X-Ray Echo from the Sagittarius C Complex and 500-year Activity History of Sagittarius A*  

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Abstract  
This paper presents Suzaku results obtained for the Sagittarius (Sgr) C region using the concept of X-ray reflection nebulae (XRNe) as the echo of past flares from a super-massive black hole, Sgr A*. The Sgr C complex is composed of several molecular clouds proximately located in projected distance. The X-ray spectra of Sgr C were analyzed based on the view that XRNe are located inside the Galactic center plasma X-ray emission with an oval distribution around Sgr A*. We found that XRNe are largely separated in the line-of-sight position, and are associated with molecular clouds in different velocity ranges detected by radio observations. We also applied the same analysis to Sgr B XRNe, and completed a long-term light curve for Sgr A* occurring in the past. As a new finding, we determined that Sgr A* has already experienced periods of high luminosity, ~500 years ago, which is longer than the previously reported value. Our results are consistent with a scenario that Sgr A* was continuously active with sporadic flux variabilities of $L_X = (1-3) \times 10^{39}$ erg s$^{-1}$ in the past 50 to 500 years. The average past luminosity was approximately 4–6 orders of magnitude higher than that presently observed. In addition, two short-term flares of 5–10 years have been found. Thus, the past X-ray flare should not be a single short-term flare, but can be interpreted as multiple flares superposed on a long-term high state.  

Key words: Galaxy: center — ISM: molecular clouds — X-Rays: super-massive black hole — X-ray spectra  

1. Introduction  
In the Galactic center (GC), the prominent 6.4 keV line of neutral iron (Fe I Kα) has been detected from giant molecular clouds (MCs), such as Sagittarius (Sgr) B (l ~ 0°; Koyama et al. 1996), Sgr C (l ~ 359°5; Murakami et al. 2001; Nakajima et al. 2009), and Sgr A (l ~ 0°; Park et al. 2004; Muno et al. 2007). The spectra show a large equivalent width ($EW_{6.4\text{keV}} \geq 1$ keV) and strong absorption ($N_H \geq 10^{22}$ H cm$^{-2}$) to the continuum, which suggests that the 6.4 keV bright MCs are due to irradiation and fluorescence by possible external X-rays (X-ray reflection nebulae: XRNe), rather than particle irradiation (e.g., Yusef-Zadeh et al. 2007). Subsequently, the XRN scenario has become more conclusive owing to the discovery of the short-term (a few years) 6.4 keV variability in the small (a few light-years) regions in Sgr B (Koyama et al. 2008) and Sgr A (Ponti et al. 2010). Moreover, in Sgr B, the same variability time of hard continuum X-rays ($E \geq 8$ keV) has been found to be in correlation with the 6.4 keV line by Terrier et al. (2010) and Nobukawa et al. (2011). These results promoted the idea of the external irradiation source being a past flare of the super-massive black hole Sgr A* (e.g., Koyama et al. 1996; Sunyaev et al. 1993; Murakami et al. 2001; Ponti et al. 2010; Nobukawa et al. 2011).  

In the XRN context, one can derive the X-ray light curve of Sgr A* for the past several hundred years. The flare luminosity and look-back (delay) time depend on the position of the XRN relative to Sgr A* and the Sun (observer). However, most of the previous estimates used solely the projected distance, or indirect information of line-of-sight positions. Ryu et al. (2009) successfully developed an original method for determining the line-of-sight position for the Sgr B XRN. Their method involves careful spectral analysis of XRNe in combination with spatial and spectral information of the GC plasma X-ray emission (GCPE). Uchiyama et al. (2011) recently performed an intensive investigation of the 6.7 keV (Fe XXV Kα) line profile for the entire GC region ($\sim 5^\circ \times 2^\circ$); thereafter, Uchiyama et al. (2013) extended this work to other emission lines of highly ionized sulfur (S), argon (Ar), and calcium (Ca). These studies quantitatively constructed the GCPE as a two-temperature plasma, and determined its three-dimensional spatial distribution.  

