Origin of the 6.4 keV line of the Galactic Ridge X-ray Emission (GRXE)

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Suzaku found that 6.4 keV line emission with nearly equal EW uniformly exist.

No region with such high EW has been discovered except the GC.

Key Question.
What is the origin of this 6.4 keV line emission in the Galactic ridge?
Asymmetric Distribution of 6.4keV line

6.4 keV line flux

Galactic Longitude l (deg)

East (left) Ridge  GC  West (right) Ridge

Intensity (1e-7 photons /s /cm$^{-2}$ /arcmin$^2$)

10

1

10$^{-1}$

4  3  2  1  0  -1  -2  -3  -4

KP  XRN

FeI (6.4 keV) l profile @ b=-0.046 pm 0.05 deg

East (left) Ridge

West (right) Ridge

Galactic Longitude l (deg)
Asymmetric Distribution of 6.4keV line

Suzaku flux ratio between the two lines also shows asymmetric distribution.

Fe center energies distribute asymmetrically.

These results suggest the source of the 6.4 keV emission line distribute asymmetrically.
6.4 keV flux - 6.7 keV flux

- GC
  - 6.4 keV line emission has diffuse origin.
  - 6.4 and 6.7 keV lines have different origins
  - Their fluxes have a scattered correlation.

- Ridge
  - The correlation is on the natural extension from the GC.
  - The 6.4 keV line fluxes also scatter.
  - The expected KP data seem to be on the line of XRNe.
**Single Origin ? or + Extra Source ?**

- Objective 1: See if the plots of EW6.4 and EW6.7 concentrate in a single point or not.

- Examine if the spatial distribution of the 6.4 keV line emission is symmetric or asymmetric with respect to the GC.

**Case A:** Single Origin (point source ?)

**Case B:** + Extra Source (diffuse ?)

- In the GC, the EWs are different from point to point.
- This is because Fe emission lines are mixture of multiple origins.

Start with Case B...
6.4 keV line emission correlates with MCs

6.4 keV line flux

I3CO (NANTEN, Takeuchi+10)
Strong 6.4 keV line emission from Clump 2

Objective 2
Search of correlation with MCs.

Objective 3
Determination of the ionizing particle.

I = 3.5° exhibits especially strong 6.4 keV line

I = 3.2° “Clump 2”
Candidates for the ionizing particles

- 6.4 keV flux \( \sim 1 \times 10^{-7} \text{ ph/cm}^2\text{/sec/arcmin}^2 \) is expected in the KP observing region.

- XRN (X-ray Reflection Nebula)
  - Already seen in the GC.
  - Sgr A\(^*\) Lx(Sgr A\(^*\)) \( \sim 10^{41} \text{ ergs/s} \)

- LECRp (Low Energy Cosmic Ray Proton)
  - NH \( \sim 1 \times 10^{24} \text{ cm}^{-2} \) (observed at Clump 2)
  - \( U_p > 75 \text{ eV/cm}^3 \) \( \leftarrow \) equipartition with \( B > 50 \mu \text{G} \) at \( R < 400 \text{ pc} \) (Crocker+11)
    \( \Rightarrow \sim 0.5 \times 10^{-7} \text{ ph/cm}^2\text{/sec/arcmin}^2 \)

- LECRe (Low Energy Cosmic Ray Electron)
  - cf. Valinia+00
  - \( U_e \sim 1 \text{ eV/cm}^3 \times \text{NH} \sim 1 \times 10^{23} \text{ cm}^{-2} \)
    \( \Rightarrow \sim 1 \times 10^{-7} \text{ ph/cm}^2\text{/sec/arcmin}^2 \)

All the three processes are possible.
EW(6.4) of the 6.4 keV component  【GC】

- EWs are different from point to point
- Successfully fit the data with a line.
- The emission is resolved into 6.4 keV- and 6.7 keV-related components.
  - The intercept is the EW of the 6.4 keV line emission against the continuum of the 6.4 keV-component.
  - EW = 1.2keV  → XRN

Apply this method to the Ridge data.
**EW(6.4) of the 6.4 keV component**  
【Ridge】

- We are unable to fit the line only with existing data.
- Adding the KP data allows us to obtain the correlation line.
- Obtain EW(6.4) of the 6.4 keV- component.
- Referring to the value, we determine the ionizing particle.
Particles (on their spectrum. Its value for the power-law spectra of edge at 7.1 keV.

