, most of the X-ray luminosities (2–10 keV) of the table 12 sources are $\lesssim 10^{33}$ erg s$^{-1}$, while those in table 13 are $\gtrsim 10^{33}$ erg s$^{-1}$. The source sizes of the inner region are also smaller than those of the outer region, except for some distance X-ray filaments from Sgr A*.

The summed luminosity (2–10 keV) of all the resolved X-ray filaments is $\sim 1.0 \times 10^{34}$ erg s$^{-1}$. Assuming that G0.17–0.42 has a luminosity of $\sim 5 \times 10^{32}$ erg s$^{-1}$, the lower limit of the detection threshold, the total luminosity is estimated to be $\sim 1.1 \times 10^{34}$ erg s$^{-1}$, $\sim 1\%$ of the GCXE.

### Table 13. Non-thermal X-ray filaments in the 0.5 × 1° region, excluding the inner 17° region.

| Source name | Size (arcsec$^2$) | $L_X$ (2–10 keV) ($10^{32}$ erg s$^{-1}$) | Comments | References$^1$ |
|------------|-----------------|---------------------------------|---------|----------------|
| G0.223−0.012 | 6 × 80 | 15 | Radio, PWN? | a |
| G0.13−0.11 | 7 × 33 | 40 | Radio, X-ray thread | a, b, c, e |
| G359.55+0.16 | 4 × 21 | 20 | | a, b, f, g, h |
| G359.43−0.14 | 4 × 21 | 5 | | a |
| G359.40−0.08 | 5 × 27 | 24 | | a |
| G0.17−0.42 | 180 × 18 | 15 | Near the Radio Arc | d |

Total luminosity (2–10 keV) $1.0 \times 10^{34}$ erg s$^{-1}$

$^1$As table 12, but the listed sources are in the area of the 0.5 × 1° region around Sgr A*, excluding those of the central region in table 12.

References. a: Johnson, Dong, and Wang (2009); b: Wang, Lu, and Lang (2002b); c: Yusef-Zadeh, Law, and Wardle (2002a) and Yusef-Zadeh et al. (2002b); d: Ponti et al. (2013); e: Mori et al. (2013); f: Wang, Gotthelf, and Lang (2002a); g: Lu, Wang, and Lang (2003); h: Yamauchi et al. (2014).
and one quarter of all the point sources in the inner GCXE region (subsection 6.1).

7 Past X-ray flares of Sgr A*

Sgr A* is the brightest radio point source located at the dynamical center of our Galaxy. Accurate observations of the motions of the IR stars in the close vicinity of Sgr A* have revealed that the mass of Sgr A* is \( \sim 4 \times 10^6 M_\odot \) (e.g., Genzel et al. 2010), and hence established that Sgr A* is an SMBH. The fine X-ray image with Chandra resolved Sgr A* from nearby X-ray sources for the first time (Baganoff et al. 2003). The resultant X-ray flux was very low at \( \sim 10^{33} \text{ erg s}^{-1} \). This quiescent SMBH flux would be due to a small mass flow rate within the Bondi radius. The accretion flow structure of \( \sim 0.6 \text{ pc} \) size would be marginally resolved (Baganoff et al. 2003).

Many X-ray outbursts, possibly due to fluctuations of mass accretion rate on a time scale of minutes–hours, have been observed with the rate of around one flare per day. The photon index in the flare spectrum is \( \Gamma \sim 2 \), similar to AGNs. The maximum peak luminosity is \( (1-4) \times 10^{35} \text{ erg s}^{-1} \), a few hundred times the quiescent flux of \( \sim 10^{33} \text{ erg s}^{-1} \) (Porquet et al. 2003, 2008). Still, this maximum flux is much lower than any of the AGNs. Has Sgr A* always been quiet in the past? This section reviews possible relics of big flares or high activity of Sgr A* in the past: the X-ray echo from Sgr A* (XRN; subsection 7.1), recombining plasma near Sgr A* (subsection 7.2), and jets and outflow structures from Sgr A* (subsection 7.3).

7.1 X-ray echo as a relic of the past activities of Sgr A*

The XRN is a dense MC of large \( N_{\text{H}} \) (see section 5). Thus, the observed GCXE spectrum behind the XRN (here, GCXE1) is largely absorbed by the MC, while that in front of the XRN (here, GCXE2) is not absorbed by the MC. The schematic view is shown in figure 19 (left). The observed spectrum at the XRN position is the sum of the GCXE1, GCXE2, and XRN spectra.

Ryu et al. (2009) fitted the Suzaku X-ray spectra from Sgr B2 XRNe with the combined models of GCXE1 plus XRN and GCXE2, where the former component has a large absorption of \( N_{\text{H}(\text{Abs1})} \) due to the absorption of the MC, while the latter has a small \( N_{\text{H}(\text{Abs2})} \). As shown in figure 19 (left), \( N_{\text{H}(\text{Abs1})} \) is \( > 10^{23} \text{ cm}^{-2} \), consistent with the absorption of the dense MC+ISM (table 7), while the best-fit \( N_{\text{H}(\text{Abs2})} \) is \( \sim 6 \times 10^{22} \text{ cm}^{-2} \), consistent with the absorption of the ISM. Assuming that the GCXE is spherically extended around Sgr A* with a uniform flux density, the line-of-sight position of the XRN is approximately estimated by the best-fit flux ratio of the GCXE1 and GCXE2 spectra. The projected position (two-dimensional) and the line-of-sight position provide the three-dimensional position of the XRN. The positions in the face-on view of the Sgr B XRNes are given in figure 19 (center). Hereafter, this method of three-dimensional position determination is called the X-ray tomography technique.

The Sgr C complex is composed of three XRNe (C1, C2, and C3: table 10). These are located close to each other in
projection. Ryu et al. (2013) applied the X-ray tomography method to the XRNe C1, C2 and C3, and found that these XRNe are largely separated in their line-of-sight positions: C1 and C3 are on the near side of the Galactic plane, while C2 is on the far side. These are separately associated with MCs in different velocity ranges of the radio observation. The face-on view of the positions of C1, C2, and C3 is shown in figure 19 (center).

Using the three-dimensional positions, the distances of the XRNe from Sgr A* are determined. Then, using the best-fit fluxes and MC absorptions ($N_{\text{H}}$) of $N_{\text{H}}(\text{Abs}1) - N_{\text{H}}(\text{Abs}2)$, the past luminosity of Sgr A* is estimated. The age of its past luminosity is the light travel time difference between the direct passage to Earth from Sgr A* and the passage from Sgr A* to Earth via the XRNe. Thus, the X-ray tomography analyses of many XRNe provide the X-ray activity history of Sgr A* as shown in figure 19 (right).

The X-ray luminosity of Sgr A* was at a continuously high level of $L_X \sim (1-3) \times 10^{39} \text{erg s}^{-1} \sim 70-500$ yr ago. Then, about 70 yr ago, the luminosity dropped to the current low level. The averaged past luminosity is $\sim 4-6$ orders of magnitude higher than the present luminosity. In addition, at least two short-term flares with a time scale of a few years are found. Thus, the high-luminosity level which continued $\sim 70-500$ yr ago is not due to a single flare of long duration, but it could be due to multiple overlapping short flares.

To fill the blank for the past $<70$ yr in the past Sgr A* activity history in figure 19 (right), a similar tomography method should be applied to the Sgr A MC complex, because these XRNe are the sample ($\sim 30-80$ Lt-yr in projection) nearest to Sgr A*. However, the tomography method requires very accurate spectra with Suzaku. Unfortunately, the XRN density in the Sgr A MC complex is too high (see table 9) to be separately observed with the limited spatial resolution of Suzaku.