On the basis of these new pictures of the GCPE, we establish a method to measure the three-dimensional positions of the Sgr C XRNe. The observation and analyses of the Sgr C data are given in sections 2 and 3. We derive a face-on view of XRNe in subsection 4.1, and compare its reliability with that of radio observations in subsection 4.2. We then combine these results with the Sgr B data and results (Ryu et al. 2009) to calculate the time delay and the corresponding X-ray flare luminosity to reconstruct a long-term (~500 years) light curve for Sgr A*, which occurred in the past. The derivation method and discussion for the activity history of Sgr A* are given in subsection 4.4.
Table 1. Suzaku Observations at the Sgr C Region.

| Target name | Obs. ID     | Obs. point (FOV center) | Obs. date     | Effective exposure |
|-------------|-------------|-------------------------|---------------|--------------------|
| Sgr C       | 500018010   | $17^h 44^m 37^s 30^s -29^\circ 28' 10\" 2$ | 2006-02-20    | 106.9 ks           |
| Sgr C       | 505031010   | $17^h 44^m 58^s 01^s -29^\circ 22' 51\" 2$ | 2010-09-25    | 82.6 ks            |

Fig. 1. Added XIS (FI + BI) images near the Sgr C region. The images are binned with $12 \times 12$ pixels and smoothed with a Gaussian kernel of $5''$.

Throughout this paper, we adopt 8.0 kpc (Ghez et al. 2008) as the distance between the Sun and Sgr A*; thus, 1\circ corresponds to 140 pc at the GC. The parameter uncertainties are quoted at the 90\% statistical confidence-level (1.64 $\sigma$) range, unless noted otherwise.

2. Observation

We made two deep pointing observations on the Sgr C region separated by $\sim 5$ years between 2006 February and 2010 September. These observations were conducted using the X-ray Imaging Spectrometer (XIS) at the focal planes of the X-ray Telescope (XRT) aboard the Suzaku satellite. The XIS system consists of three sets of front-illuminated (FI) charge coupled device (CCD) cameras (XIS 0, 2, and 3) and one set of a back-illuminated (BI) CCD camera (XIS 1); each CCD chip contains $1024 \times 1024$ pixels ($1$ pixel $= 24 \mu$m $\times 24 \mu$m) for a $17.8 \times 17.8$ field of view. Two calibration sources of $^{55}$Fe are installed to illuminate two corners of each CCD for absolute gain tuning. We operated the XIS in the normal clocking mode with a read-out cycle of 8 s. The details of Suzaku, XIS, and XRT are given in Mitsuda et al. (2007), Koyama et al. (2007a), and Serlemitsos et al. (2007), respectively. The observation log of Sgr C is given in table 1. Archive data information on Sgr B and other relevant GC regions can be found in Ryu et al. (2009) and Uchiyama et al. (2011).

3. Data Reduction and Analyses

We performed data reduction and analysis using HEADAS software version 6.12. The calibration database used to calculate the response of XIS and the effective area of XRT was
FI spectra were merged in the spectral fitting. For the images, response functions of the FI CCDs are essentially the same, including the 2.45 keV line (SXV), and displays the distribution, shows a more uniform distribution than the 6.4 keV emission temperature plasma (HP) of the GCPE (subsection 3.2), and displays the distribution of the low-temperature plasma (LP), and individual thermal diffuse sources, mainly supernova remnants candidates, with temperatures of \( kT \sim 1 \) keV. The faint diffuse sources near the Sgr C clumps are the supernova remnants G359.41–0.12 and its outflow “Chimney” (Tsuru et al. 2009). To investigate the nature of the GCPE (HP and LP), we selected two regions with relatively weak 6.4 keV emission for spectral analyses, and designate them as ref1 and ref2 (solid circles; figures 1a, 1b, and 1d).

3.2. Spectral Model

The X-ray spectra of the GC region have been extensively studied by Ryu et al. (2009) and Uchiyama et al. (2013). The spectra can be reproduced by the superposition of four components: the GCPE, the XRN emissions (XRNE), the foreground emission (FE), and the cosmic X-ray background (CXB). These components have the following properties. The GCPE has two-temperature plasmas with \( kT \sim 1 \) keV and \( kT \sim 7 \) keV for LP and HP, respectively. The XRNE is expressed as neutral iron lines (K\( \alpha \) and K\( \beta \)) associated with a power-law component. Since the XRNE is formed by Thomson scattering of a continuum component and the fluorescence of iron atoms in the MCs, it shows a large absorption (Abs1) of \( N_{\text{HI}} \sim 10^{23} \) cm\(^{-2}\) (e.g., Murakami et al. 2001), which is approximately equal to the \( N_{\text{HI}} \) through the MC. The GCPE including the HP and LP is extended in the GC region, and the MC is inside this region. Thus, a fraction \( R \) of the X-ray from the GCPE is not absorbed by the MC, while the other fraction \( 1 – R \) is absorbed by the MC (Abs1). Both GCPE and XRNE exhibit a common interstellar absorption (Abs2) of \( N_{\text{HI}} \sim 6 \times 10^{22} \) cm\(^{-2}\) between the GC and the Sun (Sakano et al. 2002; Ryu et al. 2009). The FE is approximated to a thermal plasma of \( kT \sim 1 \) keV with small absorption. The CXB (e.g., Kushino et al. 2002) has the absorption of Abs2 by twice (interstellar absorption in front of and behind the GC), in addition to Abs1 (MC). Thus, the spectral model can be expressed by equation (1). A schematic picture of this model is shown in figure 2.

