Spectral Evolution of the Black Hole X-ray Binary XTE J1752–223 Observed with MAXI

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Abstract

We present the results on the black hole candidate XTE J1752–223 from the Gas Slit Camera (GSC) on-board the Monitor of All-sky X-ray Image (MAXI) on the International Space Station. Including the onset of the outburst reported by the Proportional Counter Array on-board the Rossi X-ray Timing Explorer on 2009 October 23, the MAXI/GSC had monitored almost all of the outburst from this source approximately 10 times per day with a high sensitivity in the 2–20 keV band. We analyzed the data from the BHXB XTE J1752–223 obtained with the MAXI/GSC and other X-ray observatories in the space. The outburst in 2009-2010 from the XTE J1752–223 shows a notable features as 1) it stays on an initial low-hard state (LHS) for an unexpectedly long period of three months, 2) 2-20 keV light curves shows two different plateaus at different brightness, and 3) it shows apparently two different physical states during the first and second plateau; one display spectra seem unchanged for various brightness, while the other indicates spectral change depending upon brightness. We compared this particular outburst with others from several BHXBs and found that it somewhat resembles two outbursts from GX 339—4 which is known as a unique source displaying the long LHS except for persistent source. From two distinctive natures; (i) a relationship between spectral and flux variations, and (ii) a resemblance of light curves of outbursts showing plateau and similar time-scale, we conclude that XTE J1752–223 and GX 339-4 could be categorized in a new class of the BHXBs.

Key words: accretion disks — black hole physics — stars: individual (XTE J1752–223) — X-rays: stars

1. Introduction

Galactic black hole candidates (BHCs) are ideal objects in studying how accretion disks and coronae evolve due to changes in the accretion rate, thanks to their high photon statistics and frequent state transitions. They are characterized by transient behavior, such as a sudden X-ray brightening caused by instabilities originating in the outer accretion disk. They show various states characterized by their spectral shapes, temporal properties, and luminosities. They mostly take two major states, the “ low/hard state ” and the “ high/soft state ” (see, e.g., McClintock & Remillard 2006). In the low/hard state, the X-ray energy spectra are dominated by a power-law component with a photon index of ∼1.7 and a high energy cutoff at ∼100 keV that shows strong short-time variability (Grove et al. 1998). They can be explained by thermal Comptonization of soft photons from the accretion disk by hot plasmas with a temperature of $\sim 10^{10}$ K (e.g., Makishima et al. 2008, Takahashi et al. 2008). In a typical outburst of a transient BHC, it generally exhibits a spectral transition from the low/hard to the high/soft state through the intermediate (or very high) state when the luminosity reaches ∼10% of the Eddingtion limit. The X-ray spectra in the high/soft state are characterized by a ultra-soft component which is considered to originate from an optically-thick and geometrically-thin accretion disk (so called “ standard disk ”; Shakura & Sunyaev 1973). This emission can be successfully described by the multi-color disk (MCD) model (Mitsuda et al. 1984, Makishima et al. 1986) with the innermost temperature of ∼1 keV.

The new X-ray transient XTE J1752–223 was first detected at the 30 mCrab flux level in the 2–10 keV range on October 23, 2009 during the galactic bulge monitoring with the Proportional Counter Array (PCA) of the Rossi X-ray Timing Explorer (RXTE) (Markwardt et al. 2009a). On October 24, the source also triggered the Swift Burst Alert Telescope (BAT) at a 100 mCrab flux in the 15–50 keV range (Markwardt et al. 2009a). The position was determined to (RA,Dec)=($17^{h}52^{m}15^{s}.14$, –22°20'33".8) with 5 arc-sec uncertainty by a follow-up Swift X-Ray Telescope (XRT) localization (Markwardt et al. 2009b). The energy spectrum is consistent with a power-law with photon index 1.38 ± 0.01 and the power spectrum shows band-limited noise with a total rms of ~30 percent, suggesting that the source was in a typical LHS (Shaposhnikov et al. 2009; Munoz-Darias et al. 2010). The optical (Torres et al. 2009a), near-infrared (Torres et al. 2009b), and radio counterparts (Brocksopp et al. 2009) were also discovered within the X-ray error circle during the initial phase. Possible double-sided jets were detected on February 11, 2010 (Brocksopp et al. 2010a; Brocksopp et al. 2010b); however, the BH mass, inclination angle, and distance have not been determined yet.