Using XMM-Newton, Ponti et al. (2010) determined the line-of-sight positions of XRNe in the Sgr A MC complex. They assumed a long flare ($\sim 100$ yr) of a constant flux of $\sim 10^{39} \text{erg s}^{-1}$, and that all the XRNe in the Sgr A complex are behind the projected Galactic plane. From the observed fluxes and $N_{\text{H}}$ of the XRNe, they determined the distance to Sgr A*, and hence predicted the three-dimensional positions of the XRNe Bridge, M1, M2, and G0.11–0.11. This method of Ponti et al. (2010), however, gives no information on the light curve of Sgr A*, because the flux is, a priori, assumed to be constant.

Capelli et al. (2012) also determined the line-of-sight positions of XRNe in the Sgr A MC complex using equation (4); the XRNe with minimum $E_{6.4}$ have a scattering angle of $\theta = 90^\circ$, on the projected Galactic plane. The other XRNe with larger $E_{6.4}$ would be located either in front of or behind the line of $\theta = 90^\circ$ (equation (4)). To resolve this degeneracy of in front of or behind, they grouped the nine XRNe in table 9 into three groups according to their time variability profiles. Group 1 have decreasing flux (B1 and F), Group 2 have increasing flux (B2, C, and D), and Group 3 have constant flux (A, E, DS1, and DS2)—see sub-subsection 5.2.2. They assumed that the XRNe in the same group were irradiated by the same flare of a few tens of years duration (the observed time scale of the variability). Then, using the observed $E_{6.4}$, they determined the three-dimensional positions of the XRNe. From the observed flux and the column density $N_{\text{H}}$ of the XRNe, they made the X-ray light curve of Sgr A* in the range $\sim 70-130$ yr ago, with average luminosities of $\sim 10^{37}-10^{38} \text{erg s}^{-1}$.

As noted in sub-subsection 5.2.2, Clavel et al. (2013) found many bright Fe-Kα flares from small spots of $26'' \times 61''$ ($\sim 1 \text{pc} \times 2.4 \text{pc}$) and $15'' \sim 0.6 \text{pc}$ square. Since their flare peaks were $\sim 10$ times brighter than those in the quiescent level, they proposed that the past flares of Sgr A* are composed of multiple short flares of around a few years’ duration with a peak luminosity of $\sim 10^{39} \text{erg s}^{-1}$, overlaid on lower-level flares and longer-duration ($\sim 10$ yr) flares.

A key factor for the three-dimensional positions of the XRNe determined by Capelli et al. (2012) is the reliability of the absolute $E_{6.4}$. However, the observed $E_{6.4}$ has large systematic errors, as noted in sub-subsection 5.2.2. The $E_{6.4}$ of the XRNe depends on the subtraction of the local GCXE background. Since Capelli et al. (2012) used a common GCXE background at $b = -0.12$ for all the XRNe, but each XRN is located at a different position of $b$, the $E_{6.4}$ should be $(b - 0.12)$-dependent. In fact, $(b - 0.12)$ and $E_{6.4}$ are not randomly distributed, but show a clear anticorrelation as expected from the local GCXE subtraction effect. Accordingly, the line-of-sight positions (i.e., the predicted light curve) have significant systematic errors. The results of Ponti et al. (2010) for the three-dimensional position are inconsistent with those of Capelli et al. (2012), not only due to the different assumption of a single constant flux flare (Ponti et al. 2010) of $\sim 10^{39} \text{erg s}^{-1}$, or to multiple short flares of various luminosities of Sgr A* (Capelli et al. 2012), but also due to the systematic errors of local GCXE subtraction.

Ignoring these uncertainties, the predicted X-ray light curve of Sgr A* by Capelli et al. (2012) in the range of $\sim 70-130$ yr ago comes to the decaying phase in the past $\sim 70-500$ yr light curve in figure 19 (right). However, the flux is $\sim 10-100$ times lower than those of C1 and C3 in the same epoch. If all the XRNe are located in front of the line of $\theta = 90^\circ$, in contrast to the assumption of Capelli et al. (2012), the light curve would be systematically shifted.
toward the present age, at least, less than \(\sim 30–80\) yr. Then, it would be more smoothly connected with that of figure 19 (right).

In the close vicinity of Sgr \(A^*\), there exist two giant MCs: the 50 km s\(^{-1}\) and 20 km s\(^{-1}\) clouds. However, no Fe I-K\(\alpha\) line is found from these clouds (Park et al. 2005; Ponti et al. 2010). This would be due to the largely declined flare flux of Sgr \(A^*\) in recent decades.

### 7.2 Recombining plasma: Another relic of Sgr \(A^*\) activity

Sgr \(A^*\) is located in the Sgr A East SNR. If Sgr \(A^*\) had been a very bright plasma of \(~10^{39–40}\) erg s\(^{-1}\) \(\sim 70–500\) yr ago (see subsection 7.1) and if He-like iron in the hot plasma would be partially photoionized to H-like iron, then the plasma would emit the radiative recombination continuum (RRC) at \(\sim 8.7\) keV (Ozawa et al. 2009). The RRC structure was recently found in the Suzaku spectrum of Sgr A East (H. Uchiyama et al. 2017 private communication). Therefore, the RRC in the Sgr A East spectrum can be regarded as another relic of the past flare of Sgr \(A^*\) which occurred \(\sim 70–500\) yr ago.

Nakashima et al. (2013) found a possible relic of more energetic flares in the distant past. They found a peculiar X-ray plasma named GC-South at \((l, b) = (0^\circ, -1.5^\circ)\). The emission region was an ellipse with semimajor axis \(\sim 21^\prime\) and semiminor axis \(\sim 8^\prime\). The jet-like structure was elongated toward Sgr \(A^*\) (figure 20, left).

The X-ray spectrum of the GC-South plasma exhibits emission lines from highly ionized Si and S (figure 20, right). Although the X-ray spectrum of the GBXE around GC-South is fitted well with a CIE plasma (subsection 3.2), that of GC-South cannot be fitted with a CIE plasma, leaving sawtooth-shaped residuals at \(\sim 2.5\) keV and \(\sim 3.5\) keV, which are attributable to the RRCs of He-like Si and S, respectively (Yamaguchi et al. 2009). In fact, the GC-South spectrum can be fitted with an RP model. The electron temperature is \(~0.46\) keV, with an ionization temperature of \(~1.6\) keV in the initial epoch, and the plasma is now in a recombining phase after the relaxation time scale \(n_e t_{\text{electron}}\times\text{elapsed time}\) of \(~5.3 \times 10^{11}\) cm\(^{-3}\) s.

The absorption column density of the GC-South plasma is consistent with that of the Galactic bulge (GB). Thus, the GC-South plasma is likely to be located in the GB region (at 8 kpc distance). Then, the full size of the plasma, the mean electron density \((n_e)\), and the thermal energy are estimated to be \(\sim 97 \times 37\) pc\(^2\), \(\sim 0.16\) cm\(^{-3}\), and \(\sim 1.6 \times 10^{51}\) erg, respectively (Nakashima et al. 2013). Then, the RP plasma age, \(t = n_e t_{\text{electron}}\), is \(\sim 10^5\) yr.

A possible scenario is that the almost fully ionized (at least, for Si and S) plasma was made by a bright flare X-ray of Sgr \(A^*\) \(~10^5\) yr ago, and the plasma is now in the RP phase. Using this scenario, Nakashima et al. (2013) argued that the past flare luminosity of \(~10^5\) yr ago is near the Eddington limit of \(\sim 10^{44}\) erg s\(^{-1}\), more energetic than those of recent flares of \(~70–500\) yr ago.