\[
f(E) \propto m = \frac{\text{Abs1} \times \text{Abs2} \times (1 – R)}{1} + \frac{\text{Abs2} \times R}{1} \times (\text{HP} + \text{LP}) + \frac{\text{Abs1} \times \text{Abs2}}{1} \times \text{XRNE} + \frac{\text{Abs1} \times \text{Abs2} \times \text{Abs2}}{1} \times \text{CXB} + \text{FE}. \tag{1}
\]

Ryu et al. (2009) successfully applied this model to the X-ray spectra of the 6.4 keV clumps near Sgr B. In addition, Muno et al. (2004) and Nobukawa et al. (2010) reproduced the X-ray spectra of Sgr A regions with similar models. Therefore,
we applied the same model to the Sgr C region. In figure 3, we show a simulated spectrum (XIS/FI; 0.5–10.0 keV) with the typical GC parameters (see caption). The plasma emission code used in the present work was APEC, and the absorption was evaluated in solar abundances.

### 3.3. Spectral Fitting

As shown in figure 3, we extracted seven spectra from five regions (solid circles in figure 1). The spectra of C1 and C2 were obtained twice in the observations during 2006 and 2010, whereas C3 was only observed in 2010. All spectra were simultaneously fitted in the band of 0.5–10.0 keV using the model given in equation (1). Since the spectral model is highly complicated with many physical parameters, it is impractical to fit the data with all parameters being free. Therefore, we adopted several reasonable constraints in the fitting. The parameter settings were the same as those of Ryu et al. (2009). The FE was fixed to an APEC model with $kT$ of 8.5 keV and an abundance of $Z = 0.011$, applied by small absorption of $N_H = 0.17 \times 10^{22}$ H cm$^{-2}$ (Ryu et al. 2009). The center energy of the Fe Kα and Kβ lines were respectively fixed to 6.4 keV and 7.05 keV with a flux ratio (Kα/Kβ) of 0.125 (Kaastra & Mewe 1993). The temperature of the HP ($kT_{HP}$) was fixed to 6.5 keV (Koyama et al. 2007b), and the abundances of HP and LP were fixed to one solar ($Z = 1$). The parameter $\alpha$, normalization ratio of HP/LP, could be approximated to a constant near Sgr C. This estimation is inferred from results of Uchiyama et al. (2013) (cf. figure 3 and table 2 therein), which indicate that the two plasmas exhibit nearly the same spatial distribution with an e-folding length of $\sim 0.6$. After all, the temperature of LP ($kT_{LP}$), the normalization ratio of HP/LP ($\alpha = norm_{HP}/norm_{LP}$), the photon index ($\Gamma$) of the power law, and the equivalent width ($EW_{6.4keV}$) of the 6.4 keV line are free parameters, but are linked in all regions, including C1–3 and refl–2. These settings are designed to verify a common and consistent XRNe model. Other parameters, such as line intensity ($I_{6.4keV}$) and absorption ($N_H$), are free and independent for each region. To investigate the time variability for C1 and C2, the 6.4 keV intensities of the 2006 and 2010 spectra were set as free parameters, while other parameters were common between the two spectra.

As can be seen in figure 1b, C1 is entirely overlapped with the “Chimney,” which is a thermal plasma outflowing from G359.41–0.12. In order to include the Chimney contamination, we added the spectral model with fixed parameters ($kT$, $N_H$, Z) reported in Tsuru et al. (2009). The flux (normalization of Chimney) was calculated from the average surface brightness and the region size of C1 ($\text{radius} = 2.0$), which is 35% of the GCPE flux.

All seven spectra are generally reproduced by the model of equation (1) with a reduced $\chi^2$/d.o.f of 3773/3031 = 1.26. The fitting results are shown in figure 4, and the best-fit parameters are listed in table 2. The large $EW_{6.4keV}$ of $\sim 1.2$ keV and the strong absorption [$N_H(Abs1) \sim 10^{23}$ H cm$^{-2}$] agree with the XRNe scenario for all regions. The $N_H$ of Abs2 are in the range of (5.0–6.5) $\times 10^{22}$ H cm$^{-2}$. These values are consistent with the interstellar medium (ISM) absorption toward the GC region (Ryu et al. 2009; Nobukawa et al. 2010; Sakano et al. 2002). As for the time variability of the 6.4 keV line between the 2006 and 2010 observations, C1 exhibits a small increase of 8% at 2.9-$\sigma$ level, while C2 shows no significant change.

