A Time-Variable X-Ray Echo:  
Indications of a Past Flare of the Galactic-Center Black Hole  

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Abstract  
A time-variability study of the neutral iron line flux at 6.40 keV in the Sgr B2 region from data of Suzaku and Chandra is presented. The highly ionized iron line at 6.68 keV is due to Galactic Center Diffuse X-rays, and is thus time invariable. By comparing the 6.68 keV and 6.40 keV line fluxes, we found that the 6.40 keV flux from the Sgr B2 complex region is time variable; particularly the giant molecular cloud M 0.66–0.02, known as “Sgr B2 cloud” is highly variable. The variability of the 6.40 keV line in intensity and spatial distribution strongly supports the scenario that the molecular clouds in the Sgr B2 region are X-ray Reflection Nebulae irradiated by the Galactic Center black hole Sgr A*.

Key words: ISM: clouds—ISM: H II regions—ISM: supernova remnants

1. Introduction
Accurate astrometric and spectroscopic measurements of the Galactic Center (GC) stars revealed that the GC exhibits a $4 \times 10^6$ solar-mass black hole at the gravitational center Sgr A* (Schödel et al. 2002; Ghez et al. 2003). Massive black holes are usually violently bright at all wavelengths, particularly in X-rays, and hence are called Active Galactic Nuclei (AGN). Massive black holes are usually violently bright at all wavelengths, particularly in X-rays, and hence are called Active Galactic Nuclei (AGN). Sgr A*, however, is very quiescent with an X-ray luminosity of only $10^{33–34}$ erg s$^{-1}$ (Baganoff et al. 2001), many orders of magnitude dimmer than that of a canonical AGN. A question is whether or not Sgr A* has always been quiescent.

The radio complex Sgr B2 comprises many H II regions and molecular clouds. Koyama et al. (1996) and Murakami et al. (2000) found that molecular clouds emit peculiar X-rays with a strong 6.40 keV line (equivalent width of 1–2 keV) and deep iron absorption edge at 7.1 keV (equivalent $N_H$ of $\sim 10^{24}$ H cm$^{-2}$). A detailed morphology of the Sgr B2 cloud has been studied with Chandra (Murakami et al. 2001), and other 6.40 keV structures (e.g., M 0.74–0.09) have been found with Suzaku (Koyama et al. 2007b), both of which indicate that the Sgr B2 cloud and its complex are X-ray reflection nebulae (XRN) irradiated by the GC source Sgr A*; Sgr A* was X-ray bright about 300 years ago, the light-travel time between Sgr B2 and Sgr A*.

A counterargument of the XRN scenario is that the origin of the 6.40 keV line is due to charged particles (e.g., Valinia et al. 2000; Yusef-Zadeh et al. 2007). A direct test to distinguish these two possibilities is to detect any time variability of the 6.40 keV line flux. Muno et al. (2007) reported the Chandra discovery of a 2–3 year variability of the 6.40 keV line within 20 pc of Sgr A*. This observation suggests that Sgr A* had an X-ray luminosity of $\sim 10^{38}$ erg s$^{-1}$ around 60 years ago. This paper reports on a longer-term (5-years) time variability from an extended region of the Sgr B2 cloud. The errors quoted in this paper are at the 90% confidence level, unless otherwise mentioned.

2. Observation and Data Reduction

2.1. The Chandra Observation
Sgr B2 was observed using the Advanced CCD Imaging Spectrometer (ACIS-I) aboard the Chandra observatory (Weisskopf et al. 2002) on 2000 March 29–30. The total exposure time, after data screening was 100 ks. We used the event file provided by standard pipeline processing. Only the ASCA grades 0, 2, 3, 4, and 6 events were used in the analysis. The details of the data reduction are the same as those of Murakami et al. (2001). ACIS-I consists of four CCDs, each covering an 8.3 square on the sky, while the pixel size is 0.5. The on-axis spatial resolution is 0.5 full width at half-maximum (FWHM).

Images, spectra, ancillary response file (ARF), and response matrices have been created using CIAO v3.4 software. The absolute positional accuracy was 0.6 (Weisskopf et al. 2003).

