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X-ray Spectral Behavior in the Low/Hard States of Black Hole Candidates

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Abstract We carried out systematic spectral analysis for 10 black hole candidates (BHCs) in the low/hard states, using archival *RXTE* and *Beppo-SAX* data which cover a broad energy range of 2–250 keV. For in total 156 observations, the simple analytic model, a power law with an exponentiall cutoff modified with a smeared edge model, were adopted. Consequently, we found that the photon index was distributed over 1.2–1.8 and the cutoff energy was more than 40 keV. We also found that there is the different behaviour between the photon index/cutoff energy and the luminosity at lower ahd higher luminosities with its value of $2{\times}10^{37}$ erg s^{-1}. For example, a clear anti-correlation is found between the cutoff energy and the luminosity when its value is more than $2{\times}10^{37}$ erg s^{-1}. In addition, we performed the same analysis for 1 neutron star (NS) and 1 active galactic nuclei (AGN) for comparison. No clear differences between BHCs, NS and AGN were found, which might suggest that the accretion mechanisms in the low/hard states are independent of the mass of the central object.

Key words: accretion disks — black hole physics — radiation mechanisms:thermal — X-rays: binaries

1 INTRODUCTION

It is known that Galactic BHCs have mainly two spectral states: a soft/high state and a low/hard state. The low/hard state (LHS) is characterized by fast time variations on a time scale of msec and hard X-ray spectrum with a photon index of 1.4–1.7 (Tanaka & Shibazaki 1996) having a spectral break at ~ 100 keV (Grove et al. 1998). These high energy emissions have been generally accepted to be produced by Comptonization of soft photons in a hot corona such as advection dominated accretion flow (ADAF: Narayan & Yi 1995). However, our spectral informations about the LHS such as correlation between photon index, spectral break and luminosity are hardly adequate. Here, we carried out systematic spectral analysis for 9 BHCs, 1 NS and 1 AGN in the LHS. Broadband coverage and a number of pointing observations with *RXTE* and *Beppo-SAX* will enable us to clarify the picture about the physical geometry in the LHS.

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2 OBSERVATIONS AND DATA ANALYSIS

From large archival *RXTE* an *Beppo-SAX* data sets, we selected in total 156 pointing observations for 10 BHCs, 1 NS (GS 1826−238) and 1 Seyfert Galaxy (IC 4329A) in the LHS. Here, we defined the LHS as the state where the photon index is lower than 2.0 and the energy spectrum is dominated by a power law emissions from a point of view of spectral shape (not including timing informations). Table 1 shows the list of the sources we analyzed in this paper, including 50 observations for XTE J1550−564 and 21 observations for XTE J1118+480. We analyzed all the data in the standard manner for bright sources using the publicly available software HEASOFT 5.2. The RXTE/PCA spectra were taken from only PCU2 detector which was always turned on during any observations. The energy spectra from the two instruments (PCA and HEXTE for *RXTE*, and MECS and PDS for *Beppo-SAX*) were fitted simultaneously with a power law with an exponential cutoff [1]. We further modified this model with a smeared edge model (Ebisawa et al. 1994) instead of reflection component. From these spectral fits, we mainly obtained three parameters: a photon index α, a cutoff energy $E_{\rm cut}$ and an integrated flux over 2−200 keV. The flux in the 2–200 keV was converted into the luminosity (L_{2-200}) assuming the distance shown in Table 1.

Table 1 List of the source analyzed in this paper with distance, number of the *RXTE* and *Beppo-SAX* observation and observation epoch.

