The \textit{ASCA} and \textit{Chandra} Observations of the Galactic center

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\textbf{Abstract} This paper reports the new results of the high energy activity found with the X-ray observations of the Galactic center (GC). The \textit{Ginga} satellite discovered the largely extended hot plasma around the GC, suggesting a violent activity of the GC within $10^5$ year. \textit{ASCA} found strong 6.4 keV line emissions from the molecular clouds near the GC, which is well explained by the fluorescent caused by strong X-ray irradiations from Sgr A* of $\sim 100$–300 years ago. Recent \textit{Chandra} observations on the GC have confirmed these previous results and moreover, with its unprecedented spatial resolution, have resolved a number of non-thermal/6.4-keV X-ray filaments and jet-like structures possibly caused by Sgr A*. We infer that these complexities in morphology and spectrum of the GC X-ray are due to coupled actions of recent supernova explosions, a super massive black hole and giant molecular clouds.

\textbf{Key words:} Galaxy: center — ISM: clouds — X-rays: ISM

\section{INTRODUCTION}

The hydrogen column density to the Galactic center region (GC) and Sgr A*, the dynamical center of our Galaxy, is nearly $10^{23}$ H cm$^{-2}$. This causes a huge extinction hence GC observations in the optical band have been impossible. The extinction decreases as we shift to longer wavelength bands. In fact, the radio and infrared observations have revealed unique and many complex structures in the GC region. The photo-electric cross section also decreases rapidly as decreasing wave length in the X-ray band, hence the GC becomes visible in the hard X-ray band above about 2 keV. With the \textit{Ginga} satellite, Koyama et al. (1989) discovered strong 6.7 keV iron line emission from a largely extended region (about 1–2 degree) near the GC. Thus the hard X-ray observations are found to be very vital to investigate the high energy phenomena in the GC. \textit{ASCA}, the first satellite which had the imaging capability in the hard X-ray band, confirmed the \textit{Ginga} results and further found the 6.4 keV line emission from the giant molecular clouds near the GC (Koyama et al. 1996). \textit{Chandra} reveals more details of the 6.4 keV clouds (Murakami et al. 2000, 2001a, 2001b) and discovers many non-thermal filaments and

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jet-like structures possibly coming from Sgr A* (Baganoff et al. 2001, 2003, Wang et al. 2002, Muno et al. 2003). This paper reviews the ASCA and Chandra results and discusses the origin of the high energy activities near the GC.

2 RESULTS

2.1 Overall X-Ray Structures of the GC

Figure 1 is the ASCA CCD (SIS) spectrum in the GC of about 1° × 1° area (Koyama et al. 1996). The contributions of X-ray bright point sources are eliminated. Many emission lines from highly ionized atoms, He-like and H-like Si, S, and Ar are found. He-like Ca line is also clear. The iron lines are complex with 6.4, 6.7, and 6.9 keV emissions. The 6.7 and 6.9 keV lines are due to He-like and H-like irons. These highly ionized atoms clearly indicate that the GC has high temperature plasma. In particular, the presence of He-like and H-like irons indicates that the plasma temperature is at least a few keV. On the other hand, the 6.4 keV line is due to neutral, or low ionization irons, which indicates that cool gas is also responsible to the X-ray emission. To see the high temperature plasma and the cool gas structure, the mosaic images using the wide band X-rays from 2 to 10 keV and the narrow band image at 6.4 keV line are given in Fig. 2.

![Figure 1](image_url)

Fig. 1 The ASCA CCD (SIS) spectrum extracted from the 1° × 1° region of the GC. Point source contributions are removed.
The ASCA CCD (SIS) mosaic image of the Galactic center. (a) The continuum band image of 2–10 keV. (b) The 6.4 keV iron band image, where the continuum component is subtracted.

In the wide band image, or image of high temperature plasma, we can see a diffuse spot at Sgr A East, which is a radio SNR candidate. We also see larger scale diffuse X-ray emissions, extending to about 1° × 1°. The temperature of a few keV deduced from the 6.7 and 6.9 keV lines is higher than that bounded in this region by the Galactic gravity. Therefore the hot gas should escape within 10^5 years, the dynamical time scale (the physical size divided by the sound velocity in the hot plasma). The total thermal energy is estimated to be about 10^{54} erg, 1000 times larger than that of 1 SN explosion (Yamauchi et al. 1990). The huge energy and short escape time lead us to suspect that the GC has experienced a large explosion, or multiple SN explosions within the past 10^5 years.

