RAPID SPECTRAL CHANGES OF CYGNUS X-1 IN THE LOW/HARD STATE WITH SUZAKU

S. Yamada1, H. Negoro2, S. Torii3, H. Noda3, S. Mineshige4, and K. Makishima1,3

1 Cosmic Radiation Laboratory, Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
2 Department of Physics, College of Science and Technology, Nihon University, 1-8 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan
3 Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
4 Department of Astronomy, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

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ABSTRACT

Rapid spectral changes in the hard X-ray on a timescale down to ~0.1 s are studied by applying a “shot analysis” technique to the Suzaku observations of the black hole binary Cygnus X-1, performed on 2008 April 18 during the low/hard state. We successfully obtained the shot profiles, covering 10–200 keV with the Suzaku HXD-PIN and HXD-GSO detector. It is notable that the 100–200 keV shot profile is acquired for the first time owing to the HXD-GSO detector. The intensity changes in a time-symmetric way, though the hardness changes in a time-asymmetric way. When the shot-phase-resolved spectra are quantified with the Compton model, the Compton y-parameter and the electron temperature are found to decrease gradually through the rising phase of the shot, while the optical depth appears to increase. All the parameters return to their time-averaged values immediately within 0.1 s past the shot peak. We have not only confirmed this feature previously found in energies below ~60 keV, but also found that the spectral change is more prominent in energies above ~100 keV, implying the existence of some instant mechanism for direct entropy production. We discuss possible interpretations of the rapid spectral changes in the hard X-ray band.

Key words: accretion, accretion disks – X-rays: binaries – X-rays: individuals (Cyg X-1)

Online-only material: color figure

1. INTRODUCTION

Starting with the first identification of the black hole (BH) binary Cygnus X-1 (hereafter Cyg X-1) in the early 1970s (e.g., Oda et al. 1971; Tananbaum et al. 1972; Thorne & Price 1975), X-ray observations have played an important role in revealing spectral and temporal properties of BH binaries, which are largely classified into two distinct states: the high/soft state and the low/hard state (e.g., Remillard & McClintock 2006; Done et al. 2007). In contrast to the high/soft state characterized by the dominant disk emission (Mitsuda et al. 1984; Makishima et al. 1986) from the standard disk (Shakura & Sunyaev 1973), the spectrum in the low/hard state is expressed by a power law with a photon index of ~1.5 with an exponential cutoff at ~100 keV (e.g., Sunyaev & Truemper 1979) from a hot "corona" (e.g., Ichimaru 1977; Narayan & Yi 1995; chap. 8 in Kato et al. 2008). Rapid time variabilities on a timescale of similar to milliseconds (e.g., Miyamoto et al. 1991) only seen in the low/hard state have been studied in many ways (e.g., Nowak et al. 1999; Poutanen 2001; Pottschmidt et al. 2003; Uttley et al. 2011; Torii et al. 2011), though the origin is still a missing piece of the puzzle, presumably due to the observational difficulties of realizing both high sensitivity and large effective area.

A distinctive approach is the “shot analysis” (Negoro et al. 1994; Negoro 1995) adopted for Cyg X-1 obtained with Ginga. This method is a time-domain stacking analysis for obtaining the universal properties behind non-periodic variability. It is in time-domain analysis that we can combine spectral information in a straightforward way. They found three main features: (1) the intensity changes time symmetrically, (2) both the rise and decay curves are well represented by the superpositions of two exponential functions with time constants of ~0.1 s and ~1.0 s, and (3) the spectral variation is, by contrast, time asymmetric in the sense that it gradually softens toward the peak and instantly hardens across the peak (see Figure 2 in Negoro et al. 1994). These properties have been investigated further with RXTE (Focke et al. 2005). The time constant of ~1 s far exceeds the local (dynamical or thermal) timescale of the innermost region, and should thus reflect the accreting motion of the gas element. Mannoto et al. (1996) proposed an interesting explanation of an inward-forward-accreting blob, causing an increase in X-ray flux, is reflected as a sonic wave when it reaches the BH (Kato et al. 2008), though further observational constraints remain to be developed.