2. Analysis and light curves

2.1. MAXI/GSC

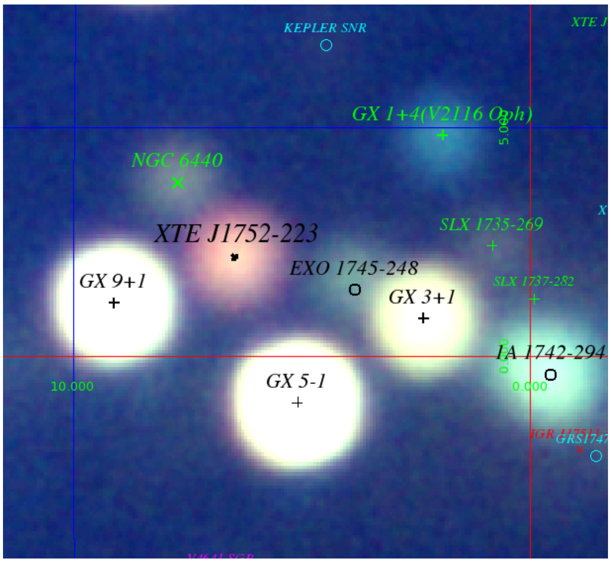

Fig. 1. MAXI/GSC false colored RGB image around the field near the XTE J1752–223(Red:2-4 keV, Green:4-8 keV, Blue:8-16 keV).

Since August 3, 2009, the highly sensitive all-sky monitor, Monitor of All-sky X-ray Image, MAXI (Matsuoka et al. 2009), has been activated on the Exposed Facility of the Japanese Experimental Module "Kibo" of the International Space Station (ISS). Soon after the discovery of XTE J1752–223, when the MAXI was still in the commissioning phase, the source was found at the 30 mCrab level in an X-ray image of the MAXI Gas Slit Camera (GSC) (Nakahira et al. 2009). The outburst lasted over eight monthes, the MAXI/GSC monitored entire the outburst including both hard-to-soft and soft-to-hard transitions. The MAXI/GSC scanned the direction of XTE J1752—223 2041 times in total from the discovery on 2009 October 23 (MJD 55127) to 2010 June 3 (MJD 55350). The total exposure times effective area becomes 534.8 cm2 ksec.

Because the XTE J1752–223 locate near the Galactic Center (l, b)=(6.42, 2.11), many bright X-ray sources are visible in this field1. To avoid the source contamination from the nearby bright sources GX 9+1 (2.82° away) and SAX J1748.9–2021 in the globular cluster NGC 6440 (Patruno et al. 2010 ATel, 2407; 2.13° away), we carefully selected the source and background regions as circles of (RA, Dec, Radius)=(268.06,-22.34, 1.16°) and (RA, Dec, Radius)=(263.04,-21.43, 2.5°) respectively.

We analyzed the GSC event data version 0.3b, which include the data taken by counters operated at the nominal high voltage (=1650 V) but excluding those of anode #1 and #2 whose energy responses have not been enough calibrated yet. We discarded events taken while the GSC FOVs were interfered by the solar panels and other ISS payloads. The events detected at the anode-end area were also screened since the background is higher there in. These event were cut with a condition that the photon incident angle (ϕ col; see Mihara et al. 2011 for the definition) is higher than 36.

2.2. Swift/BAT

The burst alert telescope (BAT), is a coded-aperture telescope designed to monitor a large fraction of the sky for the occurrences of GRBs, sensitive ranging from 15 to 150 keV. While waiting GRBs, the BAT accumulates an all-sky hard X-ray survey, and obtains detector plane histograms (DPHs). We collected all BAT observations covering the field of XTE J1752–223, between October 2009 and June 2010. All the data analysis was performed using so-called mask weighting method, which is implemented as a automatic pipeline "batsurvey" script in HEASOFT.

3. Results

3.1. Light Curves

The light curves are shown in the Fig.2, four panels from the top is the MAXI/GSC light curves corresponds to the energy band of 2–4 keV, 4–10 keV, 10–20 keV and Hardness Ratio (4–10 keV/2–4 keV). The bottom three panels are the Swift/BAT light curve of 15–50 keV, 50–150 keV and hardness ratio of (15-150 keV/15-50 keV).

