ENHANCEMENT OF THE 6.4 keV LINE IN THE INNER GALACTIC RIDGE: PROTON-INDUCED FLUORESCENCE?

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ABSTRACT

A common idea for the origin of the Galactic diffuse X-ray emission, particularly that of the iron lines from neutral and highly ionized atoms, is a superposition of many cataclysmic variables and coronally active binaries. In this scenario, the flux should symmetrically distribute between the east and west on the plane with respect to Sagittarius A* because the stellar mass distribution determined by infrared observations is nearly symmetric. This symmetry is confirmed for the highly ionized iron line as well as the continuum emission. However, a clear excess of the neutral iron line in the near east of the Galactic center compared to the near-west side is found. The flux distribution of the excess emission well correlates with the molecular column density. The X-ray spectrum of the excess emission is described by a power-law continuum plus a 6.4 keV line with a large equivalent width of ~1.3 keV, which is hardly explained by the low-energy electron bombardment scenario. The longitudinal and latitudinal distribution of the excess emission disfavors the X-ray irradiation, either by Sagittarius A* or by nearby X-ray binaries. Then, the low-energy proton bombardment is the most probable origin, although the high-energy density ~80 eV cm⁻³ in 0.1–1000 MeV is required and there is no conventional proton source in the vicinity.

Key words: cosmic rays – Galaxy: disk – X-rays: ISM

1. INTRODUCTION

K-shell iron lines are one of the most remarkable features in the Galactic diffuse X-ray emission (Galactic center X-ray emission, GCXE, and the Galactic ridge X-ray emission, GRXE). The spatial distribution of the iron lines largely extends out to |l| ~ 60° along the plane. A deep observation of the GRXE near the Galactic center (l = 0°8, b = −1°42') has resolved almost all the GRXE flux into point sources (Revnivtsev et al. 2009). This fact demonstrates that the origin of the iron lines is due to a superposition of many point sources such as cataclysmic variables (CVs) and coronally active binaries (ABs; Revnivtsev et al. 2006; Yuasa et al. 2012; Warwick et al. 2014). The spectroscopic studies with ASCA, XMM-Newton, Chandra, and Suzaku revealed that the K-shell iron lines are separated into three lines at 6.4 (neutral iron), 6.7 (He-like iron), and 7.0 keV (H-like iron; Koyama et al. 1996; Predehl et al. 2003; Muno et al. 2004; Uchiyama et al. 2013). The X-ray spectra of the GRXE and GCXE, however, are not the same, which indicates different origins (Uchiyama et al. 2013). Even in the point-source scenario, the spectra and the mixing ratio of CVs and ABs should be different between the GRXE and GCXE. Furthermore, the flux distribution of the 6.4 keV line in the GCXE is clumpy, while those of the 6.7 and 7.0 keV lines show a roughly smooth and east–west symmetric distribution with respect to Sagittarius (Sgr) A* in the Galactic center (Uchiyama et al. 2011).

The 6.4 keV clumps in the GCXE have a large equivalent width (EW ~ 1.0 keV) and are time variable (e.g., Inui et al. 2009; Ponti et al. 2010; Nobukawa et al. 2011), and hence their origin is believed to be X-ray reflection and fluorescence by external X-rays of past big flares of Sgr A* (X-ray reflection nebulae; Koyama et al. 1996). In addition to the clumps, a more uniformly distributed 6.4 keV line emission is found (Uchiyama et al. 2011), and its origin is under debate. This Letter reports the first evidence for a clear east–west asymmetry of the 6.4 keV line emission at |l| = 1°5–3°5 on the Galactic disk: the east shows an excess over the west. Based on the spatial and spectral analysis, we discuss the origin of this excess. Errors quoted in this paper are at 90% confidence levels unless otherwise specified. The distance to the Galactic center is assumed to be 8 kpc.

2. OBSERVATIONS AND DATA REDUCTION

We performed campaign observations of the inner Galactic disk near the Galactic center at −4° < l < −2° (west side) and 2° < l < 4° (east side) using the Suzaku X-ray observatory (Mitsuda et al. 2007). The observation log is listed in Table 1. The X-ray charge coupled device camera, the XIS (Koyama et al. 2007), on board Suzaku covers the energy range of 0.2–12 keV and has a field of view of 17′8 × 17′8. We excluded events during the South Atlantic Anomaly passages, at elevation angles below 3° from the night Earth rim and at elevation angles below 10° from the sunlit Earth rim. We further excluded the data of ~3 ks during background flares detected on 2013 March 17. We reprocessed the data by using xispi in the analysis software package, HEAsoft 6.15.1, and the Suzaku calibration database (CALDB) released in 2014.
May. After the screening, we obtained the total exposure times of 597 and 1187 ks for the west and east data sets, respectively.