Nobukawa et al. (2011) estimated the iron absorption coefficient in the collisional scenario and by Thomson scattering in the photoionization scenario.

This suggests that the irradiating model seemed to be more attractive than the electron impact scenario. This conclusion is supported by the fact that the equivalent width of line emission from Sgr B2 at about 1.9 solar. Nobukawa et al. (2010) found that the equivalent width of line emission from Sgr B2 should be about 4 solar, while the iron abundance in Sgr B2 requires a abundance higher than solar.

Revivtsvet al. (2004) obtained their iron abundance from the Suzaku group (Koyama et al. 2007b, 2009) who gave values from direct estimations of the iron abundance there provided by the LER group.

For line emission due to impacts of subrelativistic electrons, the cross-section can be significant. This is also generated by different processes: by bremsstrahlung production for electron (thick solid line) and by protons (thin solid line) are quite different. In the collisional scenario and by protons with relatively small energies, the cross-section is completely the same as for electrons with energy.

Below we briefly present parameters of the proton spectrum calculated by Koyama et al. (2007b). The data for injection energy 0.5-3000 keV for the soft spectra to 100 MeV is shown in figure 2. It was assumed here that the proton spectrum is given by a power-law of index -3 (see Dogiel et al. 2009c).

We notice, however, that the equivalent width of the K line has a sharp cut-off at 7.1 keV, that for protons is rather smooth, for electrons is rather smooth, for electrons with energy.

The equivalent width of the iron line, /ESC, is also generated by different processes: by bremsstrahlung and a contribution from protons with relatively small energies.

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LECR: shallow absorption

LECRp: deep absorption

### Diagram Explanation

**XRN vs LECR**

- **X-ray Reflection**: Produces X-ray reflection lines.
- **Electron Scattering**: Produces electron scattering lines.
- **Energy**
  - 2 keV
  - 6.4 keV
  - 7.1 keV

**XRN**: large EW & deep absorption

**LECR**: shallow absorption

**LECRE vs LECRp**

- **Spectral Index**
  - -4 to 0

- **EW (keV)**
  - 0.1 to 100

- **Electrons**
  - $N_H \sim 10^{21} (\text{cm}^{-2})$
  - $N_H \sim 10^{24} (\text{cm}^{-2})$

- **Protons**
  - $N_H \sim 10^{21} (\text{cm}^{-2})$
  - $N_H \sim 10^{24} (\text{cm}^{-2})$

**Dogiel+11**

- $E_{inj} = 80$ MeV
- $E_{inj} = 50$ MeV
If XRN

Reveal the Activity of Sgr A* (SMBH) in 2000 years.

Light Curve of Sgr A*

- Clump 2
- Sgr B, C
- Sgr A

Direct observation with Chandra

in 10 years (Gillessen+12)
**LECRe vs LECRp**

**ASTRO-H**

SXS (μ-calorimeter)

- **e⁻ (keV)**
  - $\sigma \sim 0$ eV

- **p (MeV)**
  - $\sigma \sim 10$ eV

**Cosmic Ray spectrum**

- 6.4 keV
- Observe for the first time
- GeV/TeV
- Log(number density)

**Total amount of energy of CR, Spectrum, Spacial distribution**

**EW**

→ **e or p**

**Line width**

→ **conclusive evidence**
Single Origin = Point Source Origin of 6.4 keV line (apart from 6.7 keV line)