The X-ray light curve shows the following notable features. There are two initial plateau phases that lasted for ~25 days and ~40 days, respectively, and the spectral hardness between them is slightly different: the second phase (Phase D in figure 2) has a softer spectrum than the first one (Phase B). The source could not be observed during phase D by any other X-ray instruments except for RXTE/ASM and Swift/BAT due to the Sun constraints. The time scales of the rising phases A and C were about 5 days and 15 days, respectively. Another notable feature is the anti-correlated behavior around the peak: The 2–4 keV flux rapidly increased after January 20, 2010 (MJD: 55216) while fluxes in the other two bands and the Swift/BAT 15–50 keV flux decreased

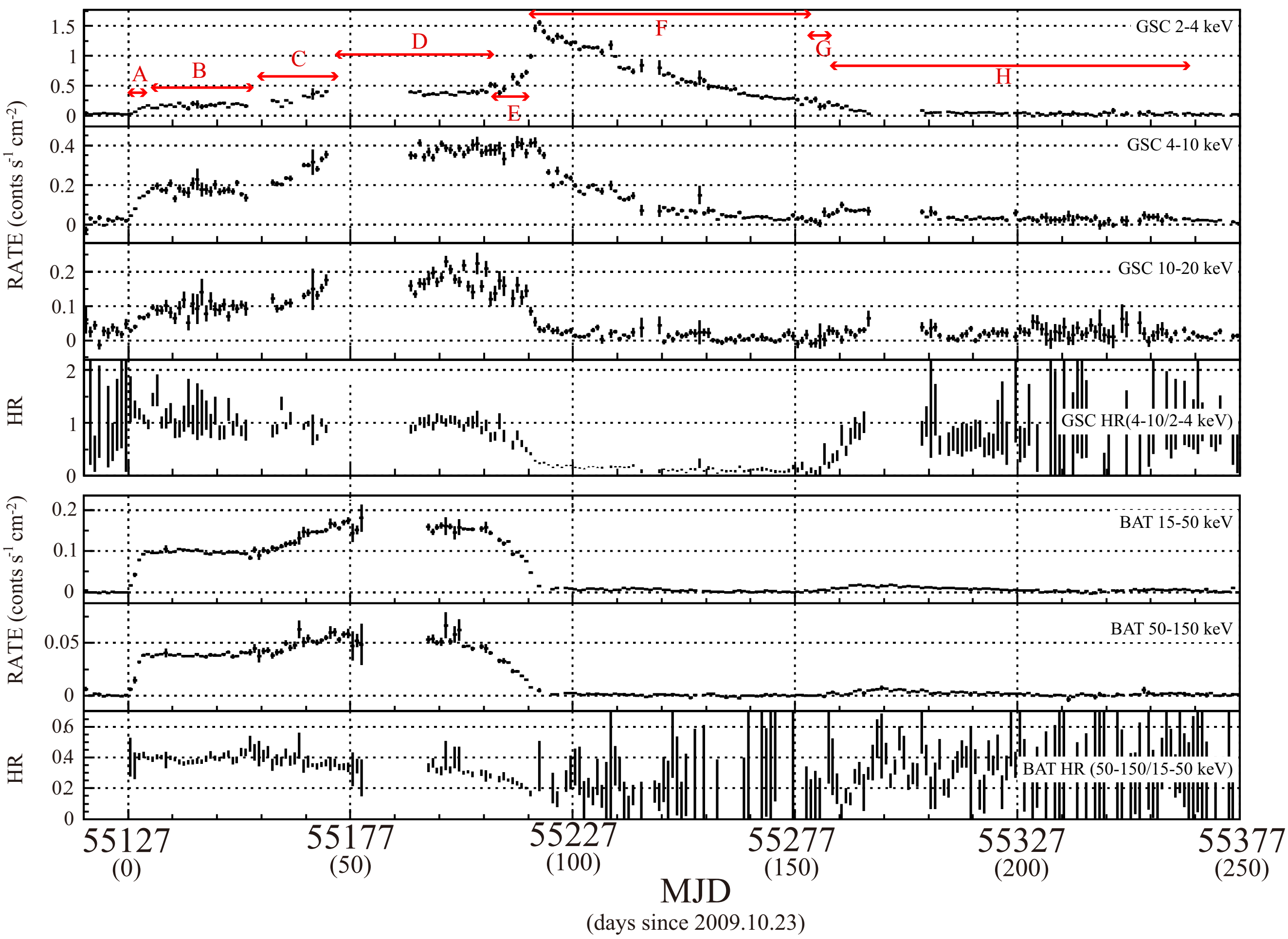

Fig. 2. MAXI/GSC and Swift BAT light curves of XTE J1752–223 in five energy ranges: 2-4, 4-10, 10-20 keV observed with MAXI/GSC (from the top to the thirds panel), and 15-50, 50-150 keV by Swift/BAT (fifth and sixth panel). The hardness ratio in 2-4 and 4-10 keV, 15-50 and 50-150 keV are shown in the forth and seventh. Each one-day integration data points were labeled as period A to H by the flux and the Hardness ratio.

(Phase E for $\sim$ 9 days). The anti-correlation between the soft and hard bands indicates a spectral transition. This fact means that it took a very long time of $\sim$ 90 days for the source to complete the transition after the onset of outburst. The 2–20 keV flux reached a peak on January 23, 2010 (MJD: 55219) at about the 430 mCrab level, then gradually decreased (Phase F). The emissions during Phase F are dominated by the soft bands ($<$ 4 keV) (see also the lower panel of Figure 2). Around March 28 (MJD: 55283), hard X-rays and the hardness ratio again increase (Phase G and H). The outburst lasted to $\sim$ 2010 June, total duration of the outburst becomes $\sim$ eight months.