### 7.3 The other possible relic of Sgr \(A^*\) activity

As noted in subsection 6.1, Chandra found three filaments (knot-1, knot-2, and knot-3) near Sgr \(A^*\). These are aligned almost in a straight line (see figure 21), but it slightly curves and points to Sgr \(A^*\). With a power-law model fit, the \(N_{\text{HI}}\) were found to be \(\sim (10–16) \times 10^{22}\) cm\(^{-2}\), consistent with the value at the GC distance. Then, the sizes and luminosities of...
knot-1, knot-2, and knot-3 are nearly the same, at \(10'' \times 4''\) and \((2-6) \times 10^{12} \text{ cm}^{-2}\), respectively (Koyama et al. 2004; Munou et al. 2008). The power-law photon indexes were flat and \(\lesssim 1.3\). From these facts, Koyama, Senda, and Murakami (2004) suggested that the three filaments have the same origin: knot-1, knot-2, and knot-3 would be due to sequential plasma ejections from a single source, Sgr A*.

The other jet-like structure, G359.944−0.052 (Jet, table 12), has a size of \(\sim 2'' \times 19''\), and is located in the close vicinity to the southeast of Sgr A* with its major axis pointing to Sgr A*. Li, Morris, and Baganoff (2013) found that the spectrum of Jet is a power law with photon index, absorption column, and luminosity (2~10 keV) of \(\sim 1.8\), \(\sim 12 \times 10^{22} \text{ cm}^{-2}\), and \(\sim 2.4 \times 10^{32} \text{ erg s}^{-1}\), respectively. The large absorption column suggests that Jet is located at the GC distance. The photon index and luminosity are typical of a jet from synchrotron emission. The position of the major axis of Jet is in alignment with the curved line connecting Sgr A*, knot-1, knot-2, and knot-3. Thus, it may be conceivable that Jet is a counter-jet of knot-1, knot-2, and knot-3, or that these are highly collimated magnetized outflows of relativistic particles emanating from Sgr A* (Li et al. 2013).

The ejection epochs of these jets (outflows) could be determined from the three-dimensional ejection angle and the velocity of the jets, but these are all unknown. However, the projected distances of the jets are small (\(\sim 0.7-8\) pc), and hence the jet ejections would be recent events. If the past flares of Sgr A* triggered the jet ejections, the flare energies would be significant to produce such prominent jets.

As noted in sub-subsection 4.2.3, Heard and Warwick (2013b) found the diffuse thermal sources NW, SE, and E in the GC region from the XMM-Newton image. They suggested that these three sources are young–intermediate-aged SNRs. However, some aspects are unusual: the sizes are smaller than typical SNRs of \(\sim 1\) keV temperature; the plasma density is a very high density of \(\sim 4.6-9.9 \text{ cm}^{-3}\); the morphology shows bipolar flow structures emanating from Sgr A* or the Sgr A East SNR with angles nearly perpendicular to the Galactic plane. The locations are only \(\sim 5-10\) pc away from Sgr A*. Therefore, Heard and Warwick proposed an alternative scenario that these thermal plasmas are outflows driven by intermittent outbursts of Sgr A*. Assuming that the velocity is \(1000 \text{ km s}^{-1}\), the high-speed stellar wind of a massive star, the timescale for the plasma to reach the \(6' (14 \text{ pc})\) distance (the most remote position of these plasmas) is \(\sim 10^4-10^5\) yr. This is the same age as GC-South (subsection 7.2).

The Fermi Bubbles are largely extended GeV gamma ray sources which appear \(\sim 50''\) above and below the GC (Dobler et al. 2010; Su et al. 2010). These could be due to starbursts or to a nuclear outburst that happened near the GC about 10 Myr ago. The same idea was first proposed by Sofue (2000) to account for the North Polar Spur (NPS). The morphology is spatially correlated with the Wilkinson Microwave Anisotropy Probe (WMAP) haze, and the edges of the bubbles also line up with the NPS in the ROSAT X-ray maps. Suzaku revealed a large amount of neutral matter absorbing the X-ray emission in the bubble direction, as well as the existence of plasma of temperature \(\sim 0.3\) keV. These are naturally interpreted as the shock-heated Galactic halo during the bubble expansion (Kataoka et al. 2013).

The 511 keV line emission by INTEGRAL (Jean et al. 2006; Weidenspointer et al. 2008) would be another hint of past activity near the GC or Sgr A*.

8 Methodology for determining the origin of the GDXE

The long-standing questions regarding the origin of the GDXE are: What fractions of the GDXE are resolved into point sources? What are the populations of the point sources? The candidate point sources should have similar spectra (plasma temperatures of more than a few keV) to the GDXE and be reasonably bright in the 2–10 keV band to explain the GDXE flux. These Galactic point sources are hereafter called X-ray active stars (XAS). The majority of the XASs are mCVs, non-mCVs, and ABs.

In the previous sections, many arguments for the origin of the GDXE and the answers to the above questions have been given. However, the predictions are often quantitatively inconsistent, and are subject to variations (e.g., in
authors, instruments). The reasons for these inconsistencies are mainly due to large errors in the observed physical parameters (both statistical and systematic), and partly due to confusing definitions of XASs (mCVs, non-mCVs, and ABs), to differences in the energy band of XLF, to differences in the analysis method of $EW_{\text{Fe-K}}$, and so on.

Thus, this section discusses these issues in detail, adopting two methodologies for determining the GDXE origin. One is direct resolution of the GDXE into the XASs. In this section, this approach is referred to as the flux integration method (FIM) for the XASs (subsection 8.1). The other is a quantitative estimation of whether or not, and to what extent, the GDXE spectrum is reproduced by the spectra of the XASs; this is referred to as the spectrum accumulation method (SAM) for the XASs (subsection 8.2).

Non-negligible systematic errors for the origin of the GDXE, regardless of the FIM or the SAM approach, are found in the spectra (e.g., $EW_{\text{Fe-K}}$) and fluxes of the GDXE and the XASs. The next subsections give interpretations and discussions with critical comments on these systematic errors.

8.1 Flux integration method

The FIM approach is a development of the previous study described in sub-subsection 2.1.1. If the instrument has enough power to resolve the XASs down to the luminosity limit of $\gtrsim 10^{32}$ erg s$^{-1}$ (2–10 keV)—the lowest luminosity of the XASs with plasma temperature of a few keV—then the FIM is a very simple and straightforward approach. However, even with the highest spatial resolution and deepest exposure observations of Chandra, the resolved XASs are limited in the high-luminosity range of $\gtrsim 4 \times 10^{39}$ erg s$^{-1}$, which is achieved only for the GBXE (Revnivtsev et al. 2009; Hong 2012). Therefore, the XAS fraction must be estimated by the extrapolation of the observed fraction from the high-luminosity band to the lowest luminosity limit of $\sim 10^{27} \text{--} 10^{28}$ erg s$^{-1}$, using the empirically made XLF—the cumulative X-ray luminosity as a function of the luminosity of the resolved XASs.

A problem of the FIM is that the actually resolved XAS fraction and its XLF have significant uncertainties and variations from author to author, namely, the systematic errors. These systematic errors come mostly from the non-X-ray background (NXB)$^5$ subtraction, which is serious in the low-luminosity band of $\lesssim 10^{31}$ erg s$^{-1}$. These systematic errors are separately discussed in subsections 9.1, 9.2, and 9.3 in detail, describing the cases of the GBXE, GRXE, and GBXE, respectively.

As for the XLF, Sazonov et al. (2006) constructed an XLF (2–10 keV) in the luminosity band of $10^{30} \text{--} 10^{34}$ erg s$^{-1}$ using the XASs in the solar neighborhood observed with RXTE and ROSAT. They claimed that the XLF is mainly composed of CVs and ABs with fluxes per $M_{\odot}$ of $\sim 1.1 \times 10^{27}$ erg s$^{-1}$ M$^{-1}_{\odot}$ and $\sim 2.0 \times 10^{27}$ erg s$^{-1}$ M$^{-1}_{\odot}$, respectively. The composition ratio of CV to AB was 1 : 2. However, a large error exists in the process of the conversion from the ROSAT luminosity band of 0.1–2.4 keV to the RXE luminosity band of 2–10 keV. In fact, they estimated that the systematic error in the conversion process is $\gtrsim 50\%$. Possibly, the XLF in the lowest luminosity range of $\sim 5 \times 10^{27} \text{--} 10^{30}$ erg s$^{-1}$ has an even larger systematic error.

