Suzaku observation of X-ray variability in soft state LMC X-1

Shu Koyama,1,* Shin'ya Yamada,2 Aya Kubota,3 Makoto S. Tashiro,1 Yukikatsu Terada,1 and Kazuo Makishima4

1Department of Physics, Saitama University, Shimo-Okubo 255, Sakura, Saitama, Saitama 338-8570, Japan
2Department of Physics, Tokyo Metropolitan University, Minami-Osawa 1-1, Hachioji, Tokyo 192-0397, Japan
3Department of Electronic Information Systems, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama 337-8570, Japan
4Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

*E-mail: koyama@heal.phy.saitama-u.ac.jp

Received 2015 January 9; Accepted 2015 February 24

Abstract

This paper reports the results of Suzaku observation of the spectral variation of the black hole binary LMC X-1 in the soft state. The observation was carried out in 2009 from July 21 to 24. the obtained net count rate was ∼30 counts s⁻¹ in the 0.5–50 keV band with ∼10% peak-to-peak flux variation. The time-averaged X-ray spectrum cannot be described by a multi-color disk and single Compton component with its reflection, but requires additional Comptonized emissions. This double Compton component model allows a slightly larger inner radius of the multi-color disk, implying a lower spin parameter. Significant spectral evolution was observed above 8 keV along with a flux decrease on a timescale of ∼10⁴–10⁵ s. By spectral fitting, we show that this behavior is well explained by changes in the hard Comptonized emission component in contrast to the maintained disk and soft Comptonized emission.

Key words: accretion, accretion disks — black hole physics — X-rays: individual (LMC X-1)

1 Introduction

X-ray spectra from stellar mass black hole (BH) binaries (BHB) are known to transit between the high/soft state (HSS) and low/hard state (LHS), in accordance with the mass accretion rate. The HSS spectrum is mainly composed of a bright thermal component that dominates the soft X-ray band accompanied by a less bright power law (PL) component that exhibits a “hard tail” in the ≥10 keV band. The thermal component is well reproduced by a multi-color disk (MCD; Mitsuda et al. 1984; Makishima et al. 1986) emission from an optically thick and geometrically thin accretion disk described by the standard disk model (Shakura & Sunyaev 1973). From the fact that the inner radius of the accretion disk derived from the MCD model is constant (e.g., Ebisawa et al. 1993; Steiner et al. 2010), the existence of an innermost stable circular orbit (ISCO), which is determined by the BH mass and spin, has been established (see also Makishima et al. 2000).

The hard-tail component seen in the HSS is thought to be produced by Compton upscattering of the MCD photons by energetic electrons. This implies a situation similar to the one that produces the dominant hard X-ray continuum in the LHS, which is understood as resulting from thermal Comptonization of the disk photons by
hot thermal electron clouds (e.g., Gierliński et al. 1997; Frontera et al. 2001; Zdziarski & Gierliński 2004; Makishima et al. 2008; Takahashi et al. 2008). However, these two phenomena show considerable differences. The hard tail in the HSS is expressed by a single PL with a photon index of $\Gamma \sim 2.0–2.5$, and often extends to $\sim 1$ MeV, in contrast to the LHS continuum which is flatter ($\Gamma < 2$) with a clear cut-off at $\sim 100$ keV. As a result, the HSS hard tail can be explained either by non-thermal Comptonization, or by a hybrid of non-thermal and thermal Comptonization processes (Zdziarski et al. 1993; Gierliński et al. 1997).

Overall, the hard-tail phenomenon is much less well understood than the soft component.

When a BHB (particularly a transient one) evolves from the LHS into the HSS, it often passes through another spectral state, called the very high state (VHS: e.g., Miyamoto et al. 1991). The VHS spectrum is characterized by luminous disk emissions with a strong PL hard tail with a steep slope of $\Gamma > 2.4$. The latter is resolved to two hard tails, and explained by non-thermal plus thermal combined Comptonization (e.g., Kubota & Done 2004; Kobayashi et al. 2003), of which the thermal fraction is thought to decrease as the system approaches the HSS from the VHS. This state evolution is also thought to involve changes in the optically thick disk, which extends down to ISCO in the HSS (as described above) but which is likely to be truncated in the LHS (e.g., Makishima et al. 2008). The VHS is thus understood as a transient stage in which the innermost disk radius gradually decreases and approaches the ISCO (Kubota & Done 2004; Done & Kubota 2006; Tamura et al. 2012). In this way, the optically thick disk and the Comptonizing clouds are suspected to be coupled to each other through the state transition. In the present paper, we examine possible relationships between the disk and the Compton clouds in BHBs by examining a VHS that is rather close to the HSS. This objective requires broadband coverage from $\sim 1$ to $\sim 100$ keV, for which Suzaku is ideal.