Figure 2b is the 6.4 keV band image, or X-ray emitting cool gas. Unlike the high temperature plasma (Fig. 2a), the 6.4 keV line is clumpy and bright in the left side of the Galaxy, the Sgr B and the Radio Arc regions. The brightest source is the giant molecular cloud Sgr B2, which is located at the northeast of the GC.

2.2 X-Ray Reflection Nebulae

2.2.1 Sgr B2

Figure 3a is the Chandra deep exposure image of Sgr B2 in the 6.4 keV line (Murakami et al. 2000), overlaid on the molecular contours (Sato et al. 2000). We can see a concave structure pointing to the GC side (Sgr A* side). This structure leads us to suspect that the 6.4 keV emission is due to the reflection and fluorescent irradiated by an external X-ray source from the Sgr A* side (Koyama et al. 1996). To demonstrate the reflection/fluorescent model, we made a simulation in Fig. 3b. In the simulation, we assume that strong X-rays (indicated by the three arrows) are coming from the lower right side (the Sgr A* side), hit a molecular cloud with the density profile given by the contours, then are reflected (Thomson scattered) and/or
fluorescent into our line of sight. Comparing Figs. 3a and 3b, we see that the simulated image (3b) reproduces the observed image (3a) very well.

The solid histogram in Fig. 4 is the simulated spectrum of the reflected and fluorescent X-rays using the same model as Fig 3b, while the crosses are the observed spectrum of Sgr B2. In the simulation, we adopt no additional assumption, but simply follow the elemental physical processes: X-rays above 7.1 keV (iron K-edge) are largely absorbed, and 30 percent of the absorbed X-rays are converted into the K$_\alpha$ (6.4 keV) and K$_\beta$ (7.0 keV) X-rays. As is given in Fig. 4, the X-ray reflection model can reproduce the observed spectrum extremely well. It reproduces not only the 6.4 keV and 7.0 keV line fluxes but also the absorption depth at the iron K-edge (7.1 keV). Here and after, we call this class of source as an X-ray reflection nebula (Murakami et al. 2000, 2001a, 2001b).

2.2.2 Other candidates of X-ray reflection nebulae

We also found other candidates of the X-ray reflection nebulae. As we already noted, there is a strong 6.4 keV spot near at Radio Arc. From this region, Tsuboi, Ukita, & Handa (1997) found a CS molecular cloud. Oka et al. (2001) also found a CO molecular cloud at the same region (named CO 0.13−0.13) with the large scale CO survey. Figure 5 is the mosaic Chandra image of M0.11−0.08, which is a molecular cloud located between Sgr A* and Radio Arc (Lindqvist et al. 1995). Overlaying the CS molecular contours (Tsuboi, Handa and Ukita 1999), we see a bright 6.4 keV line emitting zone in the GC side (Sgr A* side). Another candidate is Sgr C, which is a giant molecular cloud near at the mirror side of Sgr B2 with respect to Sgr A*. Although exposure time is limited, we see a hint of 6.4 keV line emission at the GC side (Sgr A* side) (Murakami et al. 2001a).
2.3 New X-ray Features with Chandra

Using the archive data, we have made Chandra deep exposure images in the $8.5' \times 8.5'$ region in Fig. 6a (3−8 keV band) and 6b (6.3−6.5 keV band). We see many clumps, filaments and jet-like structures (hooked lines in Fig. 6). By comparing Fig. 6a and 6b, we see many filaments and/or jets with no emission line at the iron band, hence may be non-thermal origin. We note that the three small ellipses (shown in Fig. 6a by “X-ray jets?”) line up and all have the major axis along the line pointing to Sgr A*. In addition of these jets, several non-thermal X-ray filaments have been discovered (e.g. Sakano et al. 2003, Wang et al. 2002). The fishhook-shape structure in the north-east corner of Fig. 6 is a good example of the complexity in the spectrum and morphology of the GC X-rays. From Fig. 6a and 6b, we see that the upper part may be non-thermal (no line), but the lower part emits strong 6.4 keV line like an X-ray reflection nebula.