A bright X-ray binary, GX 3+1, is located at $(l, b) = (2^\circ.294, 0^\circ.794)$, which is 30$'$–90$'$ apart from each pointing in the east observations. Since some regions of the XIS fields of view are contaminated by the stray light from GX 3+1, we used data in the other clean regions. We excluded fields of view are not exactly on the Galactic plane. We use the scale-height of 0.7 for the GRXE (Kaneda et al. 1997). Then, the relation between the best-fit intensity $I_{\text{obs}}$ at $b$ and the corrected intensity $I_{\text{cor}}$ is

$$I_{\text{obs}} = \exp \left( -\frac{|b| + 0^\circ.046|}{0^\circ.7} \right) \times I_{\text{cor}}. \tag{1}$$

The longitudinal profile of the intensity of the 6.4 and 6.7 keV lines and the continuum are shown in Figure 1. Previous studies revealed that a major fraction of the GRXE is due to unresolved point sources, mostly CVs and ABs (Revnivtsev et al. 2006, 2009; Yuasa et al. 2012; Warwick et al. 2014). The stellar distribution has been constructed from infrared observations and has an east–west symmetry (Launhardt et al. 2002; Revnivtsev et al. 2006; Nishiyama et al. 2001). The intensity of the neutral iron Kβ line is fixed to 0.125 times that of the neutral iron Kα line (Kaastra & Mewe 1993), while those of the other lines are free parameters.

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| Table 1 | Observation Log |
|---------|-----------------|
| **Western Side** |
| Obs. ID | Pointing Direction | Obs. Start (UT) | Exposure Time (ks) |
|---------|-------------------|-----------------|-------------------|
| 501052010 | $-1.5004$ | $0.0034$ | 2006 Oct 10 06:45:09 | 21.0 |
| 501053010 | $-1.8335$ | $-0.0030$ | 2006 Oct 10 21:18:59 | 23.4 |
| 503014010 | $-2.0995$ | $-0.0522$ | 2008 Sep 18 04:46:49 | 59.7 |
| 504036010 | $-2.2943$ | $-0.1163$ | 2009 Aug 29 12:05:20 | 136.5 |
| 503015010 | $-2.3502$ | $-0.0527$ | 2008 Sep 19 07:33:05 | 61.4 |
| 503016010 | $-2.6012$ | $-0.0525$ | 2008 Sep 22 06:47:49 | 57.4 |
| 503017010 | $-2.8503$ | $-0.0525$ | 2008 Sep 23 08:08:10 | 56.5 |
| 503018010 | $-3.1015$ | $-0.0517$ | 2008 Sep 24 09:27:54 | 31.9 |
| 503018020 | $-3.1004$ | $-0.0514$ | 2008 Oct 03 18:05:13 | 13.3 |
| 503018030 | $-3.1006$ | $-0.0470$ | 2009 Feb 19 07:32:01 | 12.9 |
| 503019010 | $-3.3496$ | $-0.0477$ | 2009 Feb 19 16:37:49 | 56.8 |
| 503020010 | $-3.6001$ | $-0.0473$ | 2009 Feb 21 01:15:55 | 66.2 |

| **Eastern Side** |
| Obs. ID | Pointing Direction | Obs. Start (UT) | Exposure Time (ks) |
|---------|-------------------|-----------------|-------------------|
| 501060010 | 1.5106 | 0.0027 | 2007 Mar 17 05:07:04 | 68.1 |
| 508075010 | 1.7513 | $-0.0431$ | 2014 Mar 10 01:33:32 | 109.3 |
| 502009010 | 1.8336 | $-0.0035$ | 2007 Oct 12 21:52:24 | 22.9 |
| 507069010 | 2.0003 | $-0.0439$ | 2013 Mar 15 09:48:19 | 110.3 |
| 507070010 | 2.2511 | $-0.0437$ | 2013 Mar 17 18:39:56 | 111.8 |
| 507071010 | 2.5011 | $-0.0438$ | 2013 Mar 20 02:41:04 | 112.3 |
| 507072010 | 2.7509 | $-0.0439$ | 2013 Mar 22 07:20:36 | 110.7 |
| 507073010 | 3.0011 | $-0.0434$ | 2013 Mar 24 08:46:03 | 108.9 |
| 507074010 | 3.1514 | 0.1563 | 2013 Apr 03 21:33:46 | 104.1 |
| 507075010 | 3.2512 | 0.4070 | 2013 Mar 11 09:06:19 | 109.6 |
| 508076010 | 3.2514 | $-0.0427$ | 2014 Feb 28 12:46:16 | 109.8 |
| 508077010 | 3.5043 | $-0.0380$ | 2014 Mar 02 17:09:51 | 109.4 |

Note. 