LMCX-1 is a persistently X-ray luminous BH binary that is accompanied by an O-type star with an estimated mass of $32 M_\odot$, where $M_\odot$ is the solar mass. The binary parameters are known with good accuracy: BH mass $M_{\text{BH}} = 10.9 M_\odot$, inclination angle $i = 36^\circ 4$, and distance $D = 48$ kpc (Orosz et al. 2009). For decades it has been found in the HSS or VHS, with relatively high luminosity of $\sim 10\%$ of the Eddington value. Previous observations have reported a variable inner disk radius and a steep hard-tail slope of $\Gamma \sim 3$, which are both suggestive of the VHS. This, together with its strong X-ray variations (e.g., Ruhlen et al. 2011), make the object a good source for our study. In previous studies of LMCX-1 in energy bands below 20 keV, the hard tail was in most cases reproduced by a simple PL feature with reflection (e.g., Gou et al. 2009; Ruhlen et al. 2011).

Steiner et al. (2012) showed clear evidence for an iron line in the time-averaged Suzaku spectrum, and a positive correlation between the iron line flux and Compton scattering fraction obtained from RXTE observations. Although those results suggest that the Comptonized hard-tail photons are illuminating the disk to produce the iron line photons, that study considered neither combined Comptonization nor studied spectral variations in the Suzaku data. In the present paper, we hence analyze the same Suzaku observation data, attempting to see whether the inner disk radius remained constant, and whether the hard tail exhibited the signature of combined Comptonization.

2 Observation and data reduction

Suzaku, which is the fifth Japanese X-ray satellite (Mitsuda et al. 2007), carries on board the X-ray imaging spectrometer (XIS: Koyama et al. 2007) and the hard X-ray detector (HXD: Takahashi et al. 2007; Kokubun et al. 2007). The XIS consists of four charge-coupled device cameras placed at the focus of the X-Ray Telescope (XRT: Serlemitsos et al. 2007), covering the $0.2–12$ keV energy range. However, one of four units is not operational. Of the three available XIS units, two (XIS-0 and XIS-3) are front illuminated (FI) while the other (XIS-1) is back illuminated (BI). The HXD consists of PIN silicon diodes (HXD-PIN; 10–70 keV) and Gd$_2$SiO$_5$:Ce scintillators (GSO: 50–600 keV). In 2009 from July 21 UT 18:38 to July 24 21:29, Suzaku observed the source at “XIS nominal” pointing position. The XIS was operated in standard clocking mode and with the “1/4-window” option in order to attain a time resolution of 2 s.

We used data products from Suzaku pipeline processing version 2.4.12.26 with calibration version hxd20090511, xis20090402, and xrt20080709, and software version HEADAS 6.6.2. XIS and HXD events were screened by standard criteria. We discarded events collected with Earth elevation below $5^\circ$, or with the sun-irradiated-Earth elevation below $20^\circ$ (for XIS), or when the spacecraft was in an orbit phase within 436 s after (for XIS) or 180 s before and 500 s after (for HXD) the South Atlantic Anomaly ingress/egress, or at low-cutoff rigidity regions below 6 GV. We accepted only the XIS events with standard grades (0, 2, 3, 4, and 6) in the analysis.

1 See also Coppi, P., & Maccarone, T. 2002, Abstract, April Meeting 2002 of the ASP, N17.079.

2 SUZAKU-MEMO 2007-08, available at (http://www.astro.isas.ac.jp/suzaku/doc/suzakumemo/suzakumemo-2007-08.pdf).
XIS spectra and light curves were extracted from a rectangle region of 8.6 × 4.5, attained in the 1/4 window area and centered on the image peak, while the background was also obtained from a source-free region in the same 1/4-window area. Furthermore, we excluded a circular region of 50″ around the image peak. According to the software AEPILEUPCHECKUP (Yamada et al. 2012), the remaining signals are evaluated to have a pileup fraction of < 1%. The net averaged XIS count rates were ∼15 counts s⁻¹ in the exposure time of ∼110 ks for each sensor. The XIS redistribution matrix files were calculated using the xissrmfgen tool, and the ancillary response files were simulated by the xissimarfgen tool (Ishisaki et al. 2007).