The extension of this approach toward higher energies, ~200 keV, should be crucial because it may provide a hint regarding the physics causing the rapid spectral variation. Thus, we observed Cyg X-1 in the low/hard state with Suzaku (Mitsuda et al. 2007) by utilizing both X-Ray Imaging Spectrometer (XIS; Koyama et al. 2007) located on the focus of the X-ray mirror (Serlemitsos et al. 2007) and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007; Yamada et al. 2011). The distance, mass, and inclination of Cyg X-1 are 1.86 +0.12 −0.07 kpc (Reid et al. 2011; Xiang et al. 2011), respectively. It has an O9.7 Iab supergiant, HD 226868 (Gies & Bolton 1986), with an orbital period of 5.599829 days (Brockopp et al. 1999). Unless otherwise stated, errors refer to 90% confidence limits.

2. OBSERVATION AND DATA REDUCTION

Cyg X-1 data taken with Suzaku on 2008 April 18 (ObsID = 403065010) are used in this Letter, which is one of 25 observations of its low/hard state (see Yamada 2011 for details). XIS0 was operated in timing mode, or parallel-sum (P-sum) mode, which is one of the clocking modes of XIS. A timing resolution of the P-sum mode is ~7.8 ms. Data reduction of the timing
mode is different from the standard one in the grade selection criteria: grade 0 (single event), grade 1, and grade 2 (double events) are used. The XIS background is not subtracted because it is less than 0.01% of the signal events.

The HXD data consisting of the PIN (10–60 keV) and GSO (50–300 keV) events are processed in the same manner as Torii et al. (2011). The events are selected by elevation angle (50–300 keV) events are processed in the same manner as Torii et al. (2011). The events with 7.8 ms time resolution were binned into 0.1 s bins, resulting in 20–60 counts bin$^{-1}$. Intensity changes by a factor of $\sim2$, so that the Poisson fluctuation (15% at $1\sigma$) is sufficiently smaller than the intrinsic variation. Employing $f = 1.0$ and $T = 1.5$ s, we actually applied the procedure of Equation (1) to the entire P-sum light curve, and identified 7524 shots in total. The distribution of $\Delta t$ becomes a grossly exponential distribution in agreement with the previous reports (Focke et al. 2005). Figure 1(b) shows the shot profile obtained by stacking the 7524 shots with reference to each peak. We can see two exponential slopes in the shot profile and shorter and longer decay time constants of $\sim0.1$ s and 1–2 s. Our primary focus is to extend this analysis to the HXD band, so we do not investigate further the shot profile and the XIS0 spectra due to incomplete calibration of the P-sum mode.

### 3.2. Shot Profiles of the HXD Data

According to the peak time determined with the XIS0 light curve, we have accumulated the PIN and GSO events and their NXB events. To estimate pileup effects in a phenomenological way, we purposely tried to use either 1 inside or outside the image core of XIS0 to obtain the shot profiles based on Yamada et al. (2012), though the shot profiles were not significantly changed. To investigate the energy dependence of the shots, we have utilized four energy bands: 10–20 keV and 20–60 keV from PIN, and 50–100 keV and 100–200 keV from GSO. After subtracting the NXB events from the data and correcting them for dead time, we have obtained the 10–200 keV shot profiles with the HXD data. The stacked shot profiles are divided by the count rates averaged over $-4$ to $-2$ s and 2 to 4 s to approximately correct them for the differences in the efficiency.

