The Suzaku Results of the Galactic Center Diffuse X-Ray Emission

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Abstract

The most pronounced features of the Galactic center diffuse X-ray (GCDX) are the K-shell transition lines from neutral (Fe I), He-like (Fe XXV) and H-like (Fe XXVI) irons at energies of 6.4 keV, 6.7 keV and 7.0 keV, respectively. With the high energy-resolution and the low background, particularly in the hard X-ray band of Suzaku, we obtained accurate fluxes of these lines. We constrain the GCDX region using the longitude and latitude distribution of the 6.7keV lines; The GCDX is extended $\pm 0.42°$ and $\pm 0.16°$ in the longitude and latitude e-folding scales from Sgr A*. Neither the 6.4 keV nor 6.7 keV line flux shows close proportionality to the continuum flux (5–10 keV band); the 6.4 keV line shows excess in the high flux side, and vice versa for the 6.7 keV line. On the other hand, the sum of the 6.4 keV plus 6.7 keV line fluxes with the ratio of 1:2 shows good proportionality to the continuum flux, hence we phenomenologically decompose the continuum flux of the GCDX into the 6.4 keV- and 6.7 keV-associated continuums with the flux ratio of 1:2. The GC spectrum is also fit by a 6.5 keV-temperature plasma and a power-law continuum of the photon index 1.4 plus Gaussian lines at 6.4 keV and 7.05 keV. The fluxes of these two components are nearly the same with each others. Based on these facts, we estimate the flux ratio due to the diffuse and the integrated point sources as 6: 1, consistent with that derived from the scale-height analysis of 7:1. We also determine the line-of-sight positions of the molecular clouds (MC) from the analysis of absorption and 6.4 keV flux relation of the GCDX spectra, and find that the MCs lie on the parabola with the focus at Sgr A*. This is an equi-delay-time locus of about 300 light years for the X-ray originated from Sgr A* and reflected by the MC into our line of sight. The bright 6.4 keV clumps (MCs) of the Sgr B region exhibit time variability over about 10 years. Accordingly, we suspect that Sgr A* exhibited a large flare about 300 years ago with the variability time scale of about 10 years.

Key words: Galaxy: center—ISM: supernova remnant —X-ray spectra

1. Introduction

The Galactic center diffuse X-ray (GCDX) exhibits many K-shell lines from highly ionized atoms, and hence is due to high temperature plasmas. The key lines are K-shell transitions of He-like (Fe XXV) and H-like (Fe XXVI) irons at the center energies of 6.7, 7.0 keV and 7.9 keV, respectively.

The electron and ionization temperatures of the hot plasma are constrained by the line flux ratio of Fe XXV-Kβ to Fe XXV-Kα and that of Fe XXVI-Lyα (Lyman-α line) to Fe XXV-Kα, respectively.

In addition to these highly ionized atomic lines, the Kα and Kβ lines from neutral irons (Fe I) and the Kα line from neutral nickels (Ni I) are also discovered. Likely origin of these neutral K-shell lines is due to fluorescence irradiated by external X-ray sources (e.g. Koyama et al. 1996). However alternative scenarios, such as a bombarding of energetic electrons, have been also proposed (e.g. Valinia et al. 2000; Yusef-Zadeh et al. 2002).

The 5–11.5 keV band spectrum of the GCDX is naturally explained by a 6.5 keV-temperature plasma in collisional ionization equilibrium (CIE) and a power-law component with a photon index Γ=1.4 plus Gaussian lines at 6.4 keV and 7.05 keV. The flux ratio of the former component to that from the latter component is 1:1 (Koyama et al. 2007). On the other hand, the proper combination of the equivalent width of the 6.4 keV line ($EW6.4$) and that of the 6.7 keV line ($EW6.7$) as $0.5 \times EW6.4 + EW6.7 = 0.62$(keV) shows good proportionality to the 5–10 keV band flux, the GCDX may be decomposed into the 6.4 keV- and 6.7 keV-associated continuums with the flux ratio of 1:2 (Koyama et l. 2009). One plausible answer to solve this apparent inconsistency is proposed in this paper in relation to the origin of GCDX.