The XIS 1 unfolded data deviate systematically, at energies of ≥3 keV, from those of XIS 0 and XIS 3. This is presumably due to the residual calibration uncertainties of XIS 1 (Ishida et al. 2011; sub-subsection 7.3.3 of Suzaku technical description²). Therefore we did not use the XIS 1 data in the following analysis.

The HXD screened events were used to obtain spectra and light curves from the PIN and GSO sensors. The net exposure of each sensor was 124 ks after dead-time correction. The dead-time fractions were 6.8% averaged for both PIN and GSO sensors. The cosmic X-ray background was modeled assuming an exponentially cut-off PL model (Boldt et al. 1987). Non-X-ray background (NXB) models were provided by the HXD team (Fukazawa et al. 2009). We used the model with METHOD = “LCFITDT(bgd_d),” together with the version of METHODDV = “2.0ver0804” and “2.4ver0912-64” for the data from the PIN and GSO sensors, respectively. Figure 1 shows the background-subtracted spectra. Events are significantly detected by the PIN sensor up to 50 keV, which is above the systematic uncertainty in the NXB model (3% for PIN).

In addition to LMCX-1, there were three hard X-ray sources in the PIN field of view (FOV; 30′ × 30′): PSR B0540−69.3, SN 1987A, and RX J0541.4−6936. Although the expected 20–100 keV flux of PSR B0540−69.3, $\sim 2.9 \times 10^{-11}$ erg s⁻¹ cm⁻² (Campana et al. 2008), is comparable to the observed PIN flux of $\sim 5.5 \times 10^{-11}$ erg s⁻¹ cm⁻² (modeled with a single PL), it is separated from LMCX-1 by 25″. The PIN FOV during the present observation is evaluated to have a transmission efficiency of 21%. Therefore, in the following analysis, the spectral contribution from this active pulsar was modeled by a PL with $\Gamma = 2.12$ (Campana et al. 2008), but with the flux reduced to 21% of that reported. In the light curve analysis, we subtracted the constant count rate of $1.21 \times 10^{-2}$ counts s⁻¹ in 13–50 keV, as estimated by the PIMMS⁴ tool (Mukai 1993), from the PIN light curve. The hard X-ray spectra of SN 1987A and RX J0541.4−6936 were cut-off PL with $\Gamma = 1.7$, cut-off energy of $E_c = 100$ keV, and flux of $\sim 10^{-13}$ erg s⁻¹ cm⁻²; and $\Gamma = 1.0$, $E_c = 15$ keV, and flux of $\sim 10^{-12}$ erg s⁻¹ cm⁻², respectively, as taken from the INTEGRAL source catalog⁵ (Bird et al. 2010). Their locations are off-axis to the PIN FOV, and the PIN efficiency was < 50% of the peak value. The contributions of these two sources are thus an order of magnitude below the PIN flux and hence negligible. Because the GSO FOV contained too many contaminating sources to individually evaluate, we do not use the GSO data in this paper.

### 3 Analysis of time-averaged spectra

Using the X-ray spectral fitting package XSPEC version 12.8.2 and employing the solar abundance tabulated in Anders and Grevesse (1989), we analyzed 0.8–10 keV XIS spectra and 13–50 keV HXD-PIN spectra, averaged over the entire exposure. The energy bands of 1.6–2.0 keV and 2.2–2.4 keV were excluded to avoid relatively large systematic instrumental uncertainties near the Silicon K edge (1.74 keV and 1.84 keV for Kα and Kβ, respectively) and the Gold M edge (2.29 keV), respectively. The remaining instrumental feature at $\sim 3.2$ keV by the Gold M edge was modeled by a Gaussian line with a fixed width of $\sigma = 0.1$ keV (Kubota et al. 2007). We used a combination of XIS 0 and XIS 3 after co-adding them together, and we added a 1% systematic uncertainty to all XIS energy channels. We extended the energy range of spectral fitting to 0.1–1000 keV, as used in some convolution models. We

---

² Available at (http://www.astro.isas.ac.jp/suzaku/doc/suzaku_td/).

⁴ Available at (http://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html).

