Discovery of Kα lines of neutral sulfur, argon, and calcium atoms from the Galactic Center

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Abstract

The K-shell emission line of neutral iron from the Galactic center region was firstly discovered with ASCA. Since then, the origin is one of the key issues for the structure and activity of the Galactic center. Two possible origins have so far been proposed; fluorescence due either to an X-ray or an electron irradiations. Since the cross sections of these two processes depend differently on the atomic number, detections of neutral Kα lines from other elements such as sulfur, argon, calcium, chrome and manganese atoms would provide key information for the origin. We report the Suzaku discovery of Kα lines of neutral sulfur, argon, calcium, chrome, and manganese atoms from the molecular cloud which emits the brightest neutral iron line. New constrains on the origin of the neutral K-shell lines are given with the combination of these neutral Kα lines.

Key words: Galaxy: Center — X-rays: fluorescence — ISM: Molecular Cloud

1. Introduction

Kα line of neutral Fe at 6.4 keV is one of the mysteries remaining among the high energy phenomena in the Galactic center (GC) region. The 6.4 keV neutral Fe line emission from the GC region was firstly discovered with ASCA (Koyama et al. 1996). They found clumpy emissions correlating with giant molecular clouds in the Sagittarius (Sgr) B2 and the Radio Arc regions (here after, we call such a molecular cloud a "neutral clump").

The X-ray spectrum of the Sgr B2 neutral clump has the prominent 6.4 keV line on the continuum emission with deep absorption of $\sim 10^{24}$ cm^{-2} (Murakami et al. 2000). Recently, many new neutral clumps, M 0.74−0.09, M 0.51−0.10 (Sgr B1), G 0.174−0.233, M 359.47−0.15, M 359.43−0.07, M 359.43−0.12, M 359.38−0.00 have been discovered (Koyama et al. 2007a, Yusef-Zadeh et al. 2007, Nobukawa et al. 2008, Fukuoka et al. 2009, Nakajima et al. 2009).

Koyama et al. (1996) and Murakami et al. (2000) suggested that the 6.4 keV emission from the neutral clumps is due to the K-shell ionization of the iron atoms by external X-rays, possibly from the super-massive black hole, Sgr A*. Although the present X-ray luminosity of Sgr A* is $\sim 10^{33-35}$ erg s^{-1} cm^{-2} (Baganoff et al. 2001, 2003), the luminosity required for the 6.4 keV emission is 10^{38-39} erg s^{-1} cm^{-2}. Therefore Sgr A* in a few hundreds years ago would be 10^{3-6} times brighter than now (e. g. Koyama et al. 1996).

On the other hand, Yusef-Zadeh et al. (2002, 2007) proposed that the origin of the 6.4 keV emission would be low energy cosmic ray electrons ($E_{\rm e}$ =10–100 keV), because they found that the X-rays correlated to the non-thermal radio filaments. The scenario explains not only the 6.4 keV emission, but also the cosmic-ray heating of molecular gas and diffuses TeV emission from the Galactic molecular clouds.

The lighter atoms, such as S, Ar, Ca should exist in neutral clumps. However only K-shell lines of neutral Fe and Ni atoms had been discovered so fur, except that Fukuoka et al. (2009) found a hint of neutral Ca line from the foot-point of the Radio Arc filament. Since the cross section to the atomic number is different in the X-ray and electron scenarios, discovery of the emission lines of lighter atoms than Fe and Ni would provide a new method to constrain the origin of the neutral lines from the GC region

We, accordingly, re-analyzed the X-ray data of the GC region obtained with the X-ray Imaging Spectrometers (XIS; Koyama et al. 2007c) aboard Suzaku and found the emission lines from neutral S, Ar, Ca, Cr, and Mn atoms. We report the detailed analysis and the result, and discuss the origin.