Source	Distance	Obs. Number*	Dates
—Black Hole Candidates—			
XTE J1550−564	5.3 kpc[a]	50+0	1998 Sept. ∼ 2002 Feb.
XTE J1118+480	1.8 kpc[a]	18+3	2000 Mar. ∼ 2000 July
GX 339−4	8.0 kpc[b]	15+3	1997 Feb. ∼ 1997 Nov.
XTE J1650-500	4.0 kpc[a]	14+1	2001 Sept. ∼ 2001 Dec.
Cygnus X-1	2.5 kpc[a]	11+4	1996 Mar. ∼ 2000 Nov.
GS 1354−645	10 kpc[c]	8+0	1997 Nov. ∼ 1998 Jan.
XTE J1748−288	8.0 kpc[d]	5+0	1998 July ∼ 1998 Aug.
4U 1630−472	10 kpc[e]	4+0	1998 May
XTE J1859+226	7.6 kpc[f]	3+0	1999 Oct.
GRO J1655−40	3.2 kpc[a]	1+0	1998 Aug.
—Neutron Stars—			
GS 1826−238	8.0 kpc[g]	5+6	1997 Apr. ∼ 2000 Sept.
—Seyfert Galaxies—			
IC4329A	z=0.016	0+5	1998 Jan. ∼ 2001 Jan.

* Left and right side shows *RXTE* and *Beppo-SAX*, respectively.
[a] McClintok & Remillard (2003) and reference therein;
[b] Zdziarski et al. (2004);
[c] Kitamoto et al. (1990);
[d] Hjellming et al. (1999);
[e] Callanan et al. (2000);
[f] Hynes et al. (2002);
[g] in 't Zand et al. (1999).

[1] It is known that there are some calibration uncertanties between *RXTE* and other instruments, and the five PCUs. We found that both systematic differences in spectral parameters correspond to about 0.1 in the photon index.

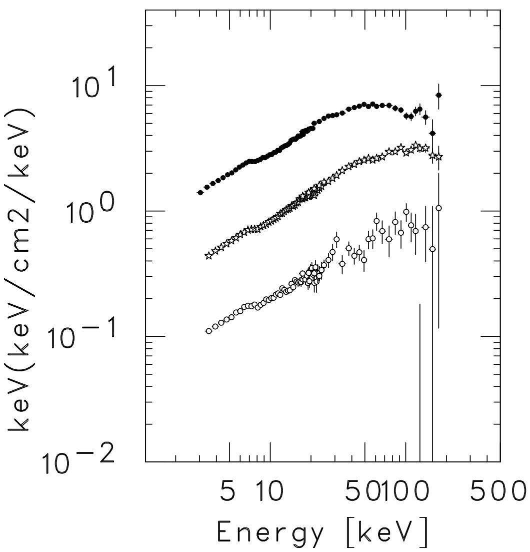

Fig. 1 *RXTE* νF_ν spectra of XTE J1550−564 in the low/hard states.

3 RESULTS AND DISCUSSIONS

3.1 XTE J1550−564

First, we limited to the case of XTE J1550−564 which was observed at the most frequent times in our samples. We present νF_ν spectra of XTE J1550−564 observed by *RXTE* in the 3–200 keV range in Fig. 1. As X-ray intensity decreases, the spectral break tends to increase from ~ 50 keV to more than 100 keV, whereas the photon index in the lower energy seems to slightly change.

To evaluate such tendencies more quantitatively, we show two plots (L_{2-200} versus $E_{\rm cut}$, and L_{2-200} versus $E_{\rm cut}$) in Fig. 2. All the points were collected from previous 1998, 2000, 2001 and 2002 outbursts as indicated by different symbols. We first notice that the data is smoothly connected in both figures in spite of the different four outbursts. The photon index α is distributed over 1.2–1.8 and the high energy cutoff $E_{\rm cut}$ is more than 40 keV. The energy spectrum becomes harder as L_{2-200} increases to 2×10^{37} erg s^{-1}. Once it exceeds this value, the photon index α seems to be distributed randomly. On the other hand, we found a clear anti-correlation between L_{2-200} and $E_{\rm cut}$. The cutoff energy $E_{\rm cut}$ follows the relation of $E_{\rm cut} \propto {\rm L}^{-1.2\pm0.1}$, although it was not well constrained in the range of L< 10^{37} erg s^{-1} due to the limited statistics of the *RXTE*/HEXTE.