⁵ Available at (http://isdc.unige.ch/integral/science/catalogue).
fitted the XIS and PIN spectra simultaneously with a cross normalization factor of 1.16 between XIS and PIN.\footnote{SUZAKU-MEMO-2008-06, available at \url{http://www.astro.isas.jaxa.jp/suzaku/doc/suzakumemo/suzakumemo-2008-06.pdf}.}

We assumed the situation where part of the MCD photons are Compton-upscattered to the hard tail, and with reflection of Comptonized emissions. We utilized a convolution model \texttt{simpl} which takes some fraction of the disk seed photons and upscatters these to higher energy (Steiner et al. 2009). In order to account for the reflection of the Comptonization continuum from ionized material, we employed the \texttt{rfxconv} model (Kolehmainen et al. 2011) which is a convolution model and calculates the reflection continuum and fluorescence based on the tables of Ross and Fabian (2005). We fixed the ionized parameter $\xi = 1000\,\text{erg cm}^{-1}$, inclination angle of $\theta = 36.38^\circ$ (Orosz et al. 2009) and assumed solar abundances. Using \texttt{kdblur} (Laor 1991) the reflected spectrum is smeared by general relativistic effects, with fixed inner and outer disk radii of $R^\text{kdblur}_{\text{in}} = 2\,R_g$ (Gou et al. 2009) and $R^\text{kdblur}_{\text{out}} = 400\,R_g$, inclination angle $i = 36.4^\circ$, and emissivity index $\beta = -3$ ($R_g = G M / c^2$, where $M$ is the mass of the central BH). The output of \texttt{simp1$^\text{source}$\text{diskbb}} is the MCD component reduced by Comptonization and upscattered emissions. To calculate the reflection of the Compton component, we divided \texttt{simpl} into \texttt{simpl$^\text{source}$} and \texttt{simpl$^\text{Compton}$} for reduced MCD and Comptonization emission, respectively. Consequently, we employed the continuum model as expressed by (\texttt{simpl$^\text{source}$} + \texttt{kdblur$^\text{source}$\text{rfxconv}$^\text{source}$\text{diskbb}})\texttt{diskbb} modified by photoelectric absorption (\texttt{phabs} in \texttt{XSPEC}) as Model 1.

Figure 2a shows the folded spectra and residuals from the best-fit model. The best-fit parameters are shown in table 1 as Model 1. This fit is unacceptable, with $\chi^2 / \text{d.o.f.} = 290.13 / 118$, and we see large residuals below 3 keV and above 20 keV. To check that the assumption of $\xi = 1000\,\text{erg cm}^{-1}$ does not affect the result, we set $\xi$ to be free. This did not resolve the problem, with results of $\chi^2 / \text{d.o.f.} = 216.84 / 117$, with $\xi = 1.43^{+0.98}_{-0.74} \times 10^4\,\text{erg cm}^{-1}$ and a reflection strength...
of $\Omega/2\pi = 6.07^{+0.11}_{-0.10}$, which is too large to be physically compatible.

To introduce a physical explanation for the excess in the 5–10 keV band, we replaced the diskbb model by the bhspec model (Davis et al. 2005; Model 2) to account for relativativity. Figure 2b shows the folded spectra and residuals from the best-fit model. The best-fit parameters are shown in table 1 as Model 2. The fit is still unacceptable with $\chi^2/d.o.f = 302.24/118$. As shown by the black and red lines in figure 2d, the application of relativistic effects makes the disk component slightly broader but the difference is compensated for by increased photoelectric absorption. We tested the fit again by allowing $\xi$ to be free, and derived $\chi^2/d.o.f = 245.15/117$, where $\xi = 3.67^{+9.63}_{-2.57}$ erg cm s$^{-1}$ and $\Omega/2\pi = 8.89^{+1.11}_{-0.05}$.

To provide an alternative picture, we introduce a combined hard and soft Comptonization model. For the soft Comptonization process, we employed a dbkbfth model (Done & Kubota 2006), which calculates Comptonized MCD spectrum from the accretion disk and the thermal plasma covering the inner region at $R_{in} < R < R_{trans}$, where $R_{in}$ and $R_{trans}$ are inner disk radius and outer radius of the thermal Comptonizing cloud. The model parameters are temperature of seed MCD, electron temperature $kT_e$, photon index $\Gamma_{th}$, $R_{trans}$, and normalization. We again include the simpl model for hard Comptonization with fixed $\Gamma = 2.1$. We assume that hard Comptonization occurs independently of soft Comptonization (i.e., hard electrons do not scatter soft Comptonized photons) and assume the same reflection process for both components. This thus gives a continuum model expressed by $phabs * [\text{simpl}_\text{source} * \text{dbkbfth}_\text{disk} + \text{dbkbfth}_\text{blur} + \text{rfxconv}_\text{disk} + \text{dbkbfth}_\text{sc}]$ (Model 3), where the subscripts of HC and SC denote the hard and soft Compton component, respectively.