The normalized shot profiles are shown in Figures 2(a)–(d). The derived profiles all appear very similar in shape to the one of XIS0. However, energy dependencies are found with certainty when their widths of the peaks are carefully inspected. In Figures 2(a) and (d), the peak value in 10–20 keV is $\sim1.7$ while it is $\sim1.5$ in 100–200 keV, indicating the general trend that the higher the photon energy is, the lower the peak becomes. This is neither due to incorrect background subtraction nor due to a decrease in the sensitivity of HXD, because the systematic

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5. See http://www.astro.isas.ac.jp/suzaku/analysis/xis/psum_recipe/Psum-recipe-20100724.pdf
6. http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
uncertainty in the NXB subtraction is at most \(\sim 3\%\) of the signal intensity even in the 100–200 keV band, and because we are referring to relative changes instead of absolute values. To clarify the differences among these profiles, we divided the normalized shot profiles in the higher three bands by that in the 10–20 keV. As shown in Figures 2(e)–(g), the hardness ratios (relative to 10–20 keV) gradually decrease toward the peak, but suddenly return to their average values immediately after (within 0.1 s) the peak. Although this feature has been found in energies below \(\sim 60\) keV in Negoro et al. (1994), we have not only confirmed the same trend up to \(\sim 200\) keV, but also found that the spectral change is more prominent in the higher energy of \(E \gtrsim 100\) keV.

3.3. Quantification of the Shot-phase-resolved Spectra

We then quantified its spectral change by accumulating the HXD spectra according to the shot phase. The NXB events were accumulated in the same ways and subtracted. Figure 3 shows three examples of the derived shot-phase-resolved HXD spectra, corresponding to 0.15 s before, right on, and 0.15 s after the peak. The exposure at the peak is 752.4 s (7524 shots \(\times 0.1\) s). To grasp their characteristics in a model-independent way, we superposed the time-averaged spectrum, and show the ratio of the shot spectra to it in Figure 3. As evidently shown in Figure 3(b) by a clear turnover of the ratio above \(\sim 100\) keV, a spectral cutoff at the peak is lower than the averaged one. Furthermore, the spectral ratio before the peak shown in Figure 3(a) appears downward, while that after the peak is almost flat, which is consistent with the gradual softening before the peak and instant hardening at the peak as seen in Figure 2.

To consider the physics underlying this spectral evolution we fitted the 13 shot-phase-resolved HXD spectra with a typical model of Comptonization, compss (Poutanen & Svensson 1996), in the same manner as that in Torii et al. (2011). The seed photon is assumed to be a disk blackbody emission (Mitsuda et al. 1984; Makishima et al. 1986, 2008) with a temperature of 0.2 keV. The free parameters in the fits are the electron temperature \(T_e\), the optical depth \(\tau\) or the Compton \(y\)-parameter, and the normalization \(N_{\text{bb}}\). Note that if \(\tau\) is fixed, \(T_e\) is affected more by a spectral slope than a spectral cutoff. To avoid such a misunderstanding, we left both \(\tau\) and \(T_e\) free. As the shot-phase-resolved spectra do not have sufficient photon statistics, we fixed the reflection fraction \(\Omega\) at a value of 0.235 because the obtained value from the time-averaged spectrum is 0.235\(^{+0.021}_{-0.020}\). This implies that we assumed that the reflection follows the primary continuum within \(\sim 0.1\) s. The fits to all the spectra have been successful, resulting in the best-fit parameters in Table 1. Even when considering the systematic error of the NXB in the GSO spectra, its contributions to the resultant values are less than \(\sim 1\%\).

As the count rate increases on a timescale similar to seconds, \(T_e\) and \(y\) decrease while \(\tau\) increases; when the count rate starts to decrease, all the parameters appear to return to the averaged values. To visualize this, we plot in Figure 4 the derived parameters in Table 1, as well as the time-averaged ones. Since our composite shot profile comprises a large number of relatively small individual shots, the averaged parameters are close to those at \(\sim 1\) s from the peak. The gradual decrease in the \(y\)-parameter before the peak is consistent with the hardness decrease as seen in Figure 2. The decrease in \(T_e\) around the peak clearly reflects the trend that the high-energy cutoff appears lowered at the peak as seen in Figure 3(b). Thus, the fitting results are consistent with the hardness ratios in Figure 2 and the spectral ratios in Figure 3. Note that \(N_{\text{bb}}\) also increases along the shot profile, though we could not confidently measure the inner radius without using the soft X-ray data (cf. Makishima et al. 2008).

