Characteristics of Energy Spectrum of the Galactic Ridge X-Ray Emission

Yasuo Tanaka[1] and Shigeo Yamauchi[2]

[1] Max-Planck-Institut für extraterrestrische Physik
[2] Department of Physics, Faculty of Science, Nara Woman's University
E-mail(YT): ytanaka@mpe.mpg.de

Abstract

The energy spectrum of the Galactic ridge X-ray emission (GRXE) observed with Suzaku is studied in relation to its origin. The multi-temperature spectrum, characterized by distinct He-like and H-like K-lines of all abundant elements, is tested whether it is consistent with the stellar origin of GRXE. It is shown that a combination of a cooling flow model representing cataclysmic variables (CVs) and two-temperature plasma model representing coronally active binaries can well reproduce the observed GRXE spectrum. The result shows that the cooling-flow source contribution is dominant in the cumulative flux, which suggests the presence of many more low-luminosity CVs or sources with CV-like spectrum than currently known. Besides, significant spectral differences are found between the bulge (near the GC) and away from the GC in the flux ratio of the H-like to He-like iron K-lines and in the hardness of the continuum. This would imply that the average properties of CVs or CV-like sources in the bulge are different from those away from the bulge. Another noticeable feature is that the equivalent width of the iron K-lines diminishes quickly with the Galactic latitude. This suggests dilution by a hard non-thermal component having a larger scale height than that of stars.

Key words: Galaxy: disk — X-rays: spectrum — X-rays: stars

1. Introduction

Investigation of the Galactic ridge X-ray emission (GRXE) has a long history. This work deals with the energy spectrum of the GRXE with particular interest in its origin. The GRXE spectrum is similar in shape all along the Galactic ridge (e.g. Tanaka 2002). For example, Fig. 1 shows the spectrum at the Scutum arm region (l^{II}, b^{II} = 28.46°, −0.20°) observed with Suzaku. Suzaku yields a high-quality spectrum with excellent energy resolution.

The GRXE spectrum has specific characteristics. As seen in Fig. 1, both He-like and H-like K-lines of all abundant elements are distinctly visible on a hard continuum, as hard as the cosmic X-ray background (CXB). The intensity ratio of the line pair of each element yields respectively different plasma temperature. Therefore, the X-ray emitting plasma is intrinsically of multi-temperature, and the temperature structure is similar along the Galactic ridge. This has been one of the puzzles for the extended diffuse plasma origin of the GRXE.

A radical development was brought forward in 2006 by Revnivtsev et al. (2006) and Sazonov et al. (2006). They presented strong evidence that the GRXE is mostly (if not 100%) of stellar origin. They proposed that cataclysmic variables and coronally active binaries are the main contributors. Their recent works further support

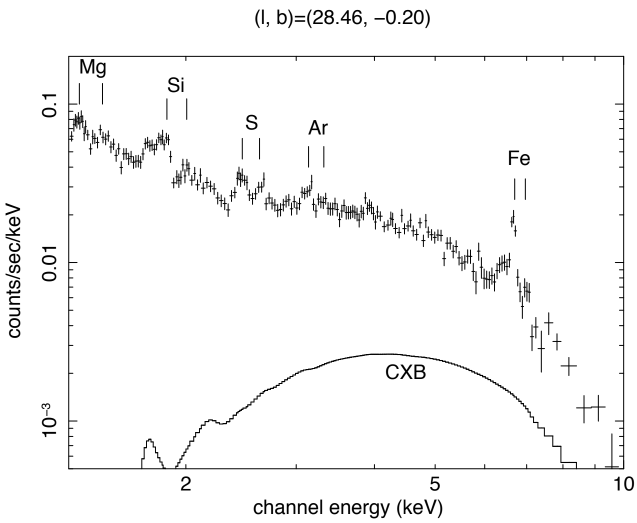

Fig. 1. GRXE spectrum in the Scutum arm region observed with Suzaku. The He-like and H-like lines of various elements are respectively indicated. Note that the peak left-side the He-like Si line is not a line, but is due to reflection anomaly of the X-ray telescope. The CXB contribution is as displayed.

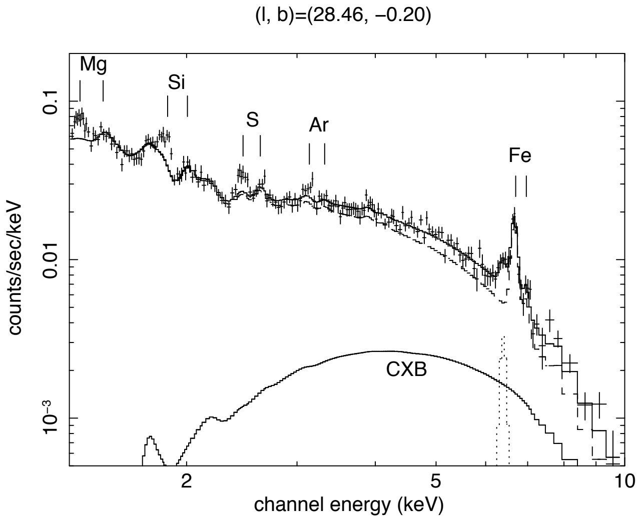

Fig. 2. The **mkcflow** model fitted to the Scutum ridge spectrum. The 6.4-keV line is separately added. While the model gives a good fit to the iron K-lines, it produces too weak He-like lines for the lower Z elements.