2.2. The Suzaku Observation
The Sgr B2 region was observed with XIS on 2005 October 10–12. XIS consists of four sets of X-ray CCD camera systems (XIS 0, 1, 2, and 3) placed on the focal planes of four X-Ray Telescopes (XRT) aboard the Suzaku satellite. XIS 0, 2, and 3 have front-illuminated (FI) CCDs, while XIS 1 has a back-illuminated (BI) CCD. Detailed descriptions of the Suzaku satellite, XRT, and XIS can be found in Mitsuda et al. (2007), Serlemitsos et al. (2007), and Koyama et al. (2007a), respectively. The XIS observation was made in the normal mode. The effective exposure time after removing the epoch of the low-Earth elevation angle (ELV $\leq 5^\circ$) and the South Atlantic Anomaly was about 89 ks. We analyzed the data using the software package HEASoft 6.2. We fine-tuned the XIS astrometry using the Chandra point sources in the field of view. The details of the data reduction are the same as that of Koyama et al. (2007b).
3. Analysis and Results

3.1. The Sgr B2 Complex

We selected the Sgr B2 region, which two observations commonly covered. The region is shown by the solid line in figure 1 (upper panel). As the background, off-plane blank-sky data were used: north ecliptic pole data for XIS and a distributed blank-sky database for ACIS. We made the ARF using real images. The background-subtracted spectra exhibit three pronounced peaks which represent Fe I-K\(^\alpha\) (6.40 keV), Fe XXV-K\(^\alpha\) (6.68 keV), and the composite lines of Fe XXVI-K\(^\alpha\) (6.96 keV), and Fe I-K\(^\beta\) (7.06 keV).

Since the Suzaku spectra have better statistics and an accurate line energy determination (Koyama et al. 2007c), we derived the best-fit model in the 5–8 keV band with a power-law and four Gaussians, with a fixed energy interval between Fe I-K\(^\alpha\) (6400 eV) and K\(^\beta\) (7058 eV) to the theoretical value (658 eV) (Kaastra & Mewe 1993). The intrinsic width of the 6.68 keV line was assumed to be 23 eV, following Koyama et al. (2007c). This line broadening is due to blending of the resonance, inter-combination and forbidden lines of He-like irons (Fe XXV-K\(^\alpha\)) and several satellite lines. Those of the other lines were assumed to be narrow (fixed to \(\Delta \gamma\) eV). The flux ratio of Fe XXVI-K\(^\alpha\) against Fe XXV-K\(^\alpha\) was fixed to be 0.3, slightly smaller than that of the Galactic Center Diffuse X-rays (GCDX) (Koyama et al. 2007c). We estimated this value based on the GCDX data plus an additional contribution of the 6.7 keV line from a new SNR candidate, G0.61+0.01, located in the Sgr B2 complex region (Koyama et al. 2007b). The best-fit spectra and parameters are given in figure 2 and table 1, respectively. \(N_H\) is \((3.0 \pm 0.1) \times 10^{23} \text{ H cm}^{-2}\), determined by the depth of the iron K-edge with the solar iron abundance.

We also fit the Chandra spectrum, but \(N_H\) and the flux of the composite lines at \(\sim 7\) keV were not well determined due to poor statistic above 7 keV energy (see figure 2, upper panel). We therefore fixed the power-law index and \(N_H\) to those

![Image](https://example.com/image1)

![Image](https://example.com/image2)

**Fig. 1.** 6.40 keV maps of the Sgr B2 complex taken with Chandra (upper panel) and Suzaku (lower panel). The coordinates are the galactic longitude and latitude. Sgr A* is at the right-hand side of these figures. The data were smoothed with 1-sigma of 10\(^\circ\). The Sgr B2 complex is shown by the solid line in the figure (upper panel), while the Sgr B2 cloud is given by the dashed line (lower panel).