Warwick (2014) constructed another XLF (2–10 keV) in the luminosity band of $10^{28} \text{--} 10^{44}$ erg s$^{-1}$, using the Galactic ridge survey data of XMM-Newton. Warwick claimed that the XLF is composed of CVs and ABs with fluxes per $M_{\odot}$ of $\sim 2.5 \times 10^{27}$ erg s$^{-1}$ M$^{-1}_{\odot}$ and $\sim 1.1 \times 10^{28}$ erg s$^{-1}$ M$^{-1}_{\odot}$, respectively. The composition ratio of CVs to ABs was 1 : 4. This ratio is noticeably different from that of Sazonov et al. (2006).

Revnivtsev et al. (2009) and Hong (2012) made another XLF (6.5–7.1 keV) in the luminosity band of $4 \times 10^{32} \text{--} 10^{33}$ erg s$^{-1}$, using the Chandra data in the GBXE field. The shapes of these XLFs are quite different. From the shape of their XLF, Revnivtsev et al. (2009) claimed that the main components are mCVs (high-luminosity band) and ABs (low-luminosity band). On the other hand, Hong (2012) claimed that the composition is mainly mCVs, quite different from Revnivtsev et al. (2009), Sazonov et al. (2006), and Warwick (2014) with their AB-dominant composition.

The apparent inconsistency in the XLF composition among these authors could come partly from the energy band difference. The AB spectra become much softer approaching the lower luminosity limit, and hence the contribution in the high-energy band (e.g., 6.5–7.1 keV) becomes smaller than that of the canonical energy band of 2–10 keV. The other possibility could be a confusion in definition between CV and AB: whether non-mCVs (dwarf nova) are included in the CVs, in the ABs, or treated independently.

Accordingly, the FIM should be applied separately to the mCVs, non-mCVs, and ABs with a unified energy band. The sum of these separate FIM estimations is the final solution of the XAS fraction in the GDXE.

8.2 Spectrum accumulation method

The SAM approach is the development of the early studies given in sub-subsection 2.1.2. Using Suzaku, Yuasa, Makishima, and Nakazawa (2012) predicted that most of the fluxes of the GDXE are due to mCVs. Hong (2012)
and Heard and Warwick (2013a) predicted the same conclusion using Chandra and XMM-Newton spectra, respectively. These scenarios of mCV-dominant origins, however, have a serious problem that the $EW_{\text{Fe-K}}$ of the mCVs is far smaller than that of the GDXE. On the other hand, Xu, Wang, and Li (2016) found that the integrated spectra of the non-mCVs (DNe) in the Suzaku archive had comparable $EW_{\text{Fe-K}}$ to the GDXE, and argued that the GRXE is mainly composed of non-mCVs, as previously proposed by Mukai and Shiokawa (1993).

The SAM approaches (Xu et al. 2016; Heard & Warwick 2013a; Yuasa et al. 2012; Hong 2012) to predicting the XAS origin for the GDXE all have common problems. Their selected XAS candidates were only mCVs and ABs, apart from the non-mCV dominant scenarios of Xu, Wang, and Li (2016) and Mukai and Shiokawa (1993). They used the limited information on the $EW_{\text{Fe-K}}$ for all the relevant objects, and did not separately examine the origins of the GCXE, GBXE, and GRXE involving all the possible candidate XASs. One important note, related to the $EW_{\text{Fe-K}}$, is that the Fe abundances in the observed thermal plasmas of the mCVs, non-mCVs, and ABs are different: $\sim 0.3$, $\sim 0.6$, and $\sim 0.2$ solar, respectively (Nobukawa et al. 2016). In particular, the observed Fe abundances in the mCV plasma of far less than 1 solar are often ignored in most of the mCV-dominant scenarios. The reasons for the low Fe abundance and the differences among the XASs could be due to different production and emission mechanisms of the plasmas among the XASs. The real physical process remains an unsolved problem, but is beyond the scope of this review.

As for the $EW_{\text{Fe-K}}$, one technical note is that the default choice of XSPEC package, equith, uses the continuum flux in the energy range of $\pm 0.3$ keV for the center energy of the relevant iron K-shell line. Thus, depending on the data analysis process, the value of $EW_{\text{Fe-K}}$, for example, would be underestimated by the extra flux of the adjacent Fe-$\alpha$ and Fe XXVI-Ly$\alpha$ lines. In the case of two-component spectra of the GDXE a thermal plasma plus a power-law emission, the $EW_{\text{Fe-K}}$ may be confused, whether it is estimated under the continuum shape of the thermal plasma ($EW_{\text{Fe-K}}$), the power-law continuum ($EW_{\text{Fe-Ly}}$), or the sum of both components.

To avoid source-to-source and author-to-author mismatches in the estimation of $EW_{\text{Fe-K}}$ and to make a proper comparison between those of the GDXE and XASs, unified data processing and analysis for all the GDXE and XASs by the same author are preferred. Nobukawa et al. (2016) determined the $EW_{\text{Fe-K}}$ of the GDXE and XASs using just the Suzaku archive in a unified analysis. The results for the GDXE are given in Table 5.

The $EW_{\text{Fe-K}}$ of the XASs has been measured by many authors, but the qualities and samples were limited (e.g., Yamauchi et al. 2016; Nobukawa et al. 2016 and references therein). Nobukawa et al. (2016) found in the best-quality Suzaku spectra that the $EW_{\text{Fe-K}}$ and $EW_{\text{Fe-Ly}}$ in the XAS spectra were explained well by a CIE plasma with free parameters of temperature and Fe abundance. The Fe-$\alpha$ line flux could be due to the surrounding cloud, and hence $EW_{\text{Fe-K}}$ was estimated by the parameters of the covering solid angle ($\Omega$), the absorption column ($N_{\text{H}}$), and the flux above 7.1 keV. They found a good correlation between the $EW_{\text{Fe-K}}$ and the temperature of the mCVs, non-mCVs, and ABs with different free parameter of $\Omega \times N_{\text{H}}$. Thus, the $EW_{\text{Fe-K}}$ was quantitatively included with the parameter $\Omega \times N_{\text{H}}$ for each mCV, non-mCV, and AB in the CIE model. Then, all the observed $EW_{\text{Fe-K}}$ were explained well by the CIE model (hereafter, the 1-T model).

Nobukawa et al. (2016) found that the X-ray luminosity of XASs were well correlated with the temperature of the 1-T model. In the XLF, the relevant luminosity ranges were $\sim 10^{31} - 10^{34}$ erg s$^{-1}$, $\sim 10^{29} - 10^{32}$ erg s$^{-1}$, and $\sim 10^{27} - 10^{30.5}$ erg s$^{-1}$, corresponding to the temperature ranges of $\sim 10–20$ keV, $\sim 3–10$ keV, and $\sim 1–3$ keV for mCVs, non-mCVs, and ABs, respectively (Table 14). Then, they constructed a two-temperature CIE model (2-T model) which is closely approximated spectra in the relevant luminosity bands of the XASs.\(^\dagger\)

\(\dagger\) It is better to refer to the original paper of Nobukawa et al. (2016), because the process to construct the 2-T models is very complicated.