The Galactic center (GC) region is complex with many molecular clouds (MCs), called as the central molecular zone (CMZ). The Sgr B complex is one of the most well-known and massive molecular clouds complex lying in the GCDX plasma, but the position in the GCDX plasma has been unclear. In this paper, I present a new metrology to derive a face-on view and show the results. A time variability of the 6.4 keV-line was discovered from the Sgr B2 clouds (Koyama et al. 2008; Inui et al. 2009).

Based on these Suzaku results of imaging spectroscopic observations on the GCDX region. I discuss the origins of the 6.7 keV, 7.0 keV and 6.4 keV lines. The distance to the GC is assumed to be 8 kpc, and quoted errors are 90% confidence level unless otherwise mentioned. I use the Galactic coordinates, hence the east means the positive Galactic longitude side and vice versa for the west.

2. High Temperature Plasma

Suzaku obtained very nice GCDX spectra above 7 keV, and discovered Kδ and Kγ of Fe XXV as well as the Kα and Kβ of neutral nickel (Ni I) and Kα of He-like nickel(Ni XXVII). Then, we can precisely estimate the continuum shape. The continuum below 6 keV does not fit the slope above 7.5 keV with a clear energy jump at around 7 keV, which is the iron K-shell absorption edge. If we miss-understand that the continuum slope should be smooth at the edge energy, then we may miss-estimate the line fluxes of important lines such as Lyα of Fe XXVI and Kβ of Fe XXV. Another word, we reliably estimate the Lyα and Kβ lines of Fe XXV, which leads us to the reliable plasma diagnostic for the first time.

To make spatial distribution of the iron lines, I divided the GC region into many small areas, and fit the individual spectra with a power-law + Gaussian lines. Hereafter, we designate the line fluxes of Fe I-Kα at 6.4 keV, Fe XXV-Kα at 6.7 keV and Fe XXVI-Lyα at 7.0 keV as $F6.4$, $F6.7$ and $F7.0$, respectively.

The Galactic longitude (l)-distributions of $F7.0$ and $F6.7$, and the flux ratio of $F7.0/F6.7$ are shown by Uchiyama et al. in this Proceedings. Although there is a clear asymmetry of $F6.7$ between the East and West side, global structure is well fitted with a two-exponential function of,

$$A_1 \times \exp(-l/h_1) + A_2 \times \exp(-l/h_2) \ .$$

The best-fit parameters are $A_1 = 2.7 \times 10^{-6}$, $A_2 = 1.6 \times 10^{-7}$, $h_1 = 0.42°$, and $h_2 = 33°$ (see Uchiyama et al. in this Proceedings).

The e-folding scale of the small width component is 0.42°, which can be called as the GCDX, while the large width component of 33° should be the Galactic ridge diffuse X-ray(GRDX).

The flux ratio ($F7.0/F6.7$) is a good indicator of the plasma temperature. The l-distribution of this flux ratio is not constant, but shows a gradual decrease as a function of the longitude distance from the Galactic center at Sgr A*; the ratio is 0.4 at the GC and decreases to 0.2 at fur-off from the GC. This indicates the plasma temperature of the GCDX is ∼7 keV, which is higher than that of the GRDX of ∼ 5.5 keV. Thus the major origin of the GCDX may differ from that of the GRDX.

The Galactic latitude (b) distribution of $F6.7$ near at the GC is also given by a two-exponential function as,

$$A_1 \times \exp(-b/h_1) + A_2 \times \exp(-b/h_2).$$

The best-fit parameters are $A_1 = 2.1 \times 10^{-6}$, $A_2 = 3.3 \times 10^{-7}$, $h_1 = 0.16°$, and $h_2 = 1.1°$ (see Uchiyama et al. in this Proceedings).