The fitting result with the third model is shown in figure 2c and table 1 as Model 3. The reduced $\chi^2$ is acceptable with 111.57/116. Equation (1) of Tamura et al. (2012) gives the relationship between $kT_e$, $\Gamma_{th}$, and optical depth assuming a source of slab geometry with seed photons at the bottom of the slab:

$$\tau = \frac{1}{2} \left\{ \frac{9}{4} + \frac{3}{\Theta_\xi \left( \Gamma_{th} + \frac{1}{2} \right)^2 - \frac{3}{4} \right\},$$

where $\Theta = kT_e/mc^2$ and the optical depth is approximately half that of spherical geometry (see also Zdziarski et al.

| parameter | Model 1 | Model 2 | Model 3 |
|-----------|---------|---------|---------|
| phabs     | $N_H (\times 10^{21} \text{cm}^{-2})$ | $5.47^{+0.07}_{-0.06}$ | $6.03^{+0.07}_{-0.06}$ | $6.06^{+0.09}_{-0.11}$ |
| diskbb    | $kT_{\text{in}} (\text{keV})$ | $0.784 \pm 0.006$ | — | — |
| bhspec    | $a_\star$ | — | $0.79 \pm 0.01$ | — |
| dkbbfth   | $T_{\text{in}} (\text{keV})$ | — | — | $0.811^{+0.012}_{-0.010}$ |
| rfconv    | $\Omega/2\pi ^\dagger$ | — | $0.64^{+0.11}_{-0.09}$ | $0.64^{+0.11}_{-0.10}$ |
| simpl     | $f_{\text{scat}} ^\ddagger$ | $0.16^{+0.22}_{-0.015}$ | $0.16^{+0.013}_{-0.014}$ | $0.03^{+0.002}_{-0.007}$ |
| $\Gamma$ | $2.88^{+0.05}_{-0.05}$ | $2.90^{+0.04}_{-0.05}$ | $2.1$ (fixed) |
| $r_{\text{in}} (\text{km}) ^\S$ | $54.8^{+0.9}_{-1.0}$ | $47.6 \pm 0.8$ | $55.0^{+1.2}_{-1.0}$ |
| $\Gamma_{th}$ | — | — | $0.67^{+0.05}_{-0.13}$ |
| $f_{\text{th}}$ | — | — | $0.12$ |

*The errors are 90% confidence level for single parameter. Model 1: Calculated from the normalization of diskbb. Model 2: Equivalent to $a_\star$ of bhspec calculated with $M_{\text{BH}} = 10.9M_\odot$. Model 3: Estimated from unabsorbed photon flux via equation (A1) in Kubota and Makishima (2004).

$^\dagger$Normalization defined as $r_{kT,\text{disk}}^2 \cos^2 (\theta)/10^{10} \text{kpc}^2$.

$^\ddagger$The solar abundances assumed, with fixed ionization parameter of $\xi = 1000$.

$^\S$Reflection strength of the ireflect model. $\Omega$ is the solid angle of the reflector.

$^\S$Scattering fraction of the simpl model.

$^\S$Inner disk radius derived from fit result.
Using this equation, the optical depth is calculated to be $\tau = 0.67^{+0.05}_{-0.11}$. Since the normalization of $\Delta k_{bbfth}$ is not equivalent to that of $\Delta k_{bb}$, we calculated the inner disk radius $r_{in}$ via equation (A1) in Kubota and Makishima (2004) using the unabsorbed photon flux. We derived $r_{in} = 55.0^{+1.7}_{-1.5}$ km, which is consistent with the estimation from Model 1. This implies that the soft Compton cloud localized within $R_{trans} = 8.9 R_{in}$ scatters 12% of disk photons.

As shown in figure 2a, the inclusion of the soft Comptonized emission shifts the disk component to a lower temperature, which makes the derived $r_{in}$ substantially larger. The fraction of hard Comptonized emission decreases and its photon index flattens, due to the soft Compton component.