2. Analysis and Results

Since the emission lines of lighter atoms are suspected to be 10–100 times weaker than that of Fe, we extensively searched for these lines from the GC region, which is on the $\sim 0.1^\circ$ east side of Sgr A*. Suzaku have deeply ob-

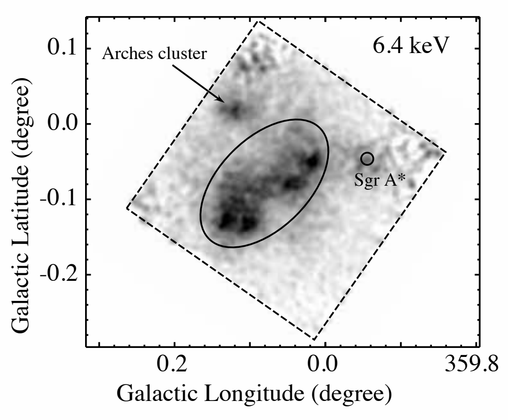

Fig. 1. The 6.4 keV neutral iron line image, where the underlying continuum flux was subtracted. The small circle indicates the position of Sgr A*. We extracted the spectrum from the solid elliptical region (the brightest neutral clump). The dashed square is the field of view (FOV) of the XIS. The bright source in the northeast edge of the FOV is the Arches cluster (Tsujimoto et al. 2007).

served the eastern vicinity of Sgr A* 4 times on September 2005, October 2005, September 2006, and September 2007. The total exposure time is 200 ks.

2.1. 6.4 keV line Image

In order to depict a neutral clump from the GC region, we made an X-ray image in the 6.4 keV line with the following procedures. We first made the X-ray images in the 5–6 keV and in the 6.3–6.5 keV bands, after the subtraction the non-X-ray background and correcting the vignetting effect. We extracted the X-ray spectra from a $8'$ circular region near the field center fit the 5–6 keV band spectrum with a power-law model. The best-fit photon index in the 5.0–6.0 keV band was obtained to be 1.25 ± 0.07. The ratio of the continuum photon flux in the 6.3–6.5 keV band to that in the 5.0–6.0 keV band estimated by this power-law index was 0.165. We multiplied the 5.0–6.0 keV band image by 0.165, and subtracted it from the 6.3–6.5 keV band image. The result is shown in figure 1.

We see a bright region near the center of the 6.4 keV line image as is shown with the solid elliptic line. Hereafter we call this region as "the brightest neutral clump".

2.2. Spectrum of the Brightest Neutral Clump

Figure 2 is the X-ray spectrum of the brightest neutral clump. The spectrum has several emission lines of heavy elements, such as Si, S, Ar, Ca, and Fe. These lines would come from the hot plasma of Galactic center diffuse X-rays (GCDX) with the temperature of k$T \sim 6.5$ keV (Koyama et al. 2007b) and possibly $\sim$1 keV (Ryu et al. 2009). On the other hand, we see K-shell lines of neutral Fe and Ni and possibly Ca at $\sim$3.7 keV. In order to extract and determine the flux of the neutral lines quantitatively, we tried model fitting of the spectrum.

2.3. Spectral Fitting

The fit model consists of hot plasma and neutral components. According to Koyama et al. (2007b), we fixed the abundances of Fe and Ni in the plasma component to 1.2 solar and 2.1 solar, respectively. We set the abundances of Si, S, Ar, and Ca as free parameters.

On the other hand, the X-ray spectrum of the neutral clump consists of emission lines of neutral atoms and a continuum absorbed by itself. As a result, we adopted the following model,

$$\text{Abs1} \times (\text{Plasma} + \text{Abs2} \times \text{Neutral Component}) + (\text{Abs1} \times \text{Abs1}) \times \text{CXB}. \quad (1)$$

Abs1 and Abs2 are absorption by an inter-stellar medium toward the GC region and by the molecular cloud of the neutral clump, respectively. The plasma component consists of two thin thermal plasma models (APEC[1]). Since the APEC model does not contain Cr and Mn lines, two gaussian lines were added at 5.68 and 6.17 keV, respectively. The neutral component is a model with gaussian lines plus a power-law continuum. The CXB component is the cosmic X-ray background. According to Kushino et al. (2002), we assumed that the spectrum of the CXB is a power-law with the photon index of 1.41 and the flux in the 2–10 keV band is 6.4×10^{-8} erg s^{-1} cm^{-2} st^{-1}. Since the CXB is integration of active galactic nuclei outside of our galaxy, absorption column density of the spectrum was assumed to be twice than that of the plasma component.

Neutral Fe and Ni lines have been already discovered (e.g. Koyama et al. 1986; 2007b). We first adopted only the K-shell lines of Fe and Ni for the neutral component (figure 3a).