* Effective exposure time after the screening (see the text).
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Figure 1. Intensity profiles of X-rays and $^{12}$CO molecular clouds on the Galactic plane ($b = -0\degree046$). The triangles, squares, and circles show the fluxes of the continuum in the 4–10 keV band (where the 6.7 keV band was excluded), the 6.7 keV line, and the 6.4 keV line, respectively. Errors are quoted at 68% confidence levels. The dashed lines show a model of stellar distribution, which is symmetric with respect to Sgr A* (Launhardt et al. 2002; Revnivtsev et al. 2006; Nishiyama et al. 2013). The red lines are the $^{12}$CO intensity profile (the unit is on the right-side axis). The blue lines are the sum of the symmetric distribution model and the $^{12}$CO intensity multiplied by $\alpha$, where $\alpha$ is a factor to convert the $^{12}$CO intensity to the 6.4 keV flux (see the text).

2013). The profile is given by the dashed lines in Figure 1. All the X-ray flux distributions, except that of the 6.4 keV line in the east, are consistent with the stellar distribution curve. A remarkable structure is the excess of the 6.4 keV line flux in the east compared to the west, and hence the excess should have a different origin from the symmetrical components due to point sources.

We plot in Figure 1 the $^{12}$CO line intensity taken by NANTEN integrated over the velocity range from $-300$ to $+300$ km s$^{-1}$ (Torii et al. 2010). Here, the local components uniformly distributed around $-20$ to $+30$ km s$^{-1}$ and the near-side 3 kpc arm having a velocity gradient from $-80$ km s$^{-1}$ at $l = -5\degree$ to $-30$ km s$^{-1}$ at $l = 5\degree$ (Dame & Thaddeus 2008) are excluded. The $^{12}$CO profile is similar to the excess distribution of the 6.4 keV line in the east, which suggests that its origin is due to molecular gas. The excess at $l = 3\degree$ coincides with the intersection point of the Galactic plane and the giant molecular cloud, Bania’s Clump 2, which extends toward the north (Bania 1977).

3.2. Spectrum of the Excess of the 6.4 keV Line in the East

Figure 2(a) shows integrated X-ray spectra from the east and west sides. The CXB is subtracted from both the spectra according to Kushino et al. (2002). Each spectrum is fitted with an absorbed power law plus four Gaussian lines at 6.4, 6.7, 7.0, and 7.06 keV. The interstellar absorption column density is fixed to $5 \times 10^{22}$ cm$^{-2}$. The intensity of 7.06 keV (the neutral iron Kβ) line is fixed to 0.125 times that of 6.4 keV (the neutral iron Kα) line. The best-fit parameters are summarized in Table 2.

We subtract the west spectrum from the east one to make the X-ray spectrum of the east excess as is shown in Figure 2(b). The excess spectrum is fitted with a power law plus a Gaussian line at 6.4 keV. The best-fit continuum and the line fluxes are $(1.9 \pm 0.3) \times 10^{-8}(E/6.4\text{ keV})^{-3\pm1}$ photons s$^{-1}$ keV$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ and $(2.5 \pm 0.6) \times 10^{-8}$ photons s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$, respectively, as shown in Table 2. Since the 6.7 keV line and its relevant continuum fluxes have a possible asymmetry between the east and west by $\pm7\%$, we take this error into account as the uncertainty of the symmetry. Then the EW is estimated to be $1.3 \pm 0.4\pm0.2$ keV, where the second and third terms are the statistical and systematical errors, respectively.