## 4 Light curves and spectral variation

Figure 3 shows background-subtracted light curves and hardness ratio variations for LMCX-1. Both the X-ray counts and hardness ratios exhibit variations on a timescale of $\sim 10^4$–$10^5$ s. In order to estimate the energy dependence of the variation, we calculate the rms value for each divided energy band using a bin size of 5760 s, which is the timescale shown in figure 3. The derived rms spectrum is shown in figure 4. The fractional rms variation clearly depends on the energy band, increasing towards the higher energy range and exceeding 10% above $\sim 6$ keV.

Figure 5 shows the hardness ratio of 6–10 keV to 4–6 keV against a 4–10 keV count rate with a time bin size of 5760 s. The hardness ratio is clearly correlated with source flux, which indicates significant spectral variation. In order to evaluate the spectral variation shown in figures 3 and 4, we divided the data into hard phase (HP) and soft phase (SP) for hardness ratios higher and lower than the average value of 0.25 (dashed line in figure 5). Figure 6 shows spectra normalized by PL with $\Gamma = 2$ for each phase and pulse-height ratio of HP/SP. The differential spectrum has a peak at around 6 keV and dominates above $\sim 10$ keV. As the pulse-height ratio shows, although the variation is < 10% in the band below 4 keV, it is $\sim 30$%–50% in the band above $\sim 8$ keV. In the time-averaged spectra (figure 2), the contribution of Compton and reflection components dominates above $\sim 6$ keV in the energy spectrum with a peak around $\sim 4–6$ keV. The behavior thus implies spectral variability of Compton and/or reflection components.

To quantify the variations in the continuum spectra, we performed a broadband spectral fit to each phase.
(HP) to 0.11 (SP), the changes in the other parameters $R_{\text{trans}}$, $kT_e$, $\Gamma_{\text{th}}$, and $f_{\text{th}}$ are insignificant.

5 Summary and discussion

We analyzed Suzaku data of LMCX-1 observed in 2009 from July 21 to 24 and obtained 0.8–50 keV spectra and light curves. The time-averaged spectra cannot be explained by simple modeling of a non-relativistic or relativistic disk and single Comptonized emission (Models 1 and 2 in table 2) and the spectra exhibit large deviations below 3 keV, around 6 keV, and above 20 keV. These residuals are successfully compensated for by adding a hard and soft Comptonization model (Model 3). The hard and soft components are described by a PL tail with $\Gamma = 2.1$ representing the excess above 20 keV from the $\text{simple}$ model and thermal Comptonization at the inner disk region of $\lesssim 9 R_{\text{in}}$ with $kT_e \sim 16$ keV and $\Gamma_{\text{th}} \sim 0.7$ to describe the 4–10 keV residuals by the $\text{dbbfbth}$ model (figure 2), respectively. Using the best-fit parameters, the unabsorbed 0.8–50 keV flux is estimated to be $8.7 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, which gives an X-ray luminosity of $2.4 \times 10^{38}$ erg s$^{-1}$ for an isotropic emission from 48 kpc. The bolometric luminosity was also calculated to be $3.3 \times 10^{38}$ erg s$^{-1}$.

In contrast to the case where the spectrum is not fitted by the single Compton model, Steiner et al. (2012) reported reduced $\chi^2 \sim 1$ by similar fitting to Model 2 from the time-averaged Suzaku spectrum of LMCX-1. This difference could mainly be caused by the absorption model for the interstellar medium (ISM). They employed the absorption model of $\text{TBvarabs}$ (Wilms et al. 2000) with ISM composition taken from Hanke et al. (2010), while we employed $\text{phabs}$ in the analysis. Replacing $\text{phabs}$ with $\text{TBvarabs}$, we obtained an improvement, with a reduction in $\chi^2$ from 2.6.

![Fig. 6](https://example.com/figure6.png)