### Table 14. Physical parameters of the mCV, non-mCV, and AB.\(^\dagger\)

| Parameter | mCV | non-mCV | AB |
|-----------|-----|---------|----|
| $kT_e$ (keV) | $23.3^{\pm 1.1}_{\pm 1.7}$ | $10.7 \pm 1.7$ | $4.25 \pm 0.18$ |
| $L_X$ (erg s$^{-1}$) | $10^{31} - 10^{34}$ | $10^{29} - 10^{32}$ | $10^{27} - 10^{30.5}$ |
| $SH$ (pc)† | $130 - 160$ | $130 - 160$ | $150 - 300$ |
| $EW_{\text{Fe-K}}$ (eV) | $169 \pm 5$ | $82 \pm 7$ | $28 \pm 5$ |
| $EW_{\text{Fe-Ly}}$ (eV) | $118 \pm 7$ | $451 \pm 10$ | $327 \pm 8$ |
| $EW_{\text{Fe-Ly}}$ (eV) | $60 \pm 7$ | $167 \pm 9$ | $45 \pm 6$ |

\(\dagger\) Errors are the 1σ confidence level.

\(\dagger\) Ak et al. (2008), Patterson (1984), Strassmeier et al. (1993).
In principle, a multi-T model would be more appropriate than the 2-T model to incorporate the temperature-dependent XLF. However, in reality, the 2-T and multi-T models show no great difference beyond the observed statistical errors in the XAS spectra. Accordingly, the GCXE, GBXE, and GRXE spectra should be compared with a combination of the 2-T models of the XASs (Nobukawa et al. 2016). The best-fit results are shown in figure 22 and table 15. Since the $EW_{\text{Fe-K}}$ of the GDXE is more similar to the non-mCVs than any other XASs, it would seem reasonable that the non-mCVs occupy the largest fraction in the best-fit results (table 15).

The best-fit $\chi^2$/d.o.f. for the GCXE, GBXE, and GRXE spectra are 2637/276, 148/95, and 282/91, respectively. Thus the SAM predicts that a combination of the XASs can explain the spectra of the GBXE, but cannot the GRXE and GCXE spectra. Detailed discussions are separately given in subsections 9.1, 9.2, and 9.3 for the GBXE, GRXE, and GCXE, respectively.

The SAM approach using the 2-T model is less sensitive to the assumed XLF than the FIM. This is a large advantage of the SAM over the FIM. Possible systematic errors due to NXB subtraction would also be less sensitive than for the FIM. In fact, the $EW_{\text{Fe-K}}$ in the Suzaku GCXE spectra was almost the same among the authors (see subsection 3.3), although the data reduction and analysis methods were independent. The 2-T model of Nobukawa et al. (2016) smeared out position-to-position variations in the GDXE,

because they used a larger area for the GDXE spectra than any of other authors or instruments.

The realistic error of the most important parameter, the mean $EW_{\text{Fe-K}}$ of non-mCVs, was statistically estimated using the standard deviation of the sample of 13 non-mCVs (Nobukawa et al. 2016), and its resultant $1\sigma$ error was $\sim$10%. As a result, the best-fit composition ratios of mCVs, non-mCVs, and ABs (table 15) would have a systematic error of $\sim\pm 0.1$. This, however, has no serious impact on the discussion of the origin of the GDXE given in section 9.

### 8.3 Combined FIM and SAM approach

In the FIM approach, the essential points are to obtain a reliable fraction of the resolved XASs and a reliable XLF down to the limiting luminosity of $\sim 10^{27}$ erg s$^{-1}$. The best instrument for the FIM is Chandra, because of the best spatial resolution of $\sim 1''$, two orders of magnitude better than Suzaku. The weakest point is its large NXB, about ten times larger than Suzaku. Therefore, possible flux errors due to the NXB subtraction are not negligible for the low-surface-brightness sources (the GBXE and GRXE, and faint XASs).

In the SAM approach, the essential points are to obtain reliable spectra of the GDXE (GBXE, GRXE, and GCXE) and the XASs (mCVs, non-mCVs, and ABs). The key parameters are the values of $EW_{\text{Fe-K}}$, which are sensitive to the continuum levels, or the NXB subtraction. Suzaku
is the best instrument for the SAM approach, because of the reasonably large effective area and the good spectral resolution. The NXB is about ten times lower than that of Chandra, and the stability and reproducibility of the NXB are far better than Chandra and XMM-Newton.

Whether we select the FIM or the SAM, to minimize the possible systematic errors we should utilize the best instruments for FIM and SAM, and make a unified analysis for the GDXE and XASs. In order to minimize the author-dependent systematic error, a simultaneous and unified study with Chandra (FIM) and Suzaku (SAM) by the same researchers is important. Currently, no such unified work has been available. Therefore, independent approaches by the FIM and SAM should be applied complementarily to the origins of the GDXE. If the fluxes are not explained by the FIM, and/or if the spectra are not explained well by the SAM, some new source other than known XASs must be involved, regardless of point-like or diffuse sources.

So far, the point-source origin of the GDXE led by the FIM is more widely accepted, because the FIM is a simple approach, and has no risk of involving any new Galactic sources or some new physical process other than emissions of the known XASs. On the other hand, although the SAM did not exclude the contribution of the known XASs in some fractions, the SAM did not avoid the risk of involving new objects or new concepts of uncommon physical processes. Due to this risk, the SAM approach has been less accepted. In the next section, the origin and structure of the GBXE (subsection 9.1), GRXE (subsection 9.2), and GCXE (subsection 9.3) are discussed separately, applying equally both the FIM and the SAM.

9 Origins of the GCXE, GBXE, and GRXE

The true origins of the GDXE are not conclusive, due to non-negligible errors in the observed results. The important fact is that the EWF_{Fe-K} and SH_{Fe-K} are all different among the GCXE, GBXE, and GRXE. Therefore, the origin of the GBXE, GRXE, and GCXE should be discussed separately, as in subsections 9.1, 9.2, and 9.3, respectively.

9.1 Galactic bulge X-ray emission

Revnivtsev et al. (2009) conducted deep observations (∼1 Ms) in the region of (l, b) = (0.1, −1:4), named the Chandra Bulge Field (CBF). Although the CBF is near the GC, Yamauchi et al. (2016) found that the flux ratio of the GBXE component to that of the GCXE at (l, b) = (0.1, −1:4) was more than ∼10 (see figure 4). Thus, the CBF is not in the GCXE region but is almost in the pure GBXE region.

In the central region of the CBF, Revnivtsev et al. (2009) applied the FIM. The XLF in the 6.0−7.1 keV band showed a slow increase in the luminosity range of ∼10^{30}−10^{32} erg s^{-1} (2−10 keV). The resolved XAS fraction at 10^{30} erg s^{-1} (2−10 keV) was ∼50%, and then showed a rapid increase in the luminosity range of ∼4 × 10^{29}−10^{30} erg s^{-1}, and finally the resolved XAS fraction became ∼80% of the GBXE at the lowest luminosity limit of ∼4 × 10^{29} erg s^{-1} (2−10 keV). Revnivtsev et al. predicted that the rapid increase of the XLF in the low-luminosity band is due to the increasing contribution of ABs, and hence the contribution of ABs to the GBXE is very large in the low-luminosity band.

In the same central region of the CBF, Hong (2012) made another XLF using the same data set and energy band as analyzed by Revnivtsev et al. (2009). His XLF showed a monotonic increase toward the low luminosity. The resolved XAS fraction at 10^{30} erg s^{-1} was already ∼60%−70%, and then showed a slow increase to ∼70% at ∼4 × 10^{29} erg s^{-1} (2−10 keV). He predicted that the smooth XLF is due to a single class of XASs, namely mCVs, and suspected that more than ∼70% of the GBXE is resolved into mCVs, in contrast to the prediction of Revnivtsev et al. (2009).