For confirmation, we also applied independent fitting with free $EW_{6.4keV}$ parameters for each region. The spectra of C1, C2, and C3 show $EW_{6.4keV}$ of 1.1–1.5 keV, 1.1–1.6 keV, and 0.7–1.3 keV, respectively. These values are consistent with the fitting result when $EW_{6.4keV}$ is a common free parameter ($EW_{6.4keV} = 1.15–1.27$ keV; table 2), and agree with the XRNe scenario of large $EW_{6.4keV}$. However, the independent $EW_{6.4keV}$ fittings result in large statistical errors in the R parameters (about 2–4 times larger than those in table 2), which is not practical for determining cloud positions (subsection 4.1) and following discussions. Thus, we adopted the fitting results with $EW_{6.4keV}$ as a common free parameter between the regions (table 2).

### 4. Results and Discussions

#### 4.1. Line-of-Sight Position of the XRNe

As illustrated in figure 2, the parameter $R$ represents the line-of-sight position of the MC in the GCPE. Depending on the distance from Sgr A*, the GCPE is more or less contaminated by the Galactic ridge plasma emission (GRPE), which has a similar two-temperature spectral structure, but a more extended spatial distribution (Uchiyama et al. 2013). To estimate the MC positions numerically, we used the spatial distributions of these plasmas.

We introduced new coordinates ($X$, $Y$) with origins at Sgr A* ($l = -0^\circ.056$, $b = -0^\circ.046$; Yusuf-Zadeh et al. 1999), in which $X$ and $Y$ correspond to the directions of $l$ and the line of sight, respectively (see figure 2). The offset of $b$ was ignored.
Fig. 4. Fitting results for all selected spectra (regions represented by black solid circles in figure 1a) near Sgr C. The F1 (XIS 0+2+3 for 2006; XIS 0+3 for 2010) spectra with 1-σ error bars and the best-fit models (cf. figure 3) are represented by solid crosses and dashed lines, respectively. The best-fit parameters are summarized in table 2.
because the relevant XRNe are all on or near the Galactic plane (i.e., \(|b| \leq 0.1\)). Uchiyama et al. (2011, 2013) derived the \(X\)-axis flux distribution for many emission lines of ionized atoms (e.g., Fe and S) in addition to the soft and hard X-ray continuum bands. The data were fitted with a two-exponential function along the Galactic plane (\(X\)-axis): \(I_{GCPE} \propto X/l_{GCPE} \) and \(I_{LP} \propto \exp(-X/l_{LP})\). The values of e-folding length for both HP and LP are similar in the GCPE and GRPE. In this paper, we assume that the X-ray flux distribution for many emission lines of ionized atoms (e.g., Fe and S) in addition to the soft and hard X-ray continuum bands.

We assume that the \(X\)-\(Y\) plane distribution of the plasmas is an oblate spheroid expanded with a two-exponential function, \(I(X,Y) = A \times \exp(-r/r_{GC}) + \exp(-r/r_{GR})\), where \(r = (X^2 + Y^2)^{1/2}\). \(A\) is the flux ratio (GCPE/GRPE), and \(r_{GC}\) and \(r_{GR}\) are the e-folding scale lengths of GCPE and GRPE, respectively. Integrating \(I(X,Y)\) along the \(Y\)-axis as \(I(X) = \int_{-\infty}^{\infty} I(X,Y) dY\), we find that the resultant projection of \(X\)-distribution has nearly the same exponential shape as observed by Uchiyama et al. (2013). We then compared \(I(X)\) with the results of Uchiyama et al. (2013) to check the shapes. The parameters were nicely determined to be \(r_{GC} = 55\) pc (or 0.24), \(r_{GR} = 5000\) pc (or 36\(^{\circ}\)), and \(A = 900\).

Considering that a MC/XRN is located at \((X_0, Y_0)\) and \(X_0\) as its \(I\) offset from Sgr A*, the line-of-sight position \((Y_0; also cf. figure 2)\) was determined from the following relation, using the obtained \(R\) value (table 2):

\[
R(Y_0) = \frac{\int_{-\infty}^{Y_0} I(X_0, Y) \ dY}{\int_{-\infty}^{\infty} I(X_0, Y) \ dY}\]

We converted the unit of \((X, Y)\) into the actual length of light year (ly). Figure 5 illustrates the resultant face-on view of XRNe around Sgr A* on the \(X\)-\(Y\) plane. Although C1 and C2 are proximately (~40 ly) located in the projection (figure 1a), C1 is in front of the \(X\)-axis, while C2 is largely behind C1 by ~400 ly beyond the \(X\)-axis.