![Image](https://example.com/image3)

![Image](https://example.com/image4)

**Fig. 2.** X-ray spectra from the Sgr B2 complex, where the off-plane blank sky spectra were subtracted. Upper panel, Chandra-ACIS; Lower panel, Suzaku-XIS(FI). In the spectra, the dashed lines are the best-fit Gaussians for the emission lines; the solid lines are those for the continuum emissions.
determined with Suzaku. We further fixed the line center energies to the Suzaku best-fit values. Still, the line and edge structures could not well fitted for the Chandra spectrum, indicating the presence of a systematic gain offset. We therefore fine-tuned the energy offset by $-20\text{ eV}$, and obtained a nice fit. The best-fit spectra and parameters are also shown in figure 2 and table 1, respectively. The flux ratios between Fe I-K $\alpha$ (6.40 keV) and Fe I-$\beta$ (7.06 keV) were determined to be 0.08 (for the Suzaku data) and 0.13 (for Chandra).

Since the 6.68 keV line is certainly due to the largely extended GCDX (Koyama et al. 2007c), this line flux must be time constant. In fact, the observed flux with Chandra is $(2.6 \pm 0.2) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$, while that of Suzaku is $(2.4 \pm 0.1) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$; no difference is found within the statistical error. This, in turn, verified the reliability to study any possible flux change of the adjacent 6.40 keV line between the Chandra and Suzaku observations. The 6.40 keV flux, in fact, decreased from $(4.5 \pm 0.2)$ to $(3.2 \pm 0.2) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ in the Chandra (2000) observation to $(3.2 \pm 0.2) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ in the Suzaku (2005) observations. Compared to the constant flux of the 6.68 keV line, the variability of the 6.40 keV line is highly confident. We note that if we relaxed the power-law index for the Chandra spectrum fit, the resultant flux of the 6.40 keV line became $(4.7 \pm 0.2) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$, while that of the 6.68 keV was $(2.6 \pm 0.2) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$. These values are the same as those listed in table 1 within statistical errors.

In order to see the 6.40 keV line variability, we depicted the 6.40 keV photons within the FWHM energy band, and subtracted the underlying continuum flux, which was estimated using the best-fit power-law spectra, shown in figure 2. The results of the 6.40 keV maps are shown in figure 1. The surface brightness is shown by color codes, which were corrected for the exposure time, vignetting, and detector efficiency for both Chandra and Suzaku. We confirmed the change in the surface brightness of the 6.40 keV line flux between the two observations. Since the angular resolution of Suzaku is limited, to compare the morphological change of the Sgr B2 cloud is difficult. However we can safely state that a drastic change of $G0.570 - 0.018$ occurred. In the Chandra images, a clear spot near the Sgr B2 cloud is found at the right-hand side of the map ($G0.570 - 0.018$; Senda et al. 2002). In the Suzaku observation, however, $G0.570 - 0.018$ has almost disappeared.

### 3.2. The Sgr B2 Cloud

The brightest spot in figure 1 is the Sgr B2 cloud. We obtained X-ray spectra of the Sgr B2 cloud from the dashed line circle given in figure 1. The background was subtracted from the region shown by the dotted line ellipse. The background-subtracted spectra of the Sgr B2 cloud are shown in figure 3.
4. Discussion

We detected a strong Kα line at 6.40 keV, and a weak Kβ line at 7.06 keV from both the Sgr B2 complex and the Sgr B2 cloud. These lines are produced when the K-shell electrons in iron atoms become vacant; subsequently an L-shell/M-shell electron decays to this vacant level. The flux ratio (Kβ/Kα) is consistent with 0.1. This ratio indicates that the M-shell is fully occupied by electrons, and hence the iron atom is nearly neutral (Kaastra & Mewe 1993). Then, a question is how to make the K-shell electron vacant (an inner-shell ionization). The inner-shell ionization can be either by X-rays or by energetic electrons.

We derived Fe Kα EW of 1.6 keV from the Sgr B2 cloud. This can be produced via the irradiation of X-rays, whereas collisional excitation by electrons could produce an EW of only 300–500 eV for the solar abundances (Tatischeff 2003). One may argue, however, that because the GC typically has abundances of 1.5–3 times solar, the observed EW might be consistent with electron origin, if the metallicity of Sgr B2 is 3-times solar. This possibility can not be entirely excluded.