3 DISCUSSION

3.1 Past Activity of Sgr A*

For the X-ray reflection nebula model, we need strong X-ray sources near at the GC, because all the reflected X-ray images are in the GC side of the molecular clouds. Coming back to Fig. 2, we however found no strong X-ray source near at the GC. The X-rays from the bright region near at Sgr A East are still too faint to reproduce the observed X-ray reflection nebulae. Therefore one possible idea is that Sgr A* was bright in the past, but now faint. We are observing the delayed X-rays, traveling extra distance between Sgr A* and the molecular clouds. In other words, we can make the past X-ray light curve using the X-ray reflection nebulae and the projected distance of each molecular cloud. The X-ray flux from Sgr A* at present is only $\sim 10^{33}$ erg s$^{-1}$ (e.g. Baganoff et al. 2001). But in the past, we suspect that the luminosity exceeded...
Fig. 5  The adaptively smoothed 6.4 keV image of M 0.11−0.08 with Chandra ACIS-I. The overlaid contours are the CS line intensity integrated over the radial velocity of 20 to 30 km s$^{-1}$ (Tsuboi, Handa & Ukita 1999).

$10^{38}$ erg s$^{-1}$, far larger than the Eddington limit of any X-ray binaries. Therefore the irradiating X-ray source should be a massive black hole at our Galactic center.

3.2 Possible Relation between Sgr A$^*$ and Sgr A East

Why is Sgr A$^*$ bright in the past $10^2 - 10^3$ year and faint at present? The X-ray bright diffuse emission in Fig. 2a and Fig. 6a is Sgr A East, a radio non-thermal source or radio SNR. In X-ray, Sgr A East shows very strong iron line at 6.7 keV, hence is due to thin thermal plasma with large metal abundances. Therefore X-ray data also support that Sgr A East is a young SNR (Sidoli & Mereghetti 1999, Maeda et al. 2002). With the X-ray and radio data, we can constrain that the SN explosion occurred several thousand of years in a rather dense gas region of about 500 cm$^{-3}$. The blast wave of the SNR made a dense shell of 2000 cm$^{-3}$ expanding with the speed of $\sim 1000$ km s$^{-1}$, leaving a cavity inside. The dense shell might have passed through the super massive black hole (Sgr A$^*$) about 1000 years ago. Then the gas fell into the black hole and emitted very strong X-rays by the Bondi Hoyle accretion. This active phase should continued about 200 years, the traveling time of the SNR shell width. After the passage of the dense shell, the massive black hole is deposited in the cavity, or in a lower density region, hence the X-ray became very faint as is observed at present.

3.3 Other Suggestions for the Recent Activity of Sgr A$^*$

Based on the observations of X-ray reflection nebulae and Sgr A East, we proposed a simplified scenario that the GC X-rays are due to combined action of an SN explosion and black hole in the near past. The discovery of non-thermal filaments and jets with Chandra may also support the past high activities of GC. If the non-thermal X-ray filaments are due to synchrotron radiation,
Fig. 6 The *Chandra* deep exposure image of Sgr A* and its vicinity (8.5′ × 8.5′). Eleven observations with ACIS-I are merged, leading a huge exposure time of about 590 ks. (a) is in the 3.0–8.0 keV band, while (b) is in 6.3–6.5 keV. Each image is adaptively smoothed and corrected for exposure variation including the CCD chip gaps and bad columns.
the time scale of energy loss of the relevant high energy electrons is proportional to $E^{-1}B^{-2}$, where $E$ and $B$ are the energy of electrons and the magnetic field strength, respectively. Since $B$ in the GC region would be higher than those in the Galactic plane, the life time of the high energy electrons must be shorter than hundreds of years, typical life time of high energy electrons in the SNR shell (Koyama et al. 1995, Bamba et al. 2003). We are thus required that the electron acceleration activity must be present until very recent years.

Since the jet-like structures are located very near the GC and are in the diffuse thermal plasma, it is difficult to extract “exact” spectra of the jets. Therefore whether the jet spectra are thermal or non-thermal is unclear, hence the origin of the jets is highly uncertain. Nevertheless we can safely assume that the jet speed must be higher than a few 1000 km s$^{-1}$, the sound velocity in the X-ray emitting plasma. Since the position of the inner jets is at about 1’ (or 2 pc in projection) from Sgr A*, the age of the inner jets must be younger than 1000 years, again suggesting recent high energy activity of Sgr A*.

In summary, the complexity in morphology and spectrum of the GC X-ray is due to the coupled actions of multiple SNe, starbursts, a super massive black hole and giant molecular clouds. In near future, we can have a unified picture of the GC high-energy activity.

References