4.2. Association with the Radio Molecular Clouds

We have shown that C1, C2, and C3 are largely separated in the line-of-sight positions, although they are proximately located at the projected distance. We searched for the radio counterparts of C1, C2, and C3 from the CS (\(J = 1\to0\)) maps (Tanaka et al. 1999) in different velocity ranges from ~250 km s\(^{-1}\) to 250 km s\(^{-1}\). As shown in figure 1c, C2 and C3 are respectively in good coincidence with MCs in the velocity ranges of ~60 ± 20 km s\(^{-1}\) and +50 ± 30 km s\(^{-1}\). On the other hand, C1 was observed in the two separated velocity ranges of ~60 ± 20 km s\(^{-1}\) and ~100 ± 20 km s\(^{-1}\). Using the data corresponding to C2 and C3, we derived a conversion factor between the X-ray column density (Abs1; table 2) and the integrated CS intensity (contours; figure 1c), which is [CS/N\(_{H}\) \(\simeq 2.5\) [km s\(^{-1}\)/(10\(^{22}\) H cm\(^{-2}\)]]]. The X-ray N\(_{H}\) of MC (Abs1) used in this study was determined directly from the absorption of GCPE continuum behind the cloud (cf. figure 2). This method is available even if the MC is not an XRN, and thus does not depend on the properties of the illuminating source. Assuming the same [CS/N\(_{H}\)] factor near Sgr C, the observed X-ray column density of C1 [(6.0–6.8) \times 10\(^{22}\) H cm\(^{-2}\); table 2] indicates a CS intensity of

Table 2. Best-fit spectral parameters of the Sgr C regions.

| Region | Obs. Yr | \(N_{H}^{\dagger}\) (Abs1) | \(N_{H}^{\ddagger}\) (Abs2) | \(I_{0.4\text{keV}}^{\dagger}\) | FE norm\(^{\ddagger}\) | GCPE norm\(_{LP}^{\dagger}\) | Fraction \(R^\#\) |
|--------|--------|----------------|----------------|----------------|----------------|----------------|----------------|
| C1     | 2006   | 6.5\(^{+0.3}_{-0.5}\) | 5.1\(^{+0.3}_{-0.3}\) | 1.60\(^{+0.05}_{-0.05}\) | 0.060\(^{+0.004}_{-0.004}\) | 3.0 ± 0.1 | 0.23\(^{+0.03}_{-0.04}\) |
|        | 2010   | 1.73\(^{+0.05}_{-0.05}\) | 1.51\(^{+0.03}_{-0.03}\) | 0.10\(^{+0.005}_{-0.005}\) | 2.0 ± 0.1 | 0.72\(^{+0.12}_{-0.03}\) |
| C2     | 2006   | 11.4\(^{+1.6}_{-1.4}\) | 6.5\(^{+0.3}_{-0.2}\) | 1.51\(^{+0.03}_{-0.03}\) | 0.10\(^{+0.005}_{-0.005}\) | 3.0 ± 0.1 | 0.26\(^{+0.03}_{-0.03}\) |
|        | 2010   | 1.51\(^{+0.03}_{-0.03}\) | 0.36\(^{+0.03}_{-0.03}\) | 0.082\(^{+0.005}_{-0.005}\) | 2.3 ± 0.1 | 0.40\(^{+0.04}_{-0.03}\) |
| C3     | 2010   | 8.7\(^{+0.4}_{-0.6}\) | 5.0\(^{+0.3}_{-0.2}\) | 1.16\(^{+0.05}_{-0.05}\) | 0.082\(^{+0.005}_{-0.005}\) | 3.3 ± 0.1 | 0.31\(^{+0.05}_{-0.05}\) |
| ref1   | 2006   | 7.9\(^{+0.5}_{-0.8}\) | 5.3\(^{+0.2}_{-0.1}\) | 0.36\(^{+0.03}_{-0.03}\) | 0.082\(^{+0.005}_{-0.005}\) | 3.3 ± 0.1 | 0.31\(^{+0.05}_{-0.05}\) |
| ref2   | 2010   | 7.6\(^{+0.5}_{-0.7}\) | 6.4\(^{+0.3}_{-0.4}\) | 0.78\(^{+0.05}_{-0.05}\) | 0.082\(^{+0.005}_{-0.005}\) | 3.3 ± 0.1 | 0.31\(^{+0.05}_{-0.05}\) |

\(\dagger\) The value of column density in the unit of \(10^{22}\) H cm\(^{-2}\).