**Table 2. Best-fit parameters for each phase.**

| Parameter | HP | SP |
|-----------|----|----|
| $N_\text{H}$ ($\times 10^{21}$ cm$^{-2}$) | 6.09$^{+0.01}_{-0.13}$ | 6.01$^{+0.07}_{-0.01}$ |
| $kT_{\text{em}}$ (keV) | 0.813$^{+0.011}_{-0.012}$ | 0.807$^{+0.007}_{-0.01}$ |
| Norm ($\times 10^{-2}$) | 1.3$^{+0.1}_{-0.8}$ | 1.42$^{+0.03}_{-1.0}$ |
| $R_{\text{trans}}$ (R$_{\odot}$) | 8.8$^{+0.6}_{-0.80}$ | 9.07$^{+1.02}_{-0.92}$ |
| $kT_e$ (keV) | 14.0$^{+4.0}_{-4.1}$ | 16.3$^{+11.6}_{-5.7}$ |
| $\Gamma_{\text{th}}$ | 3.98$^{+0.13}_{-0.14}$ | 4.04$^{+0.22}_{-0.26}$ |
| $\Omega/2\pi$ $^\dagger$ | 0.85$^{+0.24}_{-0.089_{-0.16}}$ | 0.89$^{+0.57}_{-0.16}$ |
| $f_{\text{scat}}$ | 0.048$^{+0.008}_{-0.007}$ | 0.027$^{+0.009}_{-0.009}$ |
| $\Gamma$ | 2.1 (fixed) | 2.1 (fixed) |
| $\chi^2$/d.o.f | 109.95/116 108.64/116 | 108.64/116 |
| Derived value $R_{\text{in}}$ (km)$^\#$ | 54.1$^{+1.1}_{-1.2}$ | 55.5$^{+0.7}_{-1.0}$ |
| $\tau_{\text{th}}$ | 0.70$^{+0.16}_{-0.14}$ | 0.61$^{+0.18}_{-0.18}$ |
| $f_{\text{th}}$ | 0.12 | 0.11 |

$^\dagger$The errors are 90% confidence level for single parameter.

$^\dagger$The solar abundances and ionization parameter of $\xi = 1000$ assumed.

$^\dagger$Reflection strength of the $\text{rxfconv}$ model. $\Omega$ is the solid angle of the reflector.

$^\dagger$Scattering fraction of the $\text{simple}$ model.

$^\dagger$Inner disk radius estimated from unabsorbed photon flux via equation (A1) in Kubota and Makishima (2004).
to 1.5. However, Model 3 still gives the best fit results with the reduced $\chi^2_\nu$ of 1.1. Therefore, the difference in absorption model does not affect the conclusion of this paper.

We found significant variation in both the XIS and PIN band. The count rates correlate with the hardness ratio, and different spectral changes appeared in the three energy bands of below 2 keV, above 10 keV, and 2–10 keV, which exhibited variations of $\sim$1%, $\sim$40%, and values in between, respectively (figure 6b). This implies the existence of three spectral components, which is consistent with the modeling of MCD and combined hard and soft Comptonized emission. From the spectral fits, we found that the spectral change is mainly explained by variations in the hard Comptonization fraction by a factor of $\sim$40% in contrast to keeping the MCD parameters of $T_{in}$ and $R_{in}$.

The results obtained show that the spectrum is composed of three spectral disk components and two Comptonized emissions, instead of a disk with a single Comptonized emission. This increases the inner disk radius from $47.6 \pm 0.8$ km (Model 2) to $55.0^{+1.2}_{-1.0}$ km (Model 3), and hence implies a lower BH spin.

Figure 8 shows a comparison of the best-fit parameters of soft Comptonized emission from three VHS BHBs observed by Suzaku: GX 339−4 (Tamura et al. 2012), 4U 1630−47 (Hori et al. 2014), and LMC X-1 (this work). The parameters of $kT_e$ and $f_{th}$ derived from LMC X-1 are lower than those of the other studies, although $\tau_{th}$ is similar. We also found a stable $r_{in}$ at $\sim 55$ km (corresponding to $\sim 3$–4 $R_g$ with $M = 10.9 M_\odot$), which is assumed to reach the ISCO, for LMCX-1. In contrast, the truncated inner disk radii of GX 339−4 and 4U 1630−47 were reported by Tamura et al. (2012) and Hori et al. (2014), respectively. Taking into account that the inner disk radius and the soft Comptonized emission decrease through the state evolution from VHS to HSS, we found the feature that LMC X-1 is in the VHS rather than HSS, and the inner disk radius reaches the ISCO through the relatively weak soft Comptonized emission.
Fig. 8. Comparison of derived depth parameters of $\tau_{th}$, $kT_e$, and $f_{th}$ from three objects. Squares, circles, and asterisks represent the parameters of GX 399−4 (Tamura et al. 2012), 4U 1630−47 (Hori et al. 2014), and LMCX-1 (this work), respectively.

Acknowledgement

This work is supported by a Grant-in-Aid for JSPS Fellows (No. 13J08352, S.K.) and Grants-in-Aid for Scientific Research (B) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 23340055, Y.T.; No. 22340039, M.S.T.).

