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The Galactic Ridge X-ray Emission: the 6.4 keV Line

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There exists an unresolved X-ray emission component, that extends along the Galactic plane, and called the Galactic ridge X-ray emission (GRXE). The GRXE spectrum exhibits prominent Fe K-shell lines at 6.4, 6.7, and 7.0 keV. Approximately 80% of the Fe line flux has recently been resolved into point sources; hence, a superposition of faint point sources is now considered to be the dominant origin of the GRXE. However, the remaining portion of the flux is still under debate. Therefore, we investigated longitudinal distributions of the Fe lines in $|l| < 4^\circ$ with Suzaku, and discovered an asymmetrical profile in the 6.4-keV line intensity, which is contrary to the symmetrical behavior of the 6.7 keV line. The excess of the 6.4 keV line intensity in $l = 1\overset{\circ}{.}5$–4° is associated with the ^{12}CO intensity, which consists of a hard continuum and a 6.4 keV line with an equivalent width of 1.3 ± 0.4 keV. These results indicate that the 6.4 keV excess is difficult to explain using the integration of faint point sources; the excess is probably emitted from the dense interstellar medium due to the bombardment of low-energy cosmic-ray protons with energy density of $\sim$80 eV cm^{-3}. No canonical accelerator, such as a supernova remnant or a pulsar wind nebula, can be found in the vicinity. One possible mechanism would be stochastic acceleration by Alfvénic turbulence in interstellar space.

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1. Introduction

Unresolved X-ray emission along the Galactic plane, which is called as the Galactic diffuse X-ray emission (GDXE), was first discovered in the 1960's [1]. The GDXE peaks in the $\sim 1^{\circ}$ central region (the Galactic center X-ray emission: GCXE) and smoothly extends over $\sim 60^{\circ}$ along the Galactic ridge (the Galactic ridge X-ray emission: GRXE). The most characteristic feature of the GDXE is K-shell lines of Fe at 6.4, 6.7, and 7.0 keV from Fe I, Fe XXV, and Fe XXVI, respectively [5]. The 6.7 and 7.0 keV lines originate from high temperature plasma with $kT = 5$–10 keV [5, 8]. Since the 6.4 keV line in the GCXE is well correlated with giant molecular clouds (GMCs), the most plausible scenario is an X-ray reflection nebula (XRN). The supermassive black hole, Sagittarius A* (Sgr A*) was active several hundred years ago and has been illuminating the surrounding GMCs [13, 9].

The origin of the 6.4 keV line in the GRXE remains an open issue. Recently, $\sim$80% of the GRXE flux in the Fe line band was resolved into faint point sources, most of which are thought to be cataclysmic variables (CVs) and collonally active binaries (ABs) [14]. Those sources may contribute to the 6.4-keV line emission in the GRXE. If this is not the case, other scenarios such as XRNe or cosmic-ray bombardment on the interstellar medium are possible [6, 3].

To investigate the origin of the 6.4-keV line emission, we focus on the east and west sides of the Galactic center ($|l| = 1.^{\circ}5$–4°). In the east side, there is a GMC, called Bania's Clump 2 (hereafter Clump2), whereas a little molecular cloud is seen in the west side [11]. In the case that the 6.4-keV line emission comes from the GMC, asymmetry in the line intensity should be observed. We used the Suzaku data in the $|l| < 1.^{\circ}5$–4° region, and followed the same analytical procedure as that in [10]. We take a 1σ statistical uncertainty herein, unless stated otherwise. We also discuss prospects of observations by ASTRO-H, which will be launched in 2016 [16].

2. Excess of the 6.4-keV Line Emission in the East Side

We extracted an X-ray spectrum from each observation. Figure 1 shows a sample spectrum taken from data at $(l,\ b) = (-3.^{\circ}60,\ -0.^{\circ}05)$, which has prominent 6.4, 6.7, and 7.0 keV lines. The spectra were fitted with a model consisting of bremsstrahlung (continuum) and four Gaussians for Fe I Kα, Fe XXV Heα, Fe XXVI Lyα, and Fe I Kβ (7.06 keV), as well as the cosmic X-ray background (CXB).