\(\ddagger\) Intensity in the unit of \(10^{-6}\) photons cm\(^{-2}\) s\(^{-1}\) arcmin\(^{-2}\).

\(\#\) The normalization factor of the APEC model for the foreground emission. It is normalized with the region size (\(\text{arcmin}^2\)) expressed as \(7.07 \times 10^{-3}\) \((4\pi D^2) A EM \text{ [cm}^{-2}\text{arcmin}^{-2}\text{]}\), where \(D\) and \(EM\) are the distance to the source [cm], and the emission measure [\(\text{cm}^{-2}\)], respectively.

\(\#\) R is the fraction of the GCPE not absorbed by MC (see equation (1) and figure 2), which is the indicator of the line-of-sight position for XRNe (see equation (2)).

\(\star\) The results are obtained by the simultaneous fitting of the 14 spectra from the FI and BI data.

\(\chi^2/\text{d.o.f.} = \frac{3773}{3031} = 1.26\)
15–17 K km s\(^{-1}\)). This generally excludes the \(-60\) km s\(^{-1}\) MC as the counterpart of C1, because the average CS intensity is only 5–10 K km s\(^{-1}\). The \(-100\) km s\(^{-1}\) MC has a CS intensity of 10–25 K km s\(^{-1}\), which is in agreement with the \(N_{\text{HI}}\) estimated by the X-ray data. Thus, C1 is most likely to be situated in the velocity range of \(-100 \pm 20\) km s\(^{-1}\).

Sofue (1995) identified two large \(l-V\) structures, known as “Arm I” stretching from (359°43, \(-150\) km s\(^{-1}\)) to (0°9, \(+80\) km s\(^{-1}\)) and “Arm II” stretching from (359°4, \(-80\) km s\(^{-1}\)) to (0°1, \(+60\) km s\(^{-1}\)). According to the velocities, the Sgr C1 XRN may belong to Arm I, while C2 is in Arm II. Assuming uniform circular rotation around Sgr A*, Sofue (1995) predicted that Arm I and Arm II are respectively located in the foreground and background with respect to Sgr A* (cf. figure 10 of Sofue 1995). The X-ray face-on view (figure 5) is basically consistent with the radio result.

4.3. XRN Parameters and Two-Temperature Structure of the Galactic Center Plasma

The photon index and \(EW_{6.4\,\text{keV}}\) for the 6.4 keV clumps in Sgr C are 1.54–1.71 and 1.15–1.27 keV, respectively (table 2). These values are approximately equal to the Sgr B results (Ryu et al. 2009). The large \(EW\) is in favor of the X-ray reflection and fluorescent origin (e.g., Koyama et al. 1996; Murakami et al. 2001). The photon index is consistent with the canonical active galactic nucleus (AGN; e.g., Ishisaki et al. 1996), which favors the XRN scenario, owing to the past flare of Sgr A*.

The best-fit temperature of LP\((kT_{\text{LP}})\) and the mixing ratio \((\alpha = \text{norm}_{\text{HI}}/\text{norm}_{\text{LP}})\) in the GCPE at Sgr C are 0.87–0.95 keV, and 0.23–0.29, respectively. These values are nearly equal to those in the Sgr B region: \(kT_{\text{LP}} = 0.81–0.91\) keV and \(\alpha = 0.26–0.28\) (Ryu et al. 2009). Sgr C and Sgr B are located at nearly symmetrical positions with respect to Sgr A* on the Galactic plane, and hence these results indicate that the GCPE distribution is symmetrical not only in the flux profile (Uchiyama et al. 2013), but also in the spectral shape. These results lead us to re-estimate the line-of-sight positions of Sgr B MCs using the same methods for Sgr C (subsection 4.1). The line-of-sight positions derived from parameter \(R\) of the Sgr B MCs (Ryu et al. 2009) are also plotted in figure 5.