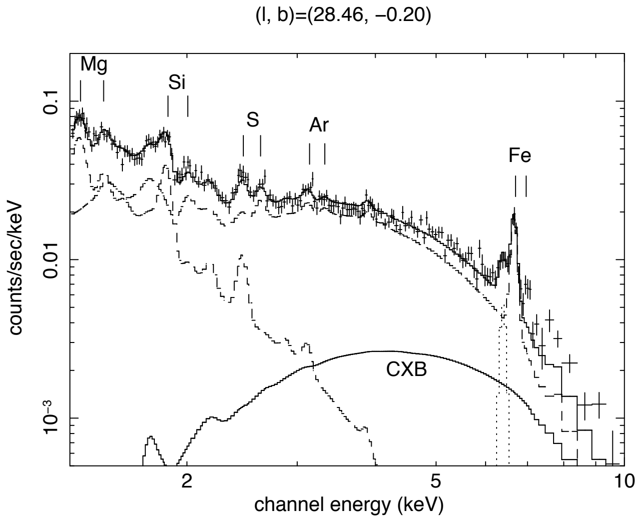

Fig. 3. Two-temperature **mekal** model fitted to the Scutum ridge spectrum. The low- and high-temp. components are respectively shown. Note that the H-like iron line is deficient.

the stellar origin for most of the GRXE (Revnivtsev & Sazonov 2007; Revnivtsev et al. 2009).

The purpose of this work is to test if the observed spectrum is consistent with this interpretation, and also to examine whether or not any other component of different origin exists.

2. Modelling Stellar Sources

2.1. Cataclysmic variables

Let us first consider cataclysmic variables (CVs). There are two classes of CVs, i.e. magnetic CVs (intermediate polars and polars) and non-magnetic CVs (dwarf novae). Dwarf novae constitute the majority of CVs. X-rays of dwarf novae are emitted from cooling plasma in the boundary layer in the course of settling onto the white dwarf surface (Pandel et al. 2005). In the case of magnetic CVs, X-rays come from shock-heated polar accretion columns. Yet, the property of the cooling flow may be similar. For simulating the X-ray spectrum of CVs, we employ *XSPEC* model of cooling flow **mkcflow** following Pandel et al. (2005) who demonstrated successful fits of this model to a number of dwarf novae.

Figure 2 shows the fitting result. CXB is included in the fit as a fixed component. We note that the absorbing column of interstellar matter is not a single value but distributed along the line of sight. Instead of calculating distributed column absorption, we adopted a partial covering model **pcfabs** (comprising two different absorption columns) for the fitting purpose only, as it enables a good fit at low energies.

The iron K-line structure is fairly well reproduced for a $T_{\rm max}$ (the initial temperature) value of approximately 10 keV. Note that the 6.4-keV line is added separately. However, for other lower Z elements, the model fails to reproduce He-like lines (too weak as seen in Fig. 2).

2.2. Coronally active binaries

We then test the spectra of coronally active binaries. It has been known that their spectra can be approximated by two thermal emission components of different plasma temperatures: one at a lower temperature around 0.5 keV and another at around 2 keV. For the thermal model, we employ **mekal**. The fit result displayed in Fig. 3 shows that this two-temperature **mekal** model can well reproduce all the K-lines, except for H-like iron K-line at 6.97 keV which is missing. Also, note that the model continuum above 7 keV is softer than observed.

2.3. Sum of the contributions of two species

Having seen the preceding results, the next step is naturally to add the contributions of the two species, i.e. **mkcflow** (representing CVs) and two-temperature **mekal** (representing coronally active binaries). Indeed, as shown in Fig. 4, this combination can fit very well to the observed GRXE spectrum ($\chi^2_{\rm r}$ = 0.94 for 315 dof) with the parameter values listed in Table 1.