4. DISCUSSION AND SUMMARY

We performed the shot analysis to extract important information on understanding rapid hard X-ray variability, which cannot be obtained by Fourier transform (FT) methods (cf. Negoro et al. 2001; Legg et al. 2012; Torii et al. 2011). In general, FT methods are less arbitrary than stacking analysis, but phase information is lost in the FT analysis. Further FT methods require more photons than a stacking method. Thus,
we chose to use the stacking method and successfully extended the higher energy limit of the shot analysis up to $\sim$200 keV by utilizing the HXD data as well as the P-sum mode of the XIS. What we found is summarized as follows: (1) the shot feature is found at least up to $\sim$200 keV with high statistical significance; (2) the shot profiles are approximately symmetric, though the hardness changes progressively more asymmetrically toward higher energies of $E \gtrsim 100$ keV; and (3) the 10–200 keV spectrum at the peak shows a lower energy cutoff than the time-averaged spectrum. By quantifying this feature in terms of the higher energy limit of the shot analysis up to 100 keV, which means that most of the luminosity is released almost time symmetrically within $\sim$1 s or much shorter. Meanwhile, the hardness changes instantly within 0.1 s as shown in Figure 2, or much shorter as shown in Negoro et al. (1994). These features could be explained by some physical impulse or a discrete phenomenon, which can change properties of the radiation source in a short time.

When accreting matter is assumed to be an ideal and non-relativistic gas, the entropy of the accreting gas, $s$, with temperature $T$ and density $\rho$ is proportional to $\ln(P/\rho^\gamma) = \ln(T/\rho^{\gamma-1})$, where $\gamma$ is the ratio of specific heat capacities ($\gamma/3$ for monatomic gas). It can be interpreted that the entropy decreases in some way as the flux increases, but instantly increases at the peak, and returns to the mean value after the peak. This suggests the existence of some instant mechanism for direct entropy production (or heating).

One of the possible ideas for the rapid intensity change has been considered to be magnetic flares analogous to the solar corona (Galeev et al. 1979), and recently this idea has become more sophisticated (cf., Poutanen & Fabian 1999; Życki 2002). The magnetic fields are amplified by the differential rotation

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Background-subtracted $\nu F_\nu$ spectra of the HXD, accumulated over different shot phases (black). The time-averaged spectrum is given in red. Panels (a)–(c) show the spectra integrated from $-0.25$ to $-0.05$ s before the peak, from $-0.05$ to 0.05 s around the peak, and from 0.05 to 0.25 s after the peak, respectively. Lower panels show the ratios to the time-averaged spectrum.

(A color version of this figure is available in the online journal.)