4.4. Activity History of Sgr A*

On the basis of the XRN scenario of the past flares of Sgr A*, we constructed parabolas, with their common foci at Sgr A*, to illustrate the equi-delay time \((T_e)\) contours of the X-ray echoes (see figure 5). The time delay \(T_e\) of the echo is given as

\[
T_e = (\sqrt{X^2 + Y^2 + Y})/c \quad \text{[yr]}. \tag{3}
\]

Using the fluorescent Fe I intensity \((I_{6.4\,\text{keV}})\), the distance \([D_e=(X^2 + Y^2)^{1/2}]\), and the column density of XRN (Abs1; table 2), the required X-ray (2–10 keV) luminosity of Sgr A* \((L_\ast\) can be expressed as below (e.g., Nobukawa et al. 2008; Sunyaev & Churazov 1998):

\[
L_\ast = 1.0 \times \left( I_{6.4\,\text{keV}}/10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2} \right) \times \left( D_e/300 \text{ ly}^2 \right) \times \left( N_{\text{HI}}/10^{22} \text{ H cm}^{-2} \right)^{-1} \left[10^{46} \text{ erg s}^{-1}\right]. \tag{4}
\]

Here, isotropic radiation of Sgr A* with a photon index of \(\Gamma = 1.6\) is assumed (table 2). We then derived \(T_e\) and \(L_\ast\) for three Sgr C XRNes (C1–3) and the Sgr B XRN (Ryu et al. 2009). The results are summarized in table 3, and a long-term light curve of Sgr A* is plotted in figure 6. Sgr A* was active with short flares, and possibly in a continuous high-luminosity state with \(L_\ast = (1–3) \times 10^{39}\) erg s\(^{-1}\) from the past \(\sim 50\) to \(\sim 500\) years ago. Thanks to measurements of the line-of-sight position of C2 (see figure 5), we find that Sgr A* experienced periods of high luminosity already 500 years ago, which extends the light curve of Inui et al. (2009) and Ponti et al. (2010) back by 200–400 years.

In the past high state, the luminosity shows sporadic variabilities (short flares) at \(\sim 200\) and \(\sim 100\) years ago, as suggested by Sgr B (M 0.74) and Sgr C1, respectively. The short flare at \(200–300\) years ago would be responsible for the short-term time variability of Sgr B2 (Nobukawa et al. 2011; Koyama et al. 2008), and hence the variability time scale would be 5–10 years. The other short flare at \(\sim 100\) years ago has a similar time-scale, as inferred by the 6.4 keV time variability (increase) of C1 in 4 years (2006–2010) at 3–\(\sigma\) level (table 2). This flare may correspond to the time variability of the Sgr A XRN. Munoz et al. (2007) and Koyama et al. (2009) reported variability of the 6.4 keV line from the Sgr A cloud on a short-time scale of 3–5 years at a \(\sim 5\) \(\sigma\) level. Then, Ponti et al. (2010) and Capelli et al. (2012) predicted that flare-like events occurred at \(\sim 100–400\) years ago, which is basically consistent with our results. Ponti et al. (2010) proposed that the flare should have started \(\sim 400\) years ago, while Capelli et al. (2012) suggested that a high period ended \(\sim 150\) years ago based on the illumination pattern in the Sgr A complex. However, the estimated flare luminosities are different: \(L_\ast \sim 10^{39}\) erg s\(^{-1}\) was suggested by Ponti et al. (2010), while \(L_\ast \sim 10^{38}\) erg s\(^{-1}\) was suggested by Capelli et al. (2012). These inconsistencies

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**Table 3: Summary of X-ray Flare Parameters**

| Flare Event | \(L_\ast\) (erg s\(^{-1}\)) | \(T_e\) (yr) | \(D_e\) (ly) | \(N_{\text{HI}}\) (H cm\(^{-2}\)) |
|-------------|-------------------|-----------|-------------|-----------------|
| C1          | \(10^{39}\)        | 200–300   | 300         | 10^{22}         |
| C2          | \(10^{39}\)        | 100–500   | 500         | 10^{22}         |
| C3          | \(10^{39}\)        | 50–300    | 300         | 10^{22}         |

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**Figure 5:** Face-on view of Sgr C XRNes (filled circles) around Sgr A*. The parabolas (dashed lines) represent the equal-time delay \((T_e)\) contours for the X-ray echoes from Sgr A*. Sgr B results from Ryu et al. (2009) (open circles) are also added (see subsection 4.3). Parameter details are given in table 3.
are mainly attributable to unclear line-of-sight positions, and partly due to the difficult estimation of $N_H$ for the Sgr A XRNe. The luminosity determined by Capelli et al. (2012) is $\sim 10^{37}$–$10^{38}$ erg s$^{-1}$ around 70 and 130 years ago, which is about 10-times lower than that obtained here: $L_\star \sim 10^{39}$ erg s$^{-1}$ at $\sim 90$ years ago. The high luminosity indicated by C1 may be attributed to a short-term flare that occurred in the fading period reported by Capelli et al. (2012). A unified analysis for the Sgr A XRNe, as performed in Sgr C and Sgr B in this paper, would solve these problems.