The small scale height component ($h_1 = 0.16°$) would be high mass origin such as SNe, while the large scale height component ($h_1 = 1.1°$) would be low mass star origin such as white dwarf and/or active stars. Thus we can define the former component ($h_1 = 0.16°$) to be GCDX and the later ($h_1 = 1.1°$) to be the Galactic bulge diffuse X-ray (GBDX).

3. Decomposition of the 6.7 keV and 6.4 keV Components

We have divided the 2-field of the GC into 2 × 16 segments, then fit the individual spectra with a power-law continuum plus Gaussian lines. Using the best fit power-law index Γ, fluxes (F) and equivalent width (EW), we made correlation plots. The power-law index Γ is nearly constant at ∼1.9 in the wide range of the flux ratio of $F6.4/F6.7$.

The line fluxes ($F6.4$ and $F6.7$) show deviations from proportionality relations to the continuum band (5–10 keV band) flux at the high flux regions; $F6.4$ shows excesses in the high flux side, and vice versa for $F6.7$. However the value $F6.7 + 0.5 \times F6.4$ is nicely proportional to the continuum flux. In other word, the equivalent widths of the 6.4 keV ($EW6.4$) and 6.7 keV ($EW6.7$) line are given by the equation;

$$0.5 \times EW6.4 + EW6.7 = 0.62(\mathrm{keV}).$$

These are illustrated in figure 2 of Koyama et al.(2009). Thus, phenomenologically, about 2/3 (1/1.5) of the 5–10 keV flux is associated to the 6.7 keV line and the other 1/3 (0.5/1.5) is associated to the 6.4 keV line. On the other hand, Koyama et al.(2007) reported that the GC spectra can be fitted by a 6.5 keV-temperature plasma and a power-law of index 1.4 plus Gaussian lines at 6.4 keV(Fe I-Kα) and 7.05 keV (Fe I-Kβ). The 6.5 keV-plasma is approximated by a power-law slope with the photon index of Γ=2.4. The fluxes of the both components are nearly equal with each other (see figure 7 of Koyama et al. 2007).

The results pf these two decompositions are shown in figure 1. We see inconsistent results; the fraction of the 6.7 keV domain is 2/3 in the former decomposition, while that of the latter is 1/2. This apparent inconsistency can be solved if 1/6 of the total GCDX is due the point source contribution, and the point source spectrum has strong 6.7 keV line.

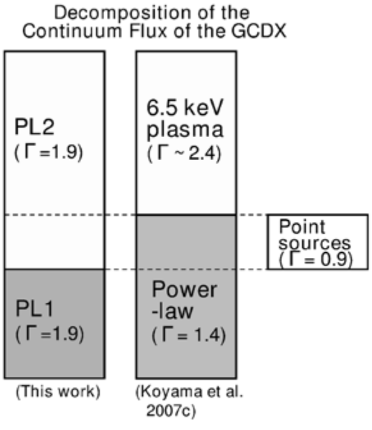

Fig. 1. The schematic diagram of the two decomposition results. (left) About 2/3 (1/1.5) of the 5–10 keV flux is associated to the 6.7 keV line and the other 1/3 (0.5/1.5) is associated to the 6.4 keV line. (right) The spectrum analysis by Koyama et al.(2007) shows that a half of the GC flux is explained by a 6.5 keV plasma and the other half is due to a power-law continuum of the photon index 1.4 plus 6.4 keV and 7.05 keV lines. (see text).

In fact, Muno et al. (2004) reported the Chandra result that a significant fraction of the GCDX is due to point sources with a flat continuum of Γ=0.9 and strong 6.7 keV line. Then from a simple calculation of

$(2 \times 2.4 + 0.9)/3 = 1.9$,

we can obtain consistent decomposition results not only in the flux ratio but also in the values of the photon index in the 6.4 and 6.7 keV domains.