When we look at the breakdown of each component in Fig. 4, the contribution of the **mkcflow** component is more than that of the **mekal** component over the 3-10 keV range. An immediate question is whether CVs can account for more than half the GRXE flux. It has been known that their contribution is far insufficient, if the local space density of CVs by Patterson (1984) ($\sim 6 \times 10^{-6}$ pc^{-3}) is used. Yamauchi et al. (2009) estimated the space density of CVs from the observed iron K-line intensity in the GRXE, and reached the same

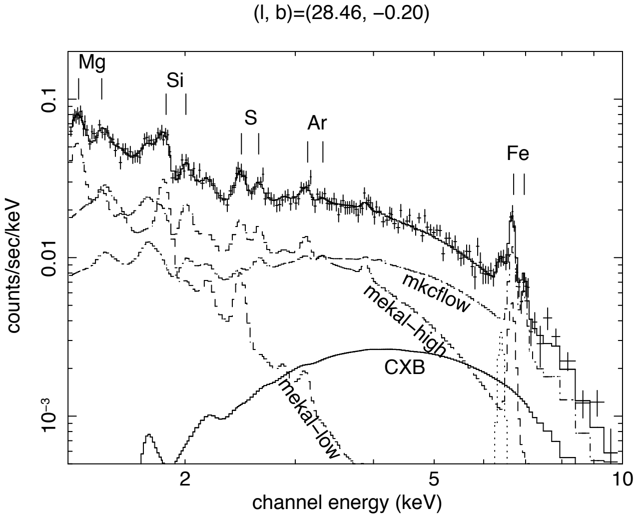

Fig. 4. Sum of the **mkcflow** component and two-temperature **mekal** components. Each component is marked.

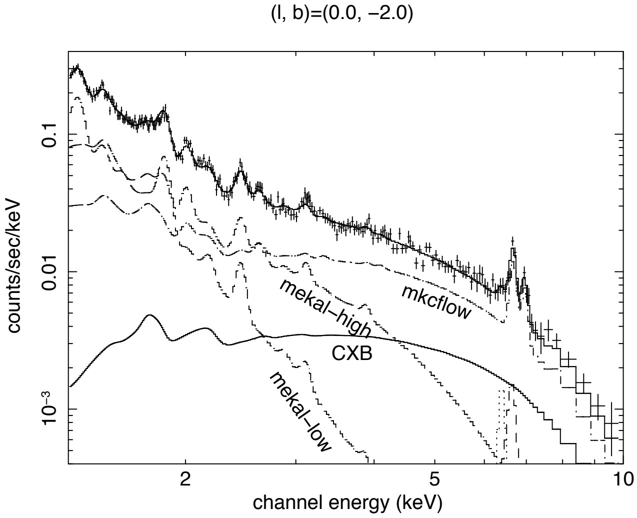

Fig. 5. Suzaku spectrum in the bulge region fitted with combination of **mkcflow** and two-temperature **mekal** models.

Table 1. Parameters of two-temp. **mekal** and **mkcflow**

model	parameter	unit	value
mekal-low	$kT_{\rm l}$	keV	0.50
mekal-high	$kT_{\rm h}$	keV	1.69
mekal common	Abund.	solar	0.47
mkcflow	$kT_{\max}$	keV	15.0
mkcflow	Abund.	solar	0.74

conclusion. The estimation by Schwope et al. (2002) suggests a possibility of an order of magnitude higher space density than that of Patterson (1984). The uncertainty should be pretty large, since their sample of low-luminosity ($L_x < 10^{30}$ erg s^{-1}) CVs is only a few.

Anyway, in order for the observed spectrum to be consistent with the stellar origin, there must exist many more low-luminosity CVs or other class of sources having similar spectral shape to CVs, whose cumulative flux should amount to more than a half of the observed GRXE flux.

3. The Spectrum in the Bulge Region Near the GC

Figure 5 is the spectrum at the direction ($l^{\rm II}$, $b^{\rm II} = 0.0°$, $-2.0°$), 2 degrees south of the Galactic Center, observed with Suzaku. This position is in the region which may be called the "bulge". It is noted that this is very close to the field ($l^{\rm II}$, $b^{\rm II} = 0.08°$, $-1.42°$) where Revnivtzev et al. (2009) conducted a 1 Ms observation with Chandra X-ray Observatory. They reported to have resolved more than 80% of the observed flux into discrete sources.

The observed spectrum can also be fitted with a combination of **mkcflow** and two-temperature **mekal**. If the same parameter values (except for the normalization values which are set free) as obtained for the Scutum ridge are used, the fit is fair yet not formally acceptable due to obvious misfits in the H-like iron line (too low intensity) and in the continuum above 7 keV (too soft). In fact, it has been known that the intensity ratio of the H-like to the He-like iron K-lines is significantly higher near the GC ($\sim$ 0.4: Koyama et al. 2007) than away from the GC ($\sim$ 0.2 in the Scutum ridge: Ebisawa et al. 2008; Yamauchi et al. 2009). The reason for this difference has not yet been understood.