After the spectral fitting with the model, some residuals remained (χ^2/d.o.f. is 355/208). The energy of the residuals correspond to that of Kα lines of S, Ar, Ca, Cr, and Mn atoms (dashed lines in figure 3a). We, then, added five gaussian lines at theoretical energy of the Kα line of S, Ar, Ca, Cr, and Mn. As shown in figure 3b, the residuals remaining in the previous fitting were significantly improved (χ^2/d.o.f. is 243/204). The best fit parameters are listed in table 1. We successfully detected the K-shell lines of neutral S, Ar, Ca, Cr, and Mn from the brightest neutral clump at the significance levels of 3.5, 3.2, 8.5, 4.5, and 4.6 σ, respectively.

3. Discussion

Two possible scenarios for the origin of the emission lines of neutral atoms from the GC region have been proposed

*1 http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/XSmodelApec.html

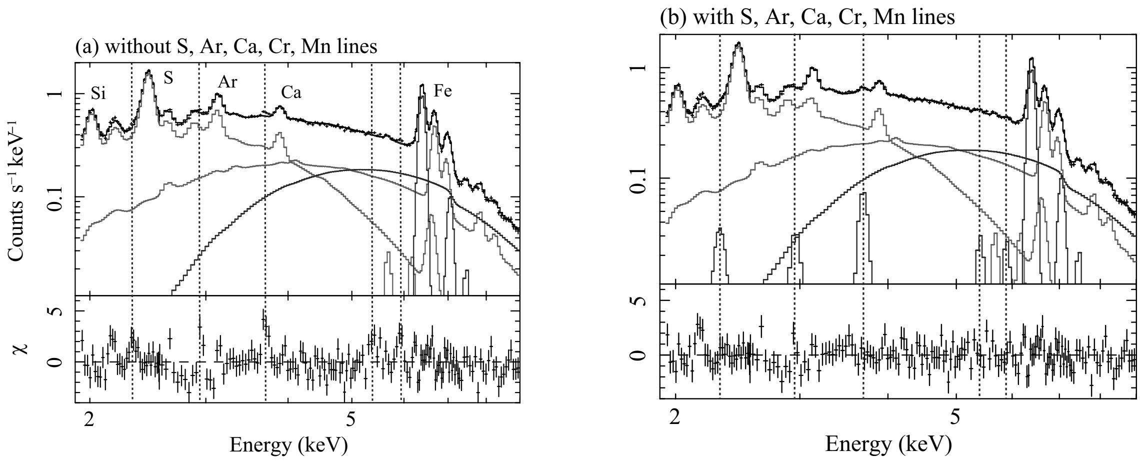

Fig. 2. Spectrum of the brightest neutral clump. (a) the spectrum is fitted with the model of the plasma component (red) plus the neutral component (blue); the plasma component consists of 2 temperature plasmas and ionized Cr and Mn lines. The neutral component consists of neutral Fe and Ni lines, and power-law. Residuals are shown in the bottom panel. (b) the same in (a), but we added neutral S, Ar, Ca, Cr, and Mn lines to the above model. Errors of the data are estimated at the 1σ confidence level.

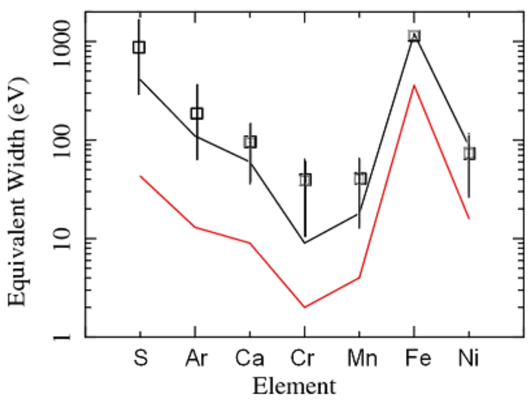

Fig. 3. Equivalent width of Kα line of various neutral atoms. Black and red lines show values in the X-ray and electron scenarios calculated by Geant4, respectively. The data points marked with square are observed value in our work. Errors are estimated at the 90% confidence level.

so far. One is X-ray fluorescence (e.g. Koyama et al. 1996) and the other is electron collision (Yusef-Zadeh et al. 2002; 2007). To account for the emission lines, the neutral atoms in the molecular cloud are ionized by external radiation of the X-rays and the electrons. In both of the scenarios, continuum emission is also produced; by the Thomson scattering of the X-rays, or by the bremsstrahlung of the electrons.