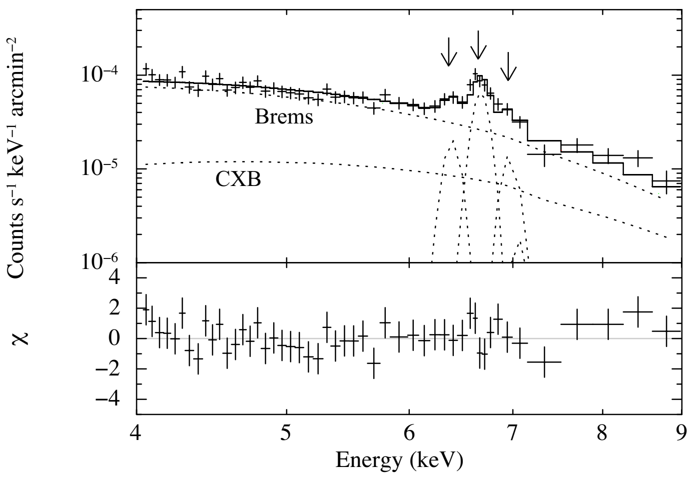

Figure 1: Sample GRXE spectrum fitted with a model, bremsstrahlung (Brems), and Fe lines at 6.4, 6.7, 7.0 (three arrows) and 7.06 keV as well as the cosmic X-ray background (CXB). This spectrum was taken from ObsID=503020010 at coordinates $(l,\ b) = (-3.^{\circ}60,\ -0.^{\circ}05)$.

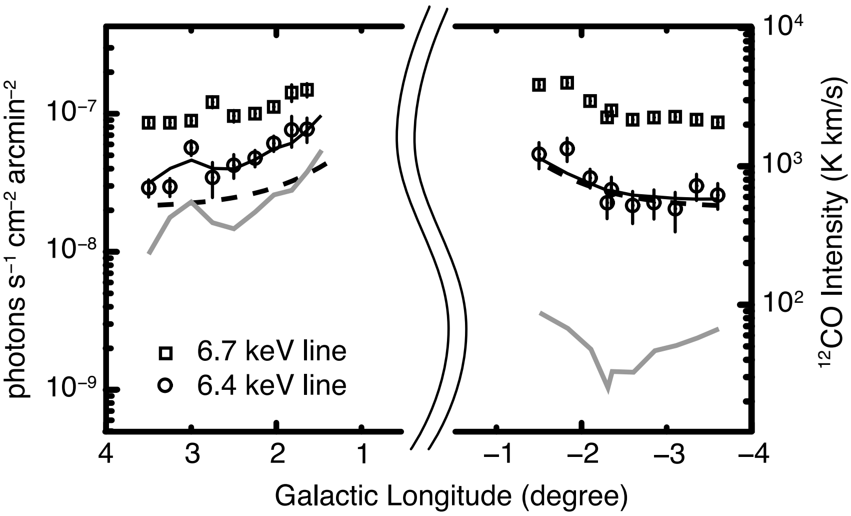

Figure 2: Distribution of the 6.4 and 6.7 keV line intensities along the Galactic plane near the central region. The 6.4 keV line distribution in the west side is fitted with the dashed curve, and the symmetrical curve is adapted to that in the east. The gray curve shows the ^{12}CO intensity profile. The solid black curve is a sum of the dashed and gray solid curves.

The surface intensity profiles for the 6.4 and 6.7 keV lines along the Galactic longitude are shown in units of photons s^{-1} cm^{-2} $arcmin^{-2}$ in Figure 2. The 6.7-keV line profile is distributed smoothly and symmetrically with respect to the Galactic center in the east and west sides of $|l| = 1.^{\circ}5$–4° (the open squares). In contract, we observed asymmetry in the 6.4-keV line profile (the open circles). The 6.4 keV line intensity in the west side (negative l) is fitted with the dashed curve in Figure 2. We symmetrically displaced the curve, and compared it with the 6.4 keV data in the east side. The east-side data is found to be approximately two times higher than that in the west. The discrepancy between the 6.4 and 6.7 keV profiles would indicate that the origin of the 6.4 keV line is different from that of the 6.7 keV line. If the 6.7 keV line emission originates from a superposition of faint point sources [14], another origin is required for the 6.4 keV line emission.