6.7 keV is from Active Binaries
6.4 keV is from CVs

Continuum of ABs reduces EW of 6.4 keV line from CVs

16 CVs in Yuasa’s D-Th
6.4 keV ~ 110 eV
6.7 keV ~ 120 eV
(given by Yuasa-san)

Ridge

Active Binaries

Sum of AB stars

Counts s⁻¹

Counts s⁻¹

Energy (keV)

Energy (keV)

235 eV

415 eV

14 pointings

19 eV

7 AB

380 eV

16 CVs in Yuasa’s D-Th
6.4 keV ~ 110 eV
6.7 keV ~ 120 eV
(given by Yuasa-san)
Point Source Origin of 6.4 keV line (apart from 6.7 keV line)

- Mixture of ABs and CVs can explain only the EWs on the line connecting the two.
- Simple mixture does not explain. 
  \[ \Rightarrow \text{Fe(Local)} \times 2-3 \] is required.

- Abundance Measurements near GC
  - Giants (old >5x10^9yr) (bulge) 
    \[ \Rightarrow 0.6 \text{ solar} \]
  - Super Giants (young ~10^8yr) (< 12’)
    \[ \Rightarrow 1.3 - 2.0 \text{ solar} \]
  - X-ray Plasma (ISM present) (< 20’)
    \[ \Rightarrow \text{Fe} \sim 1.2 \text{ solar} \] (Nobukawa+10)
    (note: Si, S = 1.9-2.5 solar)

Objective 4

Measurement of the Fe abundance gradient toward the GC (along l) and Planes (along b).
**Simulation : Spectrum and Correlation**

- CXB and NXB are already taken into account in this simulation.
- $\Delta EW_{6.4} = \pm 39 \text{ eV (90\%)}$
- $\Delta EW_{6.7} = \pm 44 \text{ eV}$

- A simulation of the correlation. (Scatter the data by hand)
- Can determine EW(6.4) with enough accuracy to distinguish the ionizing particles.
“True” Legacy : Serendipitous Discoveries

Published or Accepted 30

Line Diagnostics of GCDX
Spectrum of Sgr A East
Hard X-Ray Emission the Arches Cluster
Diffuse Iron line of the Sgr B Region
Peculiar Hot Star in the GC
A Time Variable X-Ray Echo of Sgr B2
Diffuse Hard X-ray from the GC
New XRN and SNR in the Sgr B1 Region
X-Ray Flare of A-type Star HD 161084
SNR Candidate G359.79-0.26
New X-ray views of the Galactic Center
X-Ray Observations of the GC
Variable Neutral Iron Line in Sgr B2
Spatial Distribution of the GCDX
Suzaku Observations of Sgr D HII region
SAX J1748.2-2808
XRN in the Sgr C region
Dips/Absorption Lines of AXJ1745.6-2901
Thermal plasma near the Sgr C region
Iron lines from Galactic Ridge and GC
Superbubble
Face-on view of Sgr B2
Foot-Point of the Radio Arc
Neutral Lines of Light Elements of Sgr A region
SNR and 6.4keV lines around the Great Annihilator
RRC of G359.1-0.5
Structures of Diffuse Emission from GCDX and GRDX
K-Shell Emission of Neutral Iron Line from Sagittarius B2
Suzaku Discovery of Twin Thermal Plasma from the Tornado Nebula
Spatial and Temporal Variations of the Diffuse Iron 6.4 keV Line in the Galactic Center Region
6.4 keV structure around Archies Cluster
A Time Variability of XRN in Sgr B2
3-D position of the Molecular Cloud of Sgr C in the GC
Spatial and Temporal Variations of the Diffuse Iron 6.4 keV Line in the Galactic Center Region
Broadband Spectral Decomposition of the Galactic Ridge Emission