3.2 All BHCs

We further compile all the *RXTE* and *Beppo-SAX* data from 9 other BHCs, and plot the data on Fig. 3. The luminosity in the 2–200 keV range should be normalized to the Eddignton luminosity, but the difference of the black hole mass is at most by a factor of 3 (Orosz 2002), so we did not take into account this effect.

The first remarkable result is the presence of a clear anti-correlation between L_{2-200} and $E_{\rm cut}$ when L_{2-200} is higher than 2×10^{37} erg s^{-1}, corresponding to about 1% of Eddingnton limit for 10 solar mass BH. Similar behavior is also reported in another BHC—GRO J0422+22

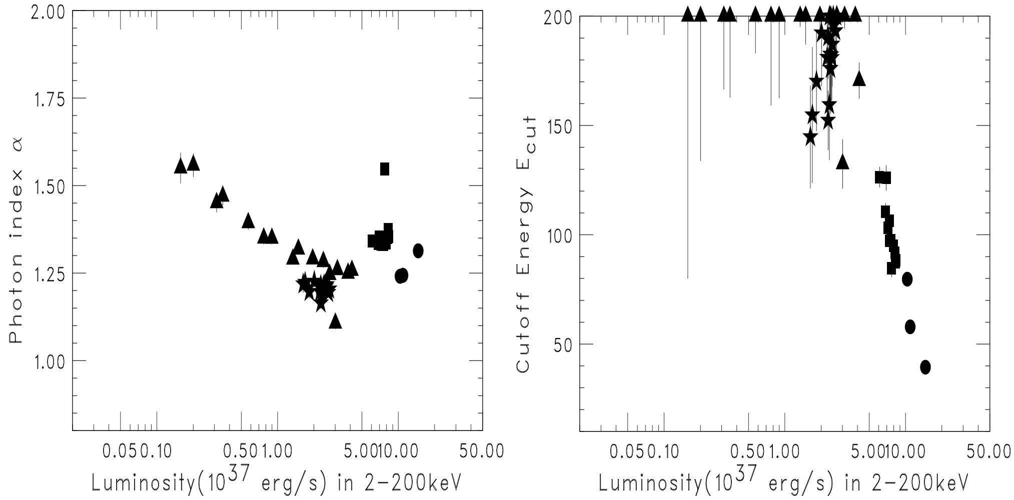

Fig. 2 Left: Correlation between L_{2-200} and α in XTE J1550−564. Right: Correlation between L_{2-200} and$E_{\rm cut}$. The symbols indicate the different four outbursts occurred in 1998 (filled circles), 2000 (filled squares), 2001 (filled stars) and 2002 (filled triangles).

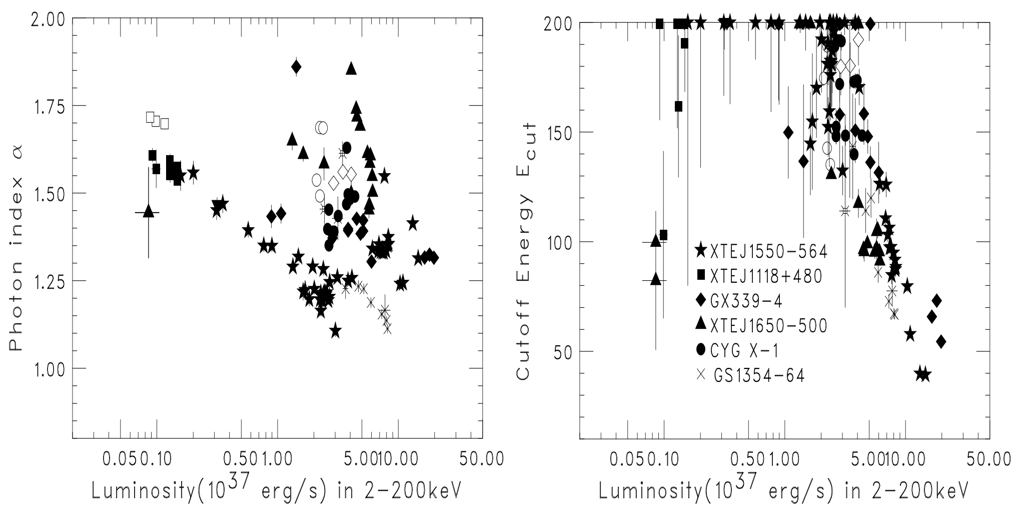

Fig. 3 Same as Fig. 3, but for the 10 BHCs shown in Table 1. The *RXTE*(filled symbols) and *Beppo-SAX*(open symbols) observations are plotted separately, taking into account the calibration uncertainties between both detectors.