Morihana et al. (2013) reported that the EWF_{Fe-K} of the resolved point sources in the CBF was ∼100 eV in the luminosity range of ∼10^{32} erg s^{-1} (2−8 keV), where they regarded the candidate point sources as mCVs and AGNs (see also Hong et al. 2009). The EWF_{Fe-K} increased by a constant rate in the range of 7 × 10^{30}−7 × 10^{31} erg s^{-1} (2−8 keV), see figure 13 of Morihana et al. (2013), possibly due to an increasing contribution of non-mCVs and/or ABs. In the range of 7 × 10^{31} erg s^{-1} (2−8 keV), the EWF_{Fe-K} became ∼300 eV, where the main contributors would be non-mCVs and/or ABs. This trend is, at least semi-quantitatively, consistent with Revnivtsev et al. (2009), but is against the mCV-dominant scenario of Hong (2012).

The causes of the significant difference in XLF profiles between Revnivtsev et al. (2009) and Hong (2012) can be found in the difference of the resolved XASs in the low-luminosity band of ∼10^{30} erg s^{-1} (2−10 keV). Most of the resolved XASs in the faintest-luminosity range are not the stars that belong to both Revnivtsev et al. (2009) and Hong (2012). This inconsistency may come from differences in NXB estimation and the related analysis between the two data, because the surface brightness of the NXB at ∼6−7 keV is ∼10 times larger than the X-ray flux in the CBF (Hong 2012). In fact, Hong (2012) reanalyzed the same data as in Revnivtsev et al. (2009), and found that the XLF inconsistency disappeared.

Another problem for these authors is their flat spectra of the CBF X-rays and those of the resolved XASs. These
are found in figure 2 of Revnivtsev et al. (2009) and in figure 5b of Hong (2012). Comparing them with the GBXE spectrum of Nobukawa et al. (2016), the flat spectra of Revnivtsev et al. (2009) and Hong (2012) could be due to under-subtraction of the NXB.\(^7\)

Morihana et al. (2013) reported that the \(EW_{6.7}\) in the CBF X-rays may be \(\sim 580\) eV,\(^8\) which is significantly smaller than that of the whole GBXE reported by Nobukawa et al. (2016) as \(\sim 720\) eV (table 5). This discrepancy could be either the difference in the selected regions, or more likely due to the incomplete NXB subtraction of Chandra.

Yuasa, Makishima, and Nakazawa (2012) observed the GBXE and GRXE regions with Suzaku. The spectra were fitted with a model spectrum of mCVs. The essence of this fit was to reproduce the \(EW_{6.0}\) and \(EW_{6.97}\) values, with the two free parameters of the mCV mass (white dwarf mass) and Fe abundances: the free parameter of mCV mass tunes the flux ratio of \(EW_{6.0}/EW_{6.97}\) (plasma temperature), while the Fe abundance tunes the absolute \(EW_{6.0}\) and \(EW_{6.97}\) value. The other important value, \(EW_{6.4}\), was an independent free parameter. Therefore, their mCV-dominant model should obviously give a nice fit to the spectra of the GBXE and GRXE, and in particular to those in the most important energy band around the Fe-K\(^\alpha\) line. The best-fit mCV mass and Fe abundance for the GBXE were \(\sim 0.7\) M\(_\odot\) and \(\sim 0.8\) solar, while those for the GRXE were \(\sim 0.7\) M\(_\odot\) and \(\sim 0.9\) solar, respectively. The 10\% smaller Fe abundance of the GBXE than the GRXE is consistent with the \(EW_{6.0}\) and \(EW_{6.97}\) of the GBXE being \(\sim 10\%\) smaller than those of the GRXE (table 5).

Since the Fe abundance in the hot plasma of the mCV in the solar neighborhood is \(\sim 0.3\) solar (e.g., Yamauchi et al. 2016; Nobukawa et al. 2016 and references therein), the hot plasma in the mCV-dominant model of Yuasa, Makishima, and Nakazawa (2012) should have around a three times larger Fe abundance than that of the solar neighborhood. However, the Fe abundances should be nearly constant in the wide range of the GRXE and GBXE regions. As noted in subsection 5.2.2, the Fe abundance over the whole GCXE is nearly the same at \(\sim 1.1\)–1.2 solar. Infrared star observations also show a global uniformity of Fe abundances in the wide range from the Galactic ridge to the Galactic center (e.g., Cunha et al. 2007 and references therein). Thus the Fe abundance is almost the same in the whole GRXE, GBXE, and GCXE regions, in conflict with the mCV-dominant scenario for the GBXE spectrum of Yuasa, Makishima, and Nakazawa (2012) and Hong (2012).

The \(SH_{6.7}\) and \(SH_{6.97}\) of \(\sim 310\) pc (2:2) and the \(SH_{6.4}\) of \(\sim 160\) pc (1:1) in the GBXE (Yamauchi et al. 2016; table 4) are globally consistent with those of \(\sim 130\)–300 pc in the XAS spectra (see table 14). Therefore, Nobukawa et al. (2016) tried the SAM approach with the 2-T model of the XASs spectra (see subsection 8.2). Unlike Yuasa, Makishima, and Nakazawa (2012), the 2-T models of Nobukawa et al. (2016) are based on the practically observed values of the temperatures and Fe abundances to predict the \(EW_{6.0}\) for all the XASs.

Nobukawa et al. (2016) obtained a reasonable fit of \(\chi^2/\text{d.o.f.} = 148/95\) with the combined 2-T models (figure 22, center; table 15). Thus, they concluded that the major fraction of the GBXE is due to the non-mCVs and ABs. The predicted AB ratio of 30\% is far smaller than that in the AB-dominant scenario by Revnivtsev et al. (2009), and far larger than those in the mCV-dominant scenarios by Yuasa, Makishima, and Nakazawa (2012) and Hong (2012). Although the flux of the non-mCVs is about ten times larger, the space density is ten times larger than those of the mCVs (Patterson 1984). Therefore, it may not be surprising that the non-mCVs are the main contributors to the GBXE, in contrast to the many previous predictions.

In summary, ignoring possible systematic errors in the FIMs, the broad consensus is that \(70\%–80\%\) of the GBXE flux is explained by either the mCVs, non-mCVs, ABs, or some mixture of these sources (Revnivtsev et al. 2009; Hong 2012). This prediction is consistent with the SAM prediction (Nobukawa et al. 2016). However, the composition ratios differ between the FIM and SAM, and even among the FIMs. Furthermore, this prediction comes from works considering limited areas of the GBXE, the CBF of \(|l|\geq 0.0\) and \(|b|\sim 1.4\) in the FIM and the off-plane field of \(|l|<0.6\) and \(1.0<|b|<3.0\) in the SAM. Therefore, unsolved questions still remain: Which is the major contributor, mCVs, non-mCVs, or ABs? How much is the mixing ratio of these sources in all the GBXE region?

## 9.2 Galactic ridge X-ray emission

The deepest point source survey in the GRXE was made with Chandra by Ebisawa et al. (2001, 2005) near \((l, b)=(28.5, -0.2)\), named the Galactic Ridge Field (GRF). Ebisawa et al. (2005) resolved \(\lesssim 10\%\) of the GRF flux into XASs at the detection threshold luminosity of \(\sim 2\times 10^{31}\) erg s\(^{-1}\) (2–10 keV). In the same region (GRF),
Revnitsev and Sazonov (2007a) reported that the resolved XAS fraction is \( \sim 19\% \) in the luminosity range of \( \sim 10^{30} - 10^{32} \) erg s\(^{-1}\) (1–7 keV). This ratio is converted to \( \sim 10\% \) at \( \sim 2 \times 10^{31} \) erg s\(^{-1}\), using the mean XLF (Sazonov et al. 2006; Hong 2012; Warwick 2014).