**Table 1**

| Phase (s) | $T_e$ (keV) | $\tau$ | $\gamma$ | $N_{\text{obs}}$ | $\chi^2_d$ |
|----------|-------------|--------|----------|-----------------|------------|
| -3.05 ± 1.00 | 89.6$^{+16.3}_{-11.4}$ | 1.51$^{+0.23}_{-0.24}$ | 1.061$^{+0.015}_{-0.017}$ | 5.3a$^{+0.56}_{-0.44}$ | 0.92 |
| -1.00 ± 0.45 | 86.5$^{+8.7}_{-6.9}$ | 1.54$^{+0.14}_{-0.15}$ | 1.044$^{+0.010}_{-0.010}$ | 5.7b$^{+0.57}_{-0.31}$ | 1.18 |
| -0.95 ± 0.20 | 81.7$^{+8.3}_{-6.6}$ | 1.62$^{+0.15}_{-0.16}$ | 1.036$^{+0.010}_{-0.010}$ | 5.9a$^{+0.59}_{-0.34}$ | 1.12 |
| -0.60 ± 0.15 | 76.4$^{+7.7}_{-6.2}$ | 1.72$^{+0.16}_{-0.16}$ | 1.030$^{+0.010}_{-0.010}$ | 6.0a$^{+0.60}_{-0.40}$ | 1.10 |
| -0.35 ± 0.10 | 75.2$^{+8.8}_{-7.0}$ | 1.73$^{+0.18}_{-0.19}$ | 1.021$^{+0.011}_{-0.012}$ | 6.4a$^{+0.63}_{-0.41}$ | 1.20 |
| -0.15 ± 0.10 | 80.7$^{+9.2}_{-7.2}$ | 1.60$^{+0.16}_{-0.17}$ | 1.013$^{+0.011}_{-0.011}$ | 7.6a$^{+0.76}_{-0.47}$ | 1.04 |
| 0.00 ± 0.05 | 65.2$^{+7.1}_{-5.6}$ | 2.01$^{+0.19}_{-0.20}$ | 1.024$^{+0.012}_{-0.012}$ | 7.7a$^{+0.77}_{-0.51}$ | 0.98 |
| 0.15 ± 0.10 | 87.1$^{+8.9}_{-7.6}$ | 1.53$^{+0.17}_{-0.18}$ | 1.044$^{+0.012}_{-0.012}$ | 7.5b$^{+0.71}_{-0.46}$ | 1.09 |
| 0.35 ± 0.10 | 84.9$^{+13.2}_{-9.3}$ | 1.55$^{+0.21}_{-0.22}$ | 1.033$^{+0.016}_{-0.016}$ | 6.5b$^{+0.65}_{-0.35}$ | 1.15 |
| 0.60 ± 0.15 | 88.6$^{+11.3}_{-8.6}$ | 1.49$^{+0.17}_{-0.18}$ | 1.032$^{+0.013}_{-0.014}$ | 6.4b$^{+0.64}_{-0.44}$ | 1.18 |
| 0.95 ± 0.20 | 82.4$^{+8.4}_{-6.8}$ | 1.63$^{+0.15}_{-0.16}$ | 1.052$^{+0.010}_{-0.010}$ | 5.7b$^{+0.58}_{-0.35}$ | 1.26 |
| 1.60 ± 0.45 | 88.0$^{+8.9}_{-7.3}$ | 1.53$^{+0.15}_{-0.15}$ | 1.051$^{+0.010}_{-0.010}$ | 5.8a$^{+0.58}_{-0.32}$ | 1.22 |
| 3.05 ± 1.00 | 87.0$^{+16.0}_{-11.1}$ | 1.55$^{+0.23}_{-0.25}$ | 1.053$^{+0.016}_{-0.017}$ | 5.3a$^{+0.53}_{-0.45}$ | 1.19 |

**Notes.**

a In units of 10$^5$ $R_0^2 D_{10}^{-2} \cos \theta$, where $R_0$, $D_{10}$, and $\theta$ are the radius (km), the distance (10 kpc), and the inclination, respectively.

b The degree of freedom is 83 for the phased-sorted spectra, and 129 for the time-averaged one.
of the disk, and rise up into the corona where they reconnect and finally liberate their energy in flare, causing electrons to accelerate. A typical magnetic model assumes the so-called "avalanche magnetic flare," in which each flare has a certain probability of triggering a neighboring one, producing long avalanches (Mineshige et al. 1994; Lyubarski 1997). An electron probability of triggering a neighboring one, producing long "avalanche magnetic flare," in which each flare has a certain depth, and the Compton parameter are presented. The 90% range specified by the time-averaged spectrum is superposed by dotted and dashed lines.

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Figure 4. Time evolution of the parameters of the Comptonization, determined by fitting the 12–300 keV HXD spectra in the 13 shot phases with the Comptonization model. From top to bottom, the electron temperature, the optical depth, and the Compton y-parameter are presented. The 90% range specified by the time-averaged spectrum is superposed by dotted and dashed lines.