The 6.4 keV profile shows a spike at $l = 3.^{\circ}0$, where Clump2 is located [11]. Thus, we compared the 6.4 keV line profile with that of ^{12}CO obtained by NANTEN [10]. Gray curves in Figure 2 indicate the ^{12}CO data. Here the scale is shown on the right axis. This profile also has a spike at the same position ($l = 3.^{\circ}0$) as that of the 6.4 keV line, which corresponds to Clump2. The ^{12}CO profile is multiplied by 4.2×10^{-11} photons s^{-1} cm^{-2} $arcmin^{-2}$ (K km $s^{-1})^{-1}$ and is added to the dashed curve. The total model (the solid black line) represents the 6.4 keV data from the east-side well, indicating that the excess emission originates from the molecular gases. The ^{12}CO intensity in the west is approximately one order of magnitude lower than that in the east, and then provides no significant contribution to the 6.4-keV line emission.

3. Spectrum of Excess Emission

To examine the spectral features of the excess emission, we subtracted the spectrum taken from the west-side from that from the east-side. The resulting excess spectrum has a prominent 6.4 keV line and a continuum as shown in Figure 3. Spectral fitting with a power law plus a Gaussian model was achieved, and a photon index $\Gamma = 3 \pm 1$ and an equivalent width (EW) 1.3 ± 0.4 keV were obtained (90% error).

4. Origin of the Excess 6.4 keV Line Emission

Since molecular gas is cold ($T \sim 10$–100 K), it cannot generate X-rays by itself. High-energy particles

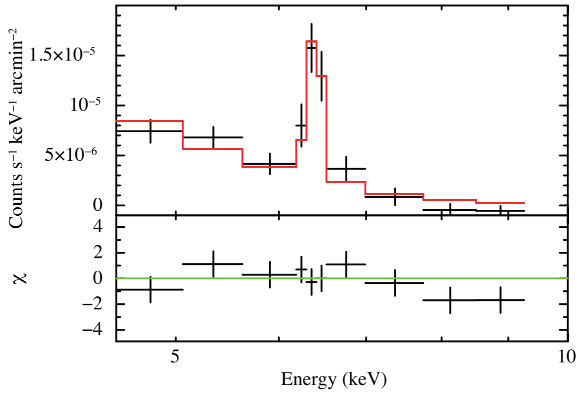

Figure 3: Top panel shows the spectrum of the 6.4 keV excess obtained by subtracting the western spectrum from the eastern one. The fitting model consists of a power-law with $\Gamma = 3 \pm 1$ and a 6.4 keV line with the equivalent width (EW) 1.3 ± 0.4 keV. The bottom panel shows residuals between the data and the model.

such as X-rays, cosmic-ray electrons, and protons impact on the molecular gas [15, 19, 3] and ionize iron atoms, resulting in the 6.4 keV line emission. Simultaneously, continuum emission is generated via Thomson scattering or bremsstrahlung for the X-ray and cosmic-ray cases, respectively. The largest difference among the scenarios is the expected EW of the 6.4 keV line [17, 8, 3]. In the case of an X-ray origin, an EW of $\sim$ 1.0 keV is expected [8]. On the other hand, EWs of 0.3–0.5 keV and $>$ 0.6 keV are calculated for the cosmic-ray electron and proton cases, respectively [3]. The EW of 1.3 ± 0.4 keV excludes the cosmic-ray electron origin.

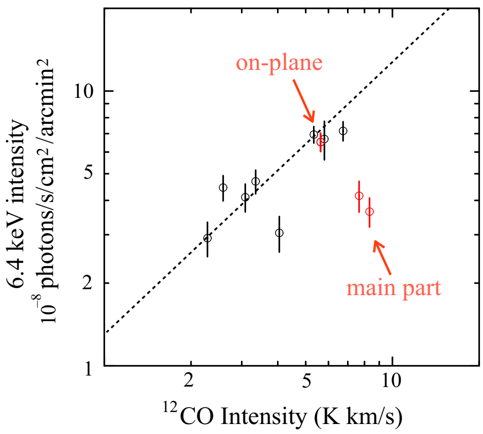

Figure 4: Correlation between the 6.4 keV line intensity and the ^{12}CO intensity. Red circles represent the main part and the on-plane data of Clump2.