In the case of cosmic-ray bombardment, the 6.4 keV line is produced via inner-shell ionization by protons in the MeV band (Dogiel et al. 2011) or by electrons in the keV band (Valinia et al. 2000; Yusef-Zadeh et al. 2002), while the continuum is due to inverse bremsstrahlung (for protons) or bremsstrahlung (for electrons). The photon index of the observed X-ray spectrum ($\Gamma = 3 \pm 1$) translates into the particle index 2.5 $\pm 1.0$. As for the X-ray irradiation, the 6.4 keV line is produced via photoionization by X-rays with energy higher than 7.1 keV (K-edge), while the continuum is due to Thomson scattering. The photon index of the observed X-ray spectrum is the same as that of the irradiating X-rays. We show the EW of the 6.4 keV line as a function of the particle or photon index in Figure 3. In both scenarios, the EW depends on the iron abundance (Tsujimoto et al. 2007; Dogiel et al. 2011). The metal abundances were determined in the Galactic center region by X-ray observations of the high-temperature plasma to be $\sim$1.9 solar for sulfur, argon, and calcium, but $\sim$1.2 solar for iron (Nobukawa et al. 2010; Uchiyama et al. 2013). Munoz et al. (2004) reported a similar result. The iron abundance of 1–1.5 solar was also measured in the X-ray reflection nebulae in Sgr B with the absorption of the Fe K-edge (Nobukawa et al. 2011). The same result was obtained by mid-infrared observations; Giveon et al. (2002) obtained two solar for heavy elements of neon, sulfur, and argon (not of iron), and Cunha et al. (2007) and Martin et al. (2015) measured the iron abundance to be 1–1.5 solar. Therefore, we adopt the iron abundance of 1–1.5 solar in Figure 3. The EW in the X-ray scenario also depends on the angle $\theta$ between the line of sight and the incident photon direction (Tsujimoto et al. 2007). Figure 3 shows the result of the reflection angle $\theta = 90\degree$, which gives the maximum EW.

The black horizontal line in Figure 3 indicates the best-fit EW, while the horizontal hatched region shows the range of the statistical and systematical errors. The allowed parameter region completely excludes the electron origin. Then, we discuss the other X-ray and proton scenarios in the following subsections.

3.3. X-Ray Irradiation Scenario

In the X-ray irradiation scenario, the 6.4 keV line flux depends on the irradiating source flux, the hydrogen column density ($N_H$), and the distance ($D$) between the irradiating source and the target. The hydrogen column density $N_H = (2.6) \times 10^{22}$ cm$^{-2}$ is obtained by multiplying the $^{12}$CO line intensity in Figure 1 by the conversion factor (called X-factor) of $0.7 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Torii et al. 2010).

A possible irradiating source is the supermassive black hole Sgr A*, as for the X-ray reflection nebula model invoked for the GC region (Sunyaev et al. 1993; Koyama et al. 1995; Ponti et al. 2010). In this case, the source luminosity should be $L_{X} \sim 10^{40} (D/450 \text{ pc})^{2}$ erg s$^{-1}$ about 1500 $\times$ (D/450 pc) years ago, where $D$ is the distance of the 6.4 keV line emitting region from Sgr A*. For the X-ray reflection nebulae in Sgr B, the
The luminosity of Sgr A* was $\sim 10^{39}$ erg s$^{-1}$ about 300 years ago (Murakami et al. 2000; Revnivtsev et al. 2004). Brighter flares of $\sim 10^{41}$–$10^{43}$ erg s$^{-1}$ in the far past ($10^5$–$10^7$ years ago) have been proposed to explain the Fermi bubbles and the recombining plasma in the south region of the Galactic center (Su et al. 2010; Nakashima et al. 2013). Thus, many big flares in the interval period between these two epochs ($\sim 700$–$1500$ years ago) may be conceivable. However, this scenario has two difficulties. The first difficulty comes from the longitudinal distribution of the excess flux of the 6.4 keV line. The observed excess flux is proportional to the $^{12}$CO intensity, which means that the X-ray intensity from Sgr A* is almost constant and does not decrease as the square of the Galactic longitude or the distance from Sgr A*; the past Sgr A* flares should have smoothly increasing flux with the square of the look-back time. A monotonous smooth decrease of flux should continue during $700$–$1500$ years ago, which is artificial, although not completely rejected. The second difficulty comes from the flux ratio of the 6.4 keV line to the $^{12}$CO intensity ($\alpha$) in the molecular cloud Clump 2. Clump 2 extends toward the north from the Galactic plane and has an elliptical shape with major and minor axes of $\sim 1^{1}\,\text{and} \sim 0^{0.5}$, respectively. We estimate the excess...
6.4 eV line flux from the on-plane ($b \sim -0.04$; Obs. ID = 507073010) and off-plane ($b \sim 0.15$–0.40; Obs. ID = 507074010 and 507075010) parts of Clump 2 by subtracting the symmetrical component from the observed flux and obtained $\alpha$ of $(5.9 \pm 0.7) \times 10^{-11}$ and $(2.1 \pm 0.6) \times 10^{-11}$ for the on- and off-plane parts, respectively (unit: photons s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (K km s$^{-1}$)). Since the flux from Sgr A* would be equal in the small separation angle between on- and off-plane parts, $\alpha$ should be also equal, which is in conflict with the observed values. From these two difficulties, we regard the X-ray irradiation by Sgr A* to be unlikely.