The fit improves significantly by modifying two **mkcflow** parameters, i.e. an increase of abundances from 0.74 solar (for the Scutum ridge, see Table 1) to $\sim$1.0 solar, and $T_{\max}$ from 15 keV to 20 keV. (Note that an increase of $T_{\max}$ alone does not solve the H-like iron K-line discrepancy.) The fit result is shown in Fig. 5.

This spectral difference between the Scutum ridge and the bulge has an important implication. Based on the stellar origin of the GRXE, the observed spectrum shows an average property of great many sources over the line of sight. Therefore, in order to explain the spectral differences, one has to invoke different properties of the bulk of sources in the bulge (or near the GC). For instance, higher $T_{\max}$ could be interpreted as a deeper white dwarf potential, hence more massive white dwarfs. Higher abundances might be due to metal-enriched accreting mass compared to the CVs away from the GC. However, we emphasize that such interpretation is still a speculation, although the significant difference in the spectra is real.

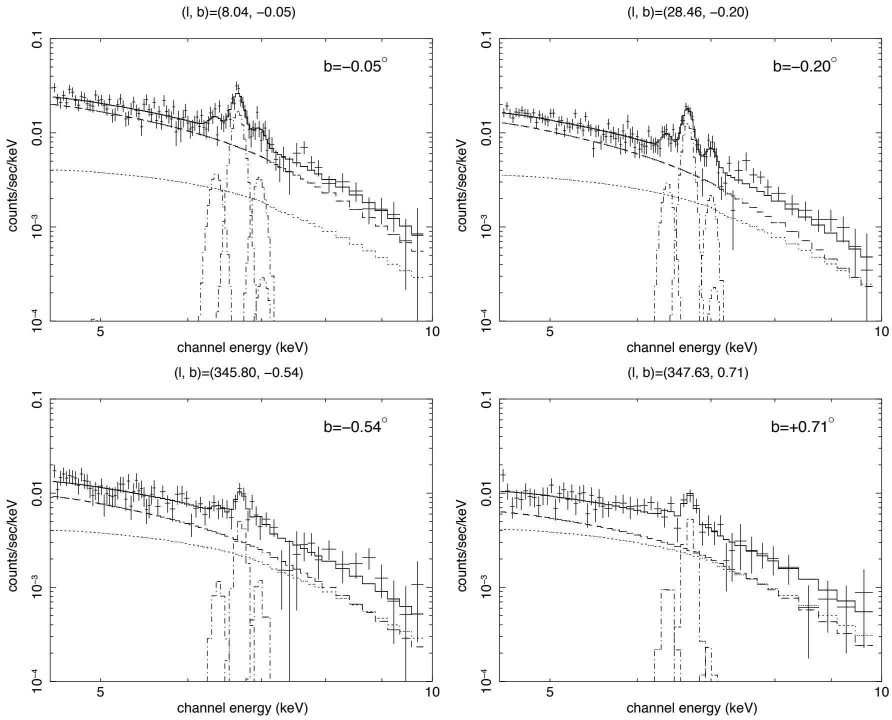

Fig. 6. The GRXE spectra at four different Galactic latitudes observed with Suzaku. Three iron K-lines (neutral, He-like and H-like lines) are respectively fitted together with a thermal bremsstrahlung continuum (dashed line) and CXB (dotted line).

4. Possible Hard Component with a Larger Scale Height

It was known from ASCA result that the equivalent width of the iron K-lines decreases quickly with Galactic latitude (Kaneda et al. 1997). This effect is clearly noticeable in Fig. 6 derived from the data of Yamauchi et al. (2009). While the equivalent widths of the iron K-lines are fairly constant along the Galactic plane (except the bulge), these diminish to a half within less than a degree of the Galactic latitude. This effect can be interpreted as due to dilution of the GRXE by another continuum having a larger scale height than that of stars or interstellar gas. This component is probably non-thermal and is roughly estimated to occupy several % of the total GRXE flux. It is worth studying this component in more detail and in particular to higher energies above 10 keV.

5. Summary

We tested whether the observed GRXE spectrum is consistent with the stellar origin of the GRXE. The results are summarized below.

(1) It is shown that combination of a cooling flow model (**mkcflow**) representing CVs (and CV-like sources) and two-temperature plasma model (**mekal**) representing coronally active binaries can well reproduce the observed GRXE spectrum.

(2) The result shows that the cumulative flux contribution of the cooling-flow sources is dominant, which suggests the presence of many more low-luminosity CVs or sources with CV-like spectrum than currently known.

(3) Significant spectral differences in the flux ratio of H-like to He-like iron K-lines and in the hardness of the continuum are found between the bulge (near the GC) and away from the GC. This would imply that the average properties of CVs or CV-like sources in the bulge are notably different from those away from the bulge.

(4) The equivalent widths of the iron K-lines diminish quickly with the Galactic latitude. This suggests dilution by a hard non-thermal component that has a larger scale height than that of stars.

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