We also observed a large N_{Fe} value (equivalent N_{H} of $\sim 10^{24}$ H cm$^{-2}$ for the Sgr B2 cloud, assuming the solar abundance). Since this value is one order of magnitude larger than the general absorptions to the GC sources ($\sim 6 \times 10^{22}$ H cm$^{-2}$) (Sakano et al. 2002), most of the absorption is due to local origin, the Sgr B2 cloud. Electrons are very difficult to explain this large N_{H}, because, at the energy of the maximum cross section of inner-shell ionization (10–100 keV), they can go into the molecular cloud only in the order of N_{H} of $10^{21–22}$ H cm$^{-2}$ (Tatischeff 2003). One argument to support the electron origin is that electron bombarding takes place at the rear side of the cloud. Although it seems artificial, this argument can not be entirely excluded.

We found more direct evidence for the X-ray irradiation origin: the time variability of the 6.40 keV line flux. The linear size across the Sgr B2 complex is about 20 light-years, but the bright part (the Sgr B2 cloud) is limited to within 10 light-years. The 6.40 keV flux changed by factor 2 within 5 years. This time scale is comparable to the light-crossing time of the cloud. Electrons having energies at the maximum cross section of the Fe I inner-shell ionization (10–100 keV) can not move as fast as the speed of light. Charged particles other than electrons are even more difficult as the origin.

A unique solution to explain the spectrum and time variability of the flux and the morphology is: the Sgr B2 cloud absorbs variable X-rays above the 7.1 keV edge energies, and simultaneously re-emits the fluorescent 6.40 keV lines. The 6.40 keV line flux can be estimated from the solid angle of the Sgr B2 cloud, the fluorescent yield of neutral iron (0.34) and the depth of the K-shell edge above 7.1 keV (Murakami et al. 2000, 2001). As a result, the observed 6.40 keV flux surely requires a near-by bright X-ray source.

The second question is then: where is the bright X-ray source? From the flux change and its time scale, this putative transient source must be bright for more than 5 years, but show a flux decrease by a factor 2. It should be brighter than 10$^{37}$ erg s$^{-1}$, if the source is located at a comparable distance of 10–20 pc as the Sgr B2 size. The GC region has been surveyed by many satellites, but no X-ray source brighter than 10$^{37}$ erg s$^{-1}$ (5 years average) has been found. Near the GC, neutron-star or black-hole binary sources occasionally flare-up to more than 10$^{37}$ erg s$^{-1}$, but the flare durations are typically only a few months.

Thus, the most-probable source to exhibit bright and relatively long-lived X-rays is a massive black hole, Sgr A*. The required luminosity to account for the Chandra flux of the Sgr B2 cloud is estimated to be 2 $\times$ 10$^{39}$ erg s$^{-1}$ (Murakami et al. 2001), while that for the Suzaku is about half. This idea has been proposed based on the early ASCA and Chandra observations. New evidence of the large-scale (10–20 light-years), long-term (5 years) flux variation of the 6.40 keV line gives decisive support for this early idea. Our GC black-hole Sgr A* shows frequent short-term (1 hour) and low-level (10–100 times of the quiescent level) flares (Baganoff et al. 2001). More than a few hundred years ago, Sgr A* had been very active in X-rays; at $\sim$300 years ago it was 10$^{37}$ times brighter than the present value, and decayed to less than half after $\sim$5 years. The X-rays hit the Sgr B2 cloud after $\sim$300 years of travel. The cloud re-emitted the 6.40 keV photons, like a time delayed-echo. The echo is now just arriving at Earth, while Sgr A* is falling into a quiescent state.

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| 6.40 keV Equivalent width (EW) | N_{H} 10^{23} H cm$^{-2}$ |
|-------------------------------|---------------------------|
| $10^{-4}$ photons cm$^{-2}$ s$^{-1}$ | keV                        |
| Suzaku                        | 2.8$^{+0.1}_{-0.5}$      | 1.6$^{+0.1}_{-0.5}$  |
| Chandra                       | 5.5$^{+0.4}_{-0.3}$      | 1.6$^{+0.4}_{-0.2}$  |

3-times solar. This possibility can not be entirely excluded.
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