In prep. or Submitted 5

Doctor Thesis : 6
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Fig. 1. Wide-band (0.7–5.5 keV) smoothed images by the (a) XIS and (b) MOS shown with the logarithmic intensity scale. Overlaid green contours in (a) are an 18 cm radio continuum map from the Very Large Array (VLA; Mehringer et al. 1998). The point source extraction aperture size and background accumulation region for PS2 and PS3 are shown in (b). See subsubsection 3.2.1 for details. For the XIS image, we merged events with the three CCDs, subtracted the non-X-ray background (Tawa et al. 2008), corrected for the vignetting, and mosaicked the two fields with different exposure times normalized. The fields of view are shown with two solid squares with 1800 in length. For the MOS image, we merged two CCDs and mosaicked the two fields with normalized exposures. The fields are shown with two circles with 300 in diameter.

by external X-ray irradiation (Murakami et al. 2000). H II regions are also an emerging class of diffuse X-ray sources with a similar spatial scale. They show a variety of spectral shapes, including soft thermal (Townsley et al. 2003; Hyodo et al. 2008), hard thermal (Moffat et al. 2002; Ezoe et al. 2006), and nonthermal (Wolk et al. 2002; Law & Yusef-Zadeh 2004; Wang et al. 2006; Tsujimoto et al. 2007; Ezoe et al. 2006) emission. In addition to the X-ray emission, the measurement of the X-ray absorption gives a constraint on the distance and hence the physical scale of extended objects.

Several X-ray observations were reported in the Sgr D region. In a BeppoSAX study (Sidoli et al. 2001), diffuse X-ray emission was significantly detected from the Sgr D SNR and marginally detected from the Sgr D H II complex. In an ASCA study (Sakano et al. 2002), the image was plagued by stray lights from a nearby bright source and was unsuitable to search for diffuse X-ray sources. In an XMM-Newton study (Sidoli et al. 2006), dozens of point sources were identified, but no diffuse emission was detected presumably due to high background. The possible diffuse X-ray detection by BeppoSAX in the Sgr D H II complex has not been confirmed and no spectral information exists for this source.

We conducted X-ray observations of the Sgr D H II complex using the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007a) onboard Suzaku (Mitsuda et al. 2007). The low background of XIS makes it particularly well-suited for finding diffuse sources of low surface brightness and yielding their high signal-to-noise ratio spectra. Indeed, a series of XIS studies in the GC region identified several new SNRs and irradiated GMCs (Koyama et al. 2007b; Mori et al. 2008; Nobukawa et al. 2008) and reported detailed spectroscopy of an H II region (Tsujimoto et al. 2007). Upon the confirmation of the previously claimed marginal diffuse detection in the Sgr D H II complex, we further aim to construct the X-ray spectrum which gives important insights into the origin of the emission and the entire complex.

Here, we present a significant detection of diffuse X-ray emission from the Sgr D H II complex with the Suzaku XIS. High signal-to-noise ratio spectra were obtained from two different diffuse sources. We discuss their X-ray characteristics and their association with sources observed in our study using the 100-m Green Bank Telescope (GBT) and in other archived multiwavelength data sets. Based on these data, we propose a new view of the Sgr D H II complex. In this paper, we supplement the Suzaku data with those taken by XMM-Newton in order to evaluate the contribution of point sources to the diffuse emission. Throughout this paper, we use east and west in the Galactic longitude direction, and north and south in the Galactic latitude direction for simplicity.

2. Observations
2.1. Suzaku

We used two XIS fields covering the Sgr D H II complex in the Suzaku GC mapping project (table 1). We hereafter call the two fields as north and south fields (figure 1a). The north field...
5 New Types of objects

Super Bubble

Chimney

RRC-SNR

Tornado

4 Unexpected Phenomena • New Perspectives

X-ray Tomography

time variable 6.4 keV line

Neutral lines from light elements

Thin Extended 6.4keV line emission
Many AX J*** were discovered by the ASCA Plane Survey, which eventually results in Suzaku’s good achievements. This KP will make many serendipitous discoveries, which leads to fruitful results with Astro-H.
Thank you.
Pointing Positions, Exposure Time and Feasibility

- 10 x 100ksec

- Stray lights from GX3+1 does not affect the Fe-line studies.
Pointing Positions, Exposure Time and Feasibility

Suzaku 6-7 keV band image