I will move back to the scale height analysis. As I said, about 1/6 of GCDX is due to point sources. Revnivtsev at al. (2009) found most of the diffuse emission at $(l, b) = (0°, -1.4°)$ is due to point sources and the spectrum is dominated by the 6.7 keV line. The X-ray flux at $(l, b) = (0°, -1.4°)$ is mainly due to the large scale height component of $h_1 = 1.1°$ (GRDX) (see the figure in Uchiyama et al. in this Proceedings). The flux of this component at $b = 0°$ is $A_2 = 3.3 \times 10^{-7}$, while that of the small scale height component on the plane is $A_2 = 2.1 \times 10^{-6}$. Thus, we conclude that $\sim 1/7 (= 3.3 \times 10^{-7}/2.1 \times 10^{-6})$ of the GCDX is due to point sources, consistent with the other decomposition result of $\sim 1/6$ by Koyama et al. (2009).

4. The 6.4 keV Line Clumps

The Galactic center (GC) region is complex with many molecular clouds (MCs), emission nebulae, supernova remnants (SNR), non-thermal radio emission and so on. The major component is the central molecular zone (CMZ) which contains mass of $3 \times 10^7 M_\odot$, approximately corresponds to 10% of the whole molecular gas in the Galaxy.

We found an over-all trend of the GCDX that the absorption $N_{\rm H}$ value shows larger values in the Galactic east side compare to that of the west side. If a molecular cloud is near side of the GCDX, then the absorption may be large due to the molecular cloud. We, therefore, tried a new methodology to derive the positions of the Sgr B molecular clouds (MCs) along the line of sight, as an application study of the Galactic center diffuse X-ray (GCDX). The GCDX spectrum is composed of a hot plasma emission of about 7 keV plus 1 keV temperatures, and a non-thermal continuum emission including the 6.4 keV line from neutral irons. The former is uniformly distributed with the e-fluxing scale of $\sim \pm 0.42°$ in longitude, while the latter is more clumpy. We examined the correlation of the absorption in the GCDX and 6.4 keV features near to the Sgr B MC complex. The results are;

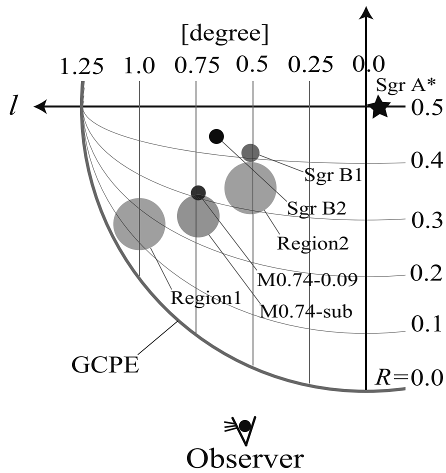

Fig. 2. The face-on view of the Sgr B molecular cloud complex. The molecular clouds are located on the parabola curve with the focus at Sgr A* by the equation $x^2 + y^2 = (300 - y)^2$ (see text).

1. The GCDX spectra suffer from two different absorptions (Abs1 and Abs2).

2. Abs1 is given by $N_{\rm H} \geq 10^{23}$ H cm^{-2}, and is proportional to $F6.4$, hence due to the MCs in front of the GCDX.

3. Abs2 is almost constant at $N_{\rm H} \simeq 6 \times 10^{22}$ H cm^{-2}, which is typical to the interstellar absorption toward the Galactic center.

Assuming that the GCDX plasma is a uniform density oblate around Sgr A* and the same flux ratio between the two temperature components, we determine the line-of-sight positions of the MCs from the flux ratio of the GCDX spectrum components, which are suffered by Abs1 and that free from Abs1. The results suggest that the Sgr B MCs are located at the near side of Sgr A* in the GCDX.