Warwick (2014) applied the FIM to the origin of the GRXE. He assumed that the resolved XAS fraction is the same as Ebisawa et al. (2005) and Revnivtsev and Sazonov (2007a). Then, he extrapolated this fraction to the low-luminosity limit of \( \sim 10^{28} \) erg s\(^{-1}\) along his XLF, which was made using the XMM-Newton archives. He argued that more than 90% of the GRXE flux in the GRF is resolved into the XASs (2–10 keV) with the composition ratio of the CVs to ABs of about 1 : 4 (subsection 8.1). These FIM results may, however, have a large uncertainty due to the ambiguity of the XLF profiles sensitive to the AB temperature near the low-luminosity limits of less reliable data. Furthermore, the observed surface brightness of the GRXE obtained with Chandra (Ebisawa et al. 2001, 2005; Revnivtsev & Sazonov 2007a) and XMM-Newton (Hands et al. 2004) is about 1.3 times larger than those of Suzaku (Ebisawa et al. 2008; Nobukawa et al. 2016). These differences may also be due to some systematic errors in the NXB subtraction in the Chandra and XMM-Newton data.

For the SAM approach, Warwick, Byckling, and Pérez-Ramírez (2014) analyzed the XMM-Newton slew survey on the Galactic plane data, and reported that the spectrum of the resolved XASs in the luminosity band of \( \sim 8 \times 10^{32} \) erg s\(^{-1}\) (2–10 keV) had \( E_{\text{W}_{0.7}} \), \( E_{\text{W}_{5.7}} \), and \( E_{\text{W}_{0.97}} \) of \( \sim 90 \), \( \sim 80 \) eV, respectively, and hence they claimed that the origin of the XLF of the GRXE is mCVs in the luminosity band of \( \sim 8 \times 10^{32} \) erg s\(^{-1}\) (2–10 keV). This conclusion may be correct, because the \( E_{\text{W}_{0.7}} \) values in this high-luminosity band are very close to those of the mCVs (Nobukawa et al. 2016).

Xu, Wang, and Li (2016) found that the Suzaku spectrum of the non-mCVs is similar to the GRXE. Since the observed luminosity of the non-mCVs did not cover the low-luminosity band of the XLF, they made a model spectrum of the non-mCV to include a full luminosity range of the XLF. The model spectrum of the non-mCV was also very similar to the GRXE. Therefore, they predicted that the majority of the GRXE is due to unresolved non-mCVs. However, they made a model of non-mCVs in which only the \( E_{\text{W}_{0.7}} \) values are taken into account.

Spectra of the GRXE have been observed with Suzaku, in regions ranging from sub-degree to a few degrees’ size at \( |l| \sim 8^\circ, 15^\circ, \) and \( 28^\circ \) on the Galactic plane by Ebisawa et al. (2008) and Yamauchi et al. (2009). Due to the low surface brightness and the limited exposure time of \( \sim 50 - 100 \) ks, not all the \( E_{\text{W}_{0.7}} \) values were determined, only the \( E_{\text{W}_{0.7}} \). The \( E_{\text{W}_{0.7}} \) values were variable, position-dependent in the range of \( \sim 350 - 640 \) eV, larger than the statistical errors of typically \( \sim 100 \) eV. These large position-dependent variations suggest that the origin of the GRXE is not fully due to the assembly of numerous XBSs.

The large statistical errors and large position-dependent variations of the \( E_{\text{W}_{0.7}} \) do not allow any quantitative study of the SAM. To increase the statistics and to smear out the position-dependent variations, Nobukawa et al. (2016) produced the GRXE spectrum using all the Suzaku archives. The total exposure time was 3 Ms, two orders of magnitude larger than those of the individual positions, and hence the statistical error of the \( E_{\text{W}_{6.7}} \) was reduced to \( \sim 10 \) eV (table 5). They fitted the GRXE spectrum with a combination of the 2-T models of the XASs (subsection 8.2). The fit was rejected with \( \chi^2/\text{d.o.f.} = 282/91 \) (table 15).

Although statistically rejected, the best-fit composition ratio of the mCV, non-mCV, and ABs was 1 : 5 : 4, similar to the GBXE of 0.3 : 6.7 : 3 (table 15). Therefore, the shapes of the XLF of the GBXE and GRXE would be similar to each other. The XAS fraction of the GBXE at the luminosity limit of \( \sim 2 \times 10^{31} \) erg s\(^{-1}\) (Revnivtsev et al. 2009; Hong 2012) is three times larger than that of the GRXE. If the same GBXE XLF is applied to the GRXE, the resolved XAS fraction of the GRXE (Ebisawa et al. 2005; Revnivtsev & Sazonov 2007a) is \( \lesssim 30\% \) at the same luminosity limit of \( \sim 2 \times 10^{31} \) erg s\(^{-1}\). Thus, the observational facts of both the FIM and the SAM suggest that the GRXE is not only composed of the XASs, but has an additional component, either a new class of points or diffuse sources.

By excluding the poor statistic band of \( \gtrsim 7.5 \) keV, the largest residual from the combined 2-T model is the excess flux of the Fe-I-K line (figure 22, right). Yamauchi et al. (2016) found that the \( \Delta l_{6.4} \) was \( \sim 70 \) pc, smaller than any of the XASs (table 14), but rather similar to that of the MCs. Nobukawa et al. (2015) found an \( E_{\text{W}_{6.4}} \) excess at the east of the Galactic plane of \( b = 2^\circ - 4^\circ \) and \( b = 0^\circ \) compared to the west of the same but negative longitude. The X-ray spectra from both the east and the west regions are shown in figure 23a. The Fe XXV-He\( \alpha \) and Fe XXVI-Ly\( \alpha \) fluxes are almost the same between the east and the west, while the Fe-I-K flux shows nearly twice the excess in the east compared to the west.

Then, Nobukawa et al. subtracted the western spectrum from the eastern one, and made the X-ray spectrum of the eastern excess, as shown in figure 23b. They fitted the spectrum with a model of a power-law continuum and a Gaussian line for the Fe-I-K line at 6.4 keV. The best-fit photon index and \( E_{\text{W}_{6.4}} \) were 3.0 ± 1.3 ± 0.4 keV, respectively. These values are explained well by a scenario of LECR\( \rho \) bombardment (figure 12). Thus, a significant contribution of the Fe-I-K line in the GRXE could come from bombardment of the MCs by LECR\( \rho \) (Nobukawa...
et al. 2015, 2016; Yamauchi et al. 2016), although the possibility of X-ray irradiation by bright XB (Sunyaev et al. 1993) or of LECRe bombardment (Valinia et al. 2000) would be partly possible.

Sato et al. (2014, 2016) and Nobukawa et al. (2017) found an excess of the Fe-Kα line from regions of seven intermediate-aged SNRs in the regions of 6° < |l| < 25° and |b| < 0.5. Since the diffuse hard X-ray flux (e.g., 5–10 keV band) was negligibly small, these SNRs were not identified as point sources, and then the excess of the Fe-Kα flux was regarded as the position-dependent fluctuation in the GRXE. Even X-ray undetected, intermediate-aged SNRs would produce LECRρ, and produce the Fe-Kα line by bombardment of the MCs.

In summary, the FIM did not explain the full flux of the GRXE by XASs. The SAM predicts the region of the excess of $\text{EW}_{6.4}$ over the assembly of the mean spectra of the XASs. Thus, an additional component is required that is spatially clumpy and emits strong Fe-Kα lines—possibly MCs by the bombardment of LECRρ.

9.3 Galactic center X-ray emission

In the deep observation with Chandra of ~600 ks exposure of the 19° × 17° (40 pc × 40 pc) field around Sgr A∗, Muno et al. (2003, 2004a) resolved ~10% and ≤20% (2–8 keV) into XASs. With a ~800 ks observation in the fan-shaped region in the GC west of 2°–4° from Sgr A∗, Revnivtsev, Vikhlinin, and Sazonov (2007b) resolved ~40% (4–8 keV band) into XASs at the same threshold luminosity of ~10^{31} \text{erg s}^{-1}. Thus, even taking account of the energy band difference, there is an extremely large difference of ~2–4 between these two authors with the mean (averaged) XAS fraction of ~25%. This mean value is about twice as small as that of the GBXE by Hong (2012). Therefore, the XAS fraction of the GCXE would be about half of the GBXE or ~40% of the GCXE.