The other possibility is that irradiation of many X-ray binaries in the east is responsible for the 6.4 eV line. This idea is essentially the same as Molaro et al. (2014). Assuming that a mean spectrum of the relevant X-ray binaries is a power law with the photon index of $\Gamma = 3$, and is surrounded by cold material with $N_H = 2-6 \times 10^{22}$ cm$^{-2}$, a fraction of 0.03%–0.1% of the total 2–10 keV flux is converted to 6.4 keV X-rays. We estimate the excess 6.4 keV luminosity in total to be $3 \times 10^{33}$ erg s$^{-1}$ in the relevant area of $2.0 \times 0.2$. Then, a total luminosity of $3 \times 10^{36}$–$10^{37}$ erg s$^{-1}$ is required to the sources inside the area. This flux exceeds the total luminosity of the GRXE in this region (1–3 × 10$^{36}$ erg s$^{-1}$) by one or two orders of magnitude. No source brighter than $10^{35}$ erg s$^{-1}$ is found in this area. Therefore, more than one or two orders of magnitude brighter X-ray binaries in the relevant region are required. In addition, the reflection angle $\theta$ should be distributed randomly. Then, the EW integrated over the reflection angle $\theta$ is $\sim 1.3$ times lower than the green belt in Figure 3 (reflection angle $\theta = 90^\circ$), and hence is out of the allowed range. Thus, this scenario is also unlikely.

### 3.4. Energy Density of Low-energy Protons

In the proton model, the excess flux of the 6.4 keV line $I_{6.4keV}$ is given by

$$I_{6.4keV} = \frac{1}{4\pi} N_H \int \sigma_{6.4keV} v A \left( \frac{E_p}{\text{1 MeV}} \right)^{-2.5} dE_p$$

where $\sigma_{6.4keV}$, $v$, $A$, $E_p$, and $N_H$ are the cross section to produce the 6.4 keV line by protons, the velocity, the number density at 1 MeV and the energy of protons, and the line-of-sight hydrogen column density, respectively. The spectral index of $-2.5$ is adopted from the best-fit result (see Figure 3). Using the $X$-factor of $0.7 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Torii et al. 2010), the 6.4 keV line flux is expressed as the $^{12}$C line intensity multiplied by the conversion factor $\alpha$, which is measured to be $4.2 \times 10^{-11}$ photons s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (K km s$^{-1}$)$^{-1}$ in Figure 1. The cross section $\sigma_{6.4keV}$ has a peak at 10 MeV and rapidly decreases below 1 MeV and above 50 MeV (Paul & Sacher 1989). We set the integration range to be 1–50 MeV, and then we obtained the normalization $A = 1.4 \times 10^{-5}$ protons cm$^{-3}$ and the energy density of 20 eV cm$^{-3}$. When the integration range is expanded to 0.1–1000 MeV, the energy density becomes 80 eV cm$^{-3}$. This is about one or two orders of magnitude higher than the canonical value $\sim 1$ eV cm$^{-3}$ that is determined by observing high-energy cosmic rays (Neronov et al. 2012).

Tatischeff et al. (2012) calculated an energy conversion rate from protons to the 6.4 keV line to be $10^{-5}$ or less. Since the total luminosity of the 6.4 keV line emission is $3 \times 10^{33}$ erg s$^{-1}$, the proton power of $>3 \times 10^{39}$ erg s$^{-1}$ is estimated. This is not far from the energy $\sim 2 \times 10^{40}$ erg s$^{-1}$ that protons input to the Galactic center (Dogiel et al. 2013).

The diffusion length of low-energy (~MeV) protons is only a few tens of parsecs (Dogiel et al. 2011), and therefore the MeV protons should be produced in situ, possibly by a supernova remnant or a pulsar wind nebula. However, no candidate source is found in the vicinity. Amano et al. (2011) indicated that cosmic-ray particles are possibly generated with stochastic acceleration by Alfvenic turbulence in the central molecular zone with a large velocity dispersion of $\sim 100$ km s$^{-1}$. Since Clump 2 exhibits a large velocity dispersion of $\sim 100$ km s$^{-1}$ (Bania 1977; Torii et al. 2010), another possibility to produce the MeV protons is the stochastic acceleration. Our results demonstrate that the 6.4 keV line can be a unique probe to investigate low-energy cosmic-ray protons.

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