The schematic view of the 6.4 keV clump distribution is given in figure 2 (see also Ryu et al. in this Proceedings); molecular clouds (MC) distribution is bar-like with the inclination angle of 20–30°. On these MCs, we can plot a parabola-line given as;

$x^2 + y^2 = (300 - y)^2$,

where x and y are the face-on coordinate in the unit of light-years and the position of $(x, y) = (0, 0)$ is at Sgr A*. This is an equi-delay-time locus of about 300 years for the X-rays originated from Sgr A* and reflected in the line of our sight.

We found time variability of $F6.4$ from the Sgr B2 region with the time scale of about 10 years as are shown in figure 1 of Koyama et al. (2008) and figure 5 of Inui et al. (2009). From these results, we propose the scenario that about 300 years ago, Sgr A* exhibited large flare of 10-years time-scale variability in the following time sequence;

1. In 1994, the X-ray front coming form Sgr A* hit the cloud and produced the 6.4 keV line, which was observed with ASCA.
2. In 2000, the clouds were in a peak phase of the X-ray flare as was observed with Chandra and XMM-Newton.
3. In 2001, the clouds were suspected to enter in a declined phase.
4. In 2004, with the XMM-Newton observation, the clouds surely entered in a declined phase.
5. The declining phase has been continued at the epoch of the Suzaku Observation in 2005, then has been largely declined until now.

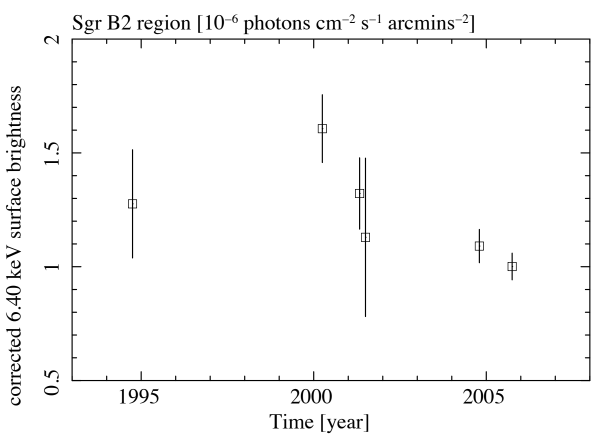

Fig. 3. The light curve of the 6.4 keV-lines in the Sgr B2 cloud complex, from the ASCA observation in 1994, the Chandra and XMM observations in 2000 and 2001, the XMM observation in 2004, to the Suzaku Observation in 2005.

5. Summary

I summarize the results of the Suzaku observation of the Galactic diffuse X-rays:

1. We separate the Galactic diffuse X-ray emission into the Galactic center diffuse X-ray(GCDX) and the Galactic ridge diffuse X-ray (GRDX) using the longitude distribution of the 6.7 keV line flux and the flux ratio of the 7.0 keV and 6.7 keV lines.
2. We also separate the Galactic diffuse X-ray emission into the GCDX and the Galactic bulge diffuse X-ray (GBDX) using the latitude distribution of the 6.7 keV line flux.
3. The GCDX is concentrated in the central region of $\pm 0.43°$ in longitude and $\pm 0.16°$ in latitude.
4. The plasma temperature of the GCDX is higher than GRDX, and hence the origins may be different.
5. The major fraction of the GCDX is diffuse emission. Integrated flux of point sources contributes $\sim 1/6$–$1/7$ of the total GCDX.
6. We determined 3-Dimensional distribution of the 6.4 keV line clumps (molecular clouds). The Sgr B cloud complex lies on an equi-delay-time locus of about 300 years with the focus point at Sgr A*.
7. The 6.4 keV line clumps are time variable, The origin is the past ($\sim$300 years) activity of Sgr A*.

This work has been carried out with the collaboration of H. Uchiyama, S. Ryu, S. Nobukawa and the other members of the Cosmic Ray Group of Kyoto University, Department of Physics. I would like to express my deep thanks to all of my colleagues.

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