With Suzaku, Uchiyama et al. (2011) made spatial profiles of the Fe-Kα lines in the GDXE with a resolution of 0.1. Then, they compared the flux distribution of the Fe XXV-Heα line, the brightest iron K-shell line, with the SMD model, where the SMD flux was normalized to the X-ray flux in the GRXE. The results are shown in figure 24. The Fe XXV-Heα flux in the GCXE region of |l| = 0.1–0.6 is ~2–4 times larger than the prediction of the SMD model (the solid lines in figure 24). The same result, the excess of the Fe XXV-Heα line above the infrared flux in the GCXE region, was found in the assembly of infrared stars obtained by the SIRIUS observations of Yasui et al. (2015).

Heard and Warwick (2013a) produced the Fe-Kα line and the 7.2–10 keV band profile along the $b = 0°$ and $l = 0°$ lines in the central GCXE region (4°–13′ from Sgr A∗). The flux of the central GCXE region was enhanced with a sharp peak near Sgr A∗. They predicted that the 2–10 keV flux per 1 $M_\odot$ at 20′ from Sgr A∗ was $\sim 5 \times 10^{27} \text{erg s}^{-1} M_\odot^{-1}$, while at 2′, it was $\sim 1 \times 10^{28} \text{erg s}^{-1} M_\odot^{-1}$. Taking into account the energy band differences, these are ~1.5 and ~3 times larger than those of the GRXE of $(3.5 \pm 0.5) \times 10^{27} \text{erg s}^{-1} M_\odot^{-1}$ (3–20 keV; Revnivtsev et al. 2006b) and the solar neighborhood of $(3.1 \pm 1.1) \times 10^{27} \text{erg s}^{-1} M_\odot^{-1}$ (2–10 keV; Sazonov et al. 2006), respectively.

The systematic enhancement of the fluxes per 1 $M_\odot$ toward Sgr A∗ makes the FIM approaches to the origin of the whole GCXE complicated. On the other hand, $\text{EW}_{\text{Fe-K}}$ are almost constant in the whole GCXE region, except for

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**Fig. 23.** (a) X-ray spectra of the inner Galactic disk at $|l| = 2°–4°$ and $b = 0°$. The red line and data are from the eastern region ($l > 0°$), while those in black are from the west ($l < 0°$). (b) X-ray spectrum of the difference between the eastern and western regions. The solid line is the best-fit model (see text). (Color online)
$EW_{6.4}$ in the XRNe (subsection 3.3), and hence the SAM approaches would be more straightforward for the origin of the whole GCXE.

Since the surface brightness of the GCXE in the iron K-shell band (6.3–7.1 keV) is about ten times larger than those of the GBXE and GRXE, reliable fluxes and spectra for the GCXE may be possible with XMM-Newton and even with Chandra. Therefore, the SAM can be reliably applied to the GCXE for the XMM-Newton and Chandra data in addition to the Suzaku data. Heard and Warwick (2013a) fitted the XMM-Newton spectra of the central GCXE region with mCV spectra of unrealistic Fe abundance (Yuasa et al. 2012; see subsection 9.1). Within 9° of Sgr A*, Munoe et al. (2004b) produced the Chandra spectrum of the resolved point sources in the luminosity range of $\sim$10^{31}–10^{33} erg s$^{-1}$. They proposed that the major component in this luminosity band is mCV. However, their estimated $EW_{6.4}$, $EW_{6.7}$, and $EW_{6.97}$ of $\sim$140 eV, $\sim$400 eV, and $\sim$230 eV, respectively, are largely different from the mCVs but are rather similar to the non-mCVs (table 14).

In order to examine the differences between the global GCXE spectrum and those of the XASs, Nobukawa et al. (2016) fitted the Suzaku GCXE spectrum with a combination of their 2-T models, which are made from the practically observed values of the temperature, $EW_{Fe-K}$ for each mCV, non-mCV, and AB (subsection 8.2). The combined 2-T model fit was completely rejected with $\chi^2$/d.o.f. = 2637/276 (table 15), simply because the $EW_{Fe-K}$ of the GCXE (table 5) is far larger than any of the XASs (table 14).

Large excesses in the GCXE spectrum from the combined 2-T models are found in the FeI-K$\alpha$ and FeXXVI-Ly$_\alpha$ lines (figure 22, left). This indicates that the $EW_{6.4}$ and $EW_{6.97}$ excesses over the 2-T model in the GCXE are larger than those in the GRXE (subsection 9.2). An important note is that the excesses of $EW_{6.4}$ and $EW_{6.97}$ in the GCXE are not due to the 1.5–3 times enhancement of the X-ray luminosity per $M_{\odot}$ in the GCXE relative to the GBXE and GRXE, but needs new components that exhibit larger $EW_{6.4}$ and $EW_{6.97}$ than any of the XASs.

The SAM results are consistent with the GCXE having a smaller SH_{Fe-K} ($\sim$31–36 pc: calculated from the e-folding $b$ in table 4) than those of the mCVs and non-mCVs ($\sim$130–160 pc), and ABs ($\sim$150–300 pc), respectively (table 14). The SH_{Fe-K} of the GCXE is similar to the SH of CMZ (Tsuboi et al. 1999; Weine n et al. 2014), and hence new components of the GCXE may be closely related to the CMZ, regardless of diffuse or point sources.

The excess of the $EW_{6.4}$ should be associated with the additional non-thermal X-ray continuum. As noted in subsection 3.3, Yuasa et al. (2008) found a power-law emission from the GCXE; most of the emission is due to the XRNe. Still, some fractions remain in the non-XRN regions of the GC west (e.g., Koyama et al. 2009; Uchiyama et al. 2013) that could be due to the LECR. If a significant fraction of the LECR is LECRp, an excess of $EW_{6.4}$ would be obtained. Thus, the $EW_{6.4}$ excess in the GCXE is an enhanced version of the GRXE (subsection 8.3).

The excess of the FeXXVI-Ly$_\alpha$ line requires another component, which emits stronger FeXXVI-Ly$_\alpha$ lines than any of the XASs. In the CMZ region of $|l| \lesssim 0.3$, the longitude profile of the Fe XXV-He$\alpha$ line in the east (positive $l$) shows a significant excess over the west, even excluding the bright SNR Sgr A East (Koyama et al. 2007c; Heard & Warwick 2013a). This excess would be due to larger populations of high-mass stars in the east than in the west (Park et al. 2004; Munoe et al. 2004a; Koyama et al. 2007c).
In the close vicinity of Sgr A*, the Fe XXV-Heα and Fe XXVI-Lyα fluxes relative to the SMD seem to be larger than about three times the GRXE (Heard & Warwick 2013a). This region corresponds to the NSC in the CMZ, which is the site of a large population of high-mass stars. The high-mass stars may contribute to the GCXE by putative star-burst activity and/or frequent SN explosions in the GMZ. The reconnection of strong magnetic fields, or big outbursts of Sgr A* (Ryu et al. 2009, 2013; Inui et al. 2009; Terrier et al. 2010; Ponti et al. 2010; Capelli et al. 2012, section 7) may also produce hot plasmas, responsible to the strong Fe XXVI-Lyα line. The CMZ and the close vicinity of Sgr A* are unique regions with more extreme physical conditions than any other regions of the Galaxy. Therefore, other physical processes, beyond our current views of the quiet Galactic region, may be concealed.

In summary, the FIMs did not explain the full flux of the GCXE by XASs. The SAM result leaves significant excesses of $EW_{6.4}$ and $EW_{6.97}$ over any combination of the XAS spectra. Thus, either diffuse sources or new-type point sources are required in the GCXE. These should have a larger $EW_{6.4}$, $EW_{6.97}$, and a smaller SHe/K than any of the XASs.

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