References

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bird, A. J., et al. 2010, ApJS, 186, 1
Boldt, E., et al. 1987, Phys. Rep., 146, 215
Campana, R., Mineo, T., de Rosa, A., Massaro, E., Dean, A. J., & Bassani, L. 2008, MNRAS, 389, 691
Davis, S. W., Blaes, O. M., Hubeny, I., & Turner, N. J. 2005, ApJ, 621, 372
Done, C., & Kubota, A. 2006, MNRAS, 371, 1216
Ebisawa, K., Makino, F., Mitsuda, K., Belloni, T., Cowley, A. P., Schmidtke, P. C., & Treves, A. 1993, ApJ, 403, 684
Frontera, F., et al. 2001, ApJ, 561, 1006
Fukazawa, Y., et al. 2009, PASJ, 61, S17
Gierliński, M., Zdziarski, A. A., Done, C., Johnson, W. N., Ebisawa, K., Ueda, Y., Haardt, F., & Pihlips, B. F. 1997, MNRAS, 288, 958
Gierliński, M., Zdziarski, A. A., Poutanen, J., Coppi, P. S., Ebisawa, K., & Johnson, W. N. 1999, MNRAS, 309, 496
Gou, L., et al. 2009, ApJ, 701, 1076
Hanke, M., Wilms, J., Nowak, M. A., Barragan, L., & Schulz, N. S. 2010, A&A, 509, L8
Hori, T., et al. 2014, ApJ, 790, 20
Ishida, M., et al. 2011, PASJ, 63, S657
Ishisaki, Y., et al. 2007, PASJ, 59, S113
Kobayashi, Y., Kubota, A., Nakazawa, K., Takahashi, T., & Makishima, K. 2003, PASJ, 55, 273
Kokubun, M., et al. 2007, PASJ, 59, S53
Kolehmainen, M., Done, C., & Diaz Trigo, M. 2011, MNRAS, 416, 311
Koyama, K., et al. 2007, PASJ, 59, S245
Kubota, A., & Done, C. 2004, MNRAS, 353, 980
Kubota, A., & Makishima, K. 2004, ApJ, 601, 428
Kubota, A., et al. 2007, PASJ, 59, S185
Laor, A. 1991, ApJ, 376, 90
Makishima, K., et al. 1986, ApJ, 308, 635
Makishima, K., et al. 2000, ApJ, 535, 632
Makishima, K., et al. 2008, PASJ, 60, 585
Mitsuda, K., et al. 1984, PASJ, 36, 741
Mitsuda, K., et al. 2007, PASJ, 59, S1
Miyamoto, S., Kimura, K., Kitamoto, S., Dotani, T., & Ebisawa, K. 1991, ApJ, 383, 784
Mukai, K. 1993, Legacy, vol. 3, p. 21–31, 3, 21
Orosz, J. A., et al. 2009, ApJ, 697, 573
Ross, R. R., & Fabian, A. C. 2005, MNRAS, 358, 211
Ruhlen, L., Smith, D. M., & Swank, J. H. 2011, ApJ, 742, 75
Serlemitsos, P. J., et al. 2007, PASJ, 59, S9
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shimura, T., & Takahara, F. 1995, ApJ, 445, 780
Steiner, J. F., McClintock, J. E., Remillard, R. A., Gou, L., Yamada, S., & Narayan, R. 2010, ApJ, 718, L117
Steiner, J. F., Narayan, R., McClintock, J. E., & Ebisawa, K. 2009, PASP, 121, 1279
Steiner, J. F., et al. 2012, MNRAS, 427, 2552
Takahashi, H., et al. 2008, PASJ, 60, S69
Takahashi, T., et al. 2007, PASJ, 59, S53
Tamura, M., Kubota, A., Yamada, S., Done, C., Kolehmainen, M., Ueda, Y., & Torii, S. 2012, ApJ, 753, 65
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Yamada, S., et al. 2012, PASJ, 64, 53
Zdziarski, A. A., & Gierliński, M. 2004, Prog. Theor. Phys., Suppl., 155, 99
Zdziarski, A. A., Johnson, W. N., & Magdziarz, P. 1996, MNRAS, 283, 193
Zdziarski, A. A., Lightman, A. P., & Maciolek-Niedzwiecki, A. 1993, ApJ, 414, L93