The average X-ray luminosity in the high state was $L_{\text{ave}} \sim 2 \times 10^{39}$ erg s$^{-1}$, which is only $\sim 4 \times 10^{-6}$ of the Sgr A* Eddington limit ($L_E \simeq 5 \times 10^{44}$ erg s$^{-1}$) with a mass of $4 \times 10^6 M_\odot$ (Ghez et al. 2008). Still, from this luminosity, we may state that Sgr A* has been a low-luminosity AGN (e.g., M 81: Ishisaki et al. 1996) for the past 50 years.

The present X-ray luminosity of Sgr A* is $L_\star \sim 10^{33}$–$10^{35}$ erg s$^{-1}$ (Baganoff et al. 2001; Porquet et al. 2003), and hence a sudden luminosity drop by 4–6 orders of magnitude should have occurred within $\sim 100$ years. Schawinski et al. (2010) reported that the quasar IC 2497 with a mass of $\sim 10^9 M_\odot$ experienced a dramatic luminosity drop by more than 4 orders of magnitude in 45000–70000 years. On the other hand, for Galactic X-ray binaries with a black-hole mass of $\sim 10 M_\odot$ (e.g., GRS 1915+10: Greiner et al. 1996), a state change from high/soft to low/hard was detected on a time scale of 1 hour. Assuming that the state-change time scale is proportional to black-hole mass, at a mass of $4 \times 10^6 M_\odot$, 70000 years (for $10^9 M_\odot$) and 1 hour (for $10^6 M_\odot$) correspond to 280 years and 46 years, respectively. Then, the time scale of the luminosity drop for Sgr A* is estimated to be as fast as 50–300 years, which is consistent with the prediction in our light curve (figure 6).

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Table 3. Three-dimensional parameters of XRNe and past luminosity of Sgr A*.

| XRN ID | Obs. Year | $X$ [ly] | $Y$ [ly] | $D_\star$ [ly] | $T_\ast$ [yr] | $L_\star$ [10$^{39}$ erg s$^{-1}$] |
|--------|-----------|---------|---------|---------------|--------------|------------------|
| Sgr C1 | 2010      | $-230$  | $-241^{+40}_{-60}$ | $333^{+50}_{-30}$ | $93^{+10}_{-10}$ | $3.1^{+1.1}_{-0.5}$ |
| Sgr C2 | 2010      | $-216$  | $189^{+200}_{-30}$ | $287^{+150}_{-20}$ | $476^{+350}_{-50}$ | $1.2^{+0.2}_{-0.2}$ |
| Sgr C3 | 2010      | $-162$  | $-173^{+30}_{-50}$ | $237^{+20}_{-20}$ | $64^{+10}_{-10}$ | $0.8^{+0.2}_{-0.1}$ |
| Sgr B2 | 2005      | $327$   | $-55^{+50}_{-60}$ | $331^{+50}_{-5}$ | $281^{+50}_{-40}$ | $1.7^{+0.2}_{-0.1}$ |
| Sgr B1 | 2006      | $258$   | $-75^{+50}_{-50}$ | $269^{+20}_{-10}$ | $198^{+40}_{30}$ | $1.0^{+0.2}_{-0.1}$ |
| M 0.74–0.09 | 2005 | $363$   | $-202^{+50}_{-60}$ | $416^{+30}_{-20}$ | $219^{+30}_{-20}$ | $2.7^{+0.4}_{-0.3}$ |
| M 0.74-sub | 2007 | $363$   | $-280^{+80}_{-60}$ | $459^{+40}_{-40}$ | $182^{+40}_{20}$ | $2.8^{+0.5}_{-0.5}$ |

1 The uncertainties of $Y$ are at 90% confidence level (statistical). Errors of $D_\star$, $T_\ast$, and $L_\star$ are estimated using the $Y$ ranges.

2 Coordinates $X$ and $Y$ correspond to the positions in the Galactic longitude ($l$) and the line of sight from Sgr A*, respectively.

3 Distance from Sgr A* calculated from $D_\star = (X^2 + Y^2)^{1/2}$.

4 Time delay of echo from Sgr A* calculated from equation (3) and counted from 2010.

5 Required past X-ray luminosity of Sgr A* calculated from equation (4), also see text.

Fig. 6. X-ray light curve of Sgr A* in the past 500 years. Data points of Sgr C and Sgr B are shown by filled and open circles, respectively. Error bars contain distance uncertainties (see table 3). The inset panel shows the short-term variability (1–σ error) indicated by the two observations of C1 on the 6.4 keV line (see table 2), in which the distance uncertainties are not included. The present luminosity of Sgr A* is quoted from Baganoff et al. (2001) and Porquet et al. (2003).
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