Since the cross sections of the two processes depent on the atomic number differently, the two scenarios would make different X-ray spectra. We calculated the X-ray spectra produced by the X-ray and electron scenarios with the Monte Carlo simulator, Geant4[2] . In this calculation, we assumed that the density of the molecular cloud is uniform, the absorption column is 10^{23} cm^{-2}, and the elemental abundances are solar. In order to reproduce the observed photon index of ~2, we also assumed that the incident X-ray photon index and electron energy index are 2 and 3, respectively.

The result is shown in figure 3. The black and red lines indicate the X-ray and electron scenarios, respectively. The equivalent widths in the X-ray scenario are larger than those in the electron scenario. The ratio of the equivalent width is ~4 in Fe, ~10 in S. It suggests that light element can constrain the origin more strongly than heavy element if the statistic is the same.

We also compared the equivalent widths observed in our work with the calculated values (marked with squares in figure 3). Equivalent width of each atom may support the X-ray scenario rather than the electron scenario. If all of the neutral lines are due to the electron origin, metal abundances in the GC region should be 4 to 10 times larger than that of the sun. On the other hand, the X-ray scenario is reasonable since the metal abundances are consistent with that of the sun.

We note that our calculation has some systematical uncertainties owing to the assumption of metal abundance, geometry of the molecular cloud, or energy index of the incident radiations. However, the conclusion might not fatally change because the metal abundances in the GC region are less than twice to the solar value and the geometry of the molecular cloud change the equivalent width by 50% even if we estimate it largely.

4. Summary

We firstly detected K-shell lines of neutral S, Ar, Ca, Cr, and Mn atoms in addition to those of Fe, and Ni, from the brightest neutral clump in the Galactic center

*2 http://www.geant4.org/geant4/

Table 1. Fitting result.

Component		Unit	Value
Abs1	NH	10^{22} cm^{-2}	7.1 ± 0.3
Abs2	NH	10^{22} cm^{-2}	17 ± 3
Plasma	kT_1	keV	0.99 ± 0.02
	kT_2	keV	7.0 ± 0.3
	$Z_{\rm Si}$	solar	1.3 ± 0.1
	$Z_{\rm S,Ar,Ca}$	solar	1.6 ± 0.1
	$Z_{\rm Fe}$	solar	1.2 (fixed)
	$Z_{\rm Ni}$	solar	2.1 (fixed)
	Cr XXIII Kα	intensity*	$9.2^{+3.2}_{-2.7} \times 10^{-6}$
	Mn XXIV Kα	intensity*	$10.0^{+2.4}_{-3.5} \times 10^{-6}$
Neutral	Power-law	Γ	1.85 ± 0.15
gaussians	energy (keV)	intensity*	EW** (keV)
S I Kα	2.31 (fixed)	$8.0^{+3.1}_{-3.6} \times 10^{-6}$	900^{+1000}_{-600}
Ar I Kα	2.97 (fixed)	$6.9^{+3.1}_{-3.6} \times 10^{-6}$	200^{+180}_{-140}
Ca I Kα	3.69 (fixed)	$1.6^{+0.3}_{-0.3} \times 10^{-5}$	110^{+50}_{-80}
Cr I Kα	5.41 (fixed)	$7.0^{+2.5}_{-2.5} \times 10^{-6}$	40^{+70}_{-30}
Mn I Kα	5.90 (fixed)	$6.9^{+2.6}_{-2.4} \times 10^{-6}$	50^{+30}_{-30}
Fe I Kα	6.40 (fixed)	$2.70^{+0.03}_{-0.03} \times 10^{-4}$	1140^{+60}_{-50}
Fe I Kβ	7.06 (fixed)	$3.7^{+0.3}_{-0.3} \times 10^{-5}$	170^{+40}_{-30}
Ni I Kα	7.47 (fixed)	$9.6^{+2.7}_{-2.7} \times 10^{-6}$	60^{+30}_{-40}

Errors are estimated at the 90% confidence level.
* unit is photon s^{-1} cm^{-2}.
** Equivalent width of the emission line respective to the power-law in the Neutral component.

region. Two possible scenarios, X-ray fluorescence and electron collision have been proposed for the origin of the neutral lines (e.g. Koyama et al. 1996; Yusef-Zadeh et al. 2002). We calculated the produced spectra in the both scenarios by Geant4, and found that equivalent width is a key to solve the origin. As a result, all of the observed equivalent widths of the neutral lines might support the X-ray scenario rather than the electron one.

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