(Esin et al. 1998). This behavior can be explained as due to the more efficient cooling of the energy electron at higher luminosities, which is well explained by ADAF in the quiescent states and low/hard states (Esin et al. 1998). The second remarkable result is the anti-correlation between L_{2-200} and α when L_{2-200} is less than $2{\times}10^{37}$ erg s^{-1}. When L_{2-200} is larger than $2{\times}10^{37}$ erg s^{-1}, no clear correlation is found. In this case, the photon index α may be controlled by not only luminosity but other physical parameters.

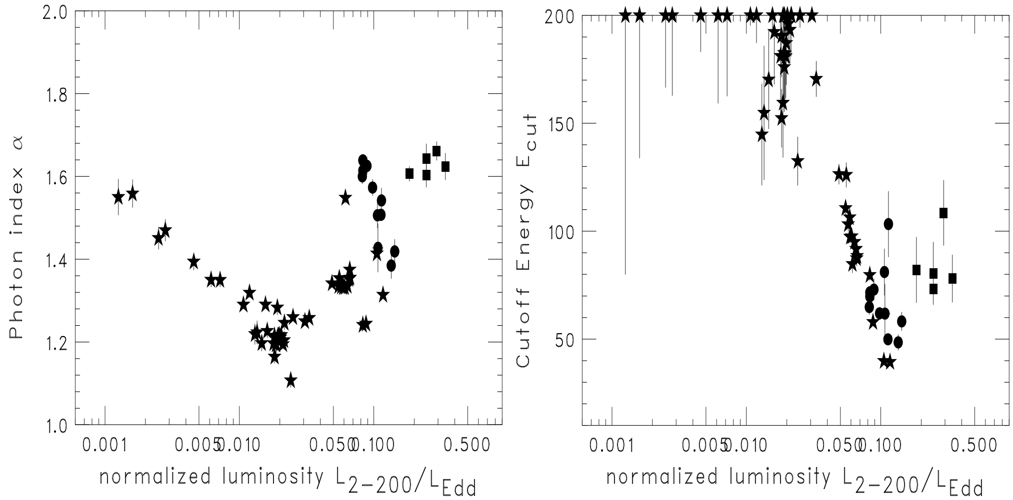

Fig. 4 Same as Fig. 3, but for the three sources: XTE J1550−564(filled stars), GS1826−238 (filled circles) and IC4329A (filled squares).

3.3 Difference between BHCs, NSs and AGNs

In order to find the universal picture in the LHS, we also select the three sources as representatives from each category: XTE J1550−564 for BHCs, GS 1826−238 for NSs and IC 4329A for AGNs. The luminosity L_{2-200} was normalized by the Eddignton luminosity (L_{Edd}) assuming the mass of the central object as 10 (Orosz et al. 2002), 1.4 and 1.23×10^8 solar mass (Nikolajuk et al. 2004), respectively. Considering that the Eddignton ratio L_{2-200}/L_{Edd} has a large uncertainty by a factor of about 1 order due to estimations of distance and mass, there may be no significant differences in the three sources. This fact might suggest that the common radiation mechanisms act in the LHS of BHCs, NSs and AGNs and that the accretion geometry can be scaled by a mass of the central objects. However, we need to confirm these important results by collecting much more samples using it RXTE data for other BHCs and NSs, and *Beppo-SAX*/PDS for AGN. Future studies using *INTEGRAL* and *Astro-E2* mission are powerful for determining an energy cutoff with a higher accuracy.

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