In the case of an X-ray origin, one possible irradiating source is a past big flare of Sagittarius A* (Sgr A*) [5]. The calculation by [8] provides the required luminosity of $\sim 10^{41}$ erg s^{-1} ($\sim$1500 years ago). The XRNe in the Galactic center region indicate that Sgr A* had a luminosity of $\sim 10^{39}$ erg s^{-1} several hundreds of years ago [5, 13, 9]. Clump2 is elongated along the latitudinal direction (positive b), and the main part is located at $b \sim 0.^{\circ}3$. Figure 4 shows the relation between the 6.4 keV line and the ^{12}CO intensities taken from the same data set as that used in Figure 2. The two arrows indicate the main and on-plane parts. The ^{12}CO intensity in the main part is higher than that in the on-plane part, whereas the 6.4 keV line exhibits the reverse relationship. Since both parts are the same distance from Sgr A*, this observational result is in conflict with the XRN scenario. In the case where many X-ray sources illuminate the molecular gas, a total luminosity of $\sim 10^{36}$ erg s^{-1} or more is required. However, no such sources have been observed in the area at $l = -1.^{\circ}5$–$-4.^{\circ}0$.

Thus, the cosmic-ray proton origin is favored. The cross section of K-shell ionization for iron has a peak at the proton kinetic energy of $E \sim 10$–30 MeV [12]. From the 6.4 keV line intensity and the molecular gas density, the proton energy density is estimated to be 80 eV cm^{-3}, which is one order of magnitude higher than a typical value of 1 eV cm^{-3} for high-energy cosmic-rays > 1 GeV [7].

Since MeV protons scarcely diffuse due to interstellar magnetic fields [3], they should be accelerated in situ. However, neither a supernova remnant nor a pulsar wind nebula has been reported in the vicinity. A scenario of stochastic acceleration via Alfvénic turbulence has been proposed for cosmic-rays in the Galactic center because large velocity dispersions ~ 100 km s^{-1} are observed in the area [2]. Clump 2 also has a velocity dispersion of ~ 100 km s^{-1} [18]. This scenario may be accepted as the origin of the excess 6.4 keV emission in the GRXE.

5. Prospects for Observations by ASTRO-H

In the case of the proton bombardment, the 6.4 keV line broadens to ~ 10 eV due to multiple ionization [4]. If the origin is X-rays or electrons, the 6.4 keV line should be narrow. There have been no X-ray observations performed with energy resolution less than 10 eV for diffuse emission so far. We will soon be able to measure the line broadening using the microcalorimeter SXS (Soft X-ray Spectrometer) onboard ASTRO-H, whose energy resolution is 5 eV.

We performed a simulation assuming that we observe the $l = 3.^{\circ}0$ region with an exposure time of 300 ks using ASTRO-H/SXS. We considered two cases wherein (a) half of the 6.4 keV line emission in the eastern side originates from MeV protons and (b) all of the 6.4 keV line emission is due to an X-ray origin. In the case of (a), although the origin of the symmetrical component between the east and west sides (the dashed lines in Figure 2) has not been constrained yet, we assume that it is due to a superposition of faint CVs, where the 6.4 keV line does not broaden. Figure 5 shows the simulated spectra in the energy band of the 6.4 keV and 6.7 keV lines. In the case of (a), the superposition of the proton and point-source origins provides a line width of 5 ± 2 eV. Contrarily, a line width < 2 eV would be obtained in case (b). In addition to the EW, we derive the contribution of low-energy cosmic-ray protons to the 6.4 keV line in the GRXE more quantitatively.

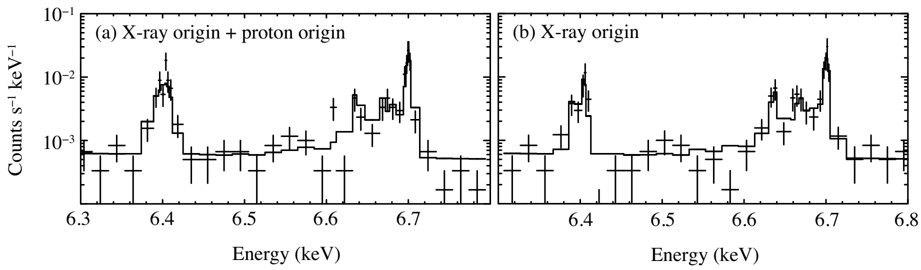

Figure 5: Simulated spectra from the ASTRO-H/SXS in the case of equal contributions from X-rays and protons (a) and in the case of only the X-ray contribution (b). A line broadening of 5 ± 2 eV would be obtained in the case (a).

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