Figure 3 shows a hardness-intensity diagram for the currently on-going outburst in XTE J1752–223. Because of the anti-correlated behavior between the soft and hard X-rays during Phases E and G, the data points track the Q-shaped curve, i.e. hysteresis behavior, as seen in other BHCs (Homan & Belloni 2005). The two plateau phases B and D correspond to the LHS, while the softer phase F corresponds with the HSS. Thus, the state transition from the LHS to the HSS can be clearly identified with the MAXI/GSC data alone.

3.2. Spectral Evolution in the High Soft State

We analyzed the MAXI/GSC spectral data from MJD 55200–55292, which contains both hard-to-soft and soft-to-hard transitions (corresponds periods E, F and G). The data were separated into 49 datasets. We employed the standard model for BHCs in the high/soft state, a multi-color disk (MCD; diskbb in XSPEC) model plus a power-law representing the hard tail. So the model becomes *wabs*(diskbb+powerlaw)*, whose hydrogen column density (N_H) is fixed at 0.6×10^{22} cm^2 from the Swift and Suzaku. We firstly applied this model to all the data. When the MCD model was required, γ was fixed at 2.2 because it is difficult to determine from each spectrum due to the poor statistics. When MCD com-

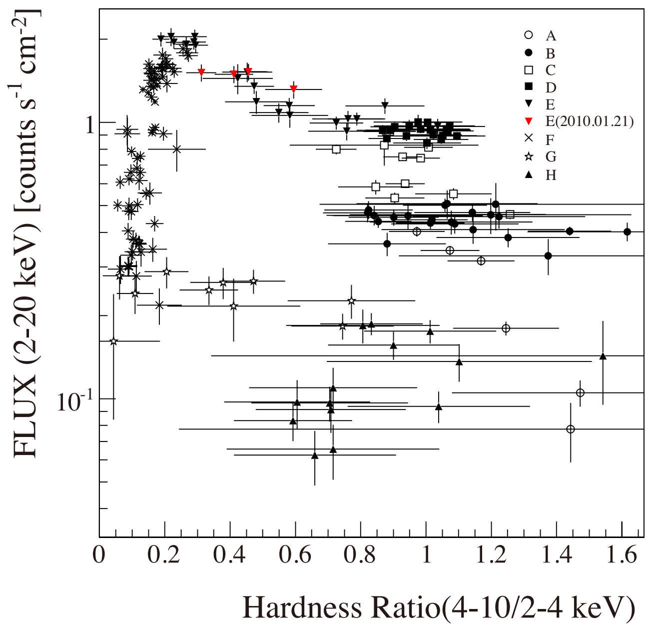

Fig. 3. Hardness-intensity diagram during the outburst from XTE J1752−223(2009-2010). Six hour integration were used for the period **E**, and Filled red data points show the data when increased radio emissions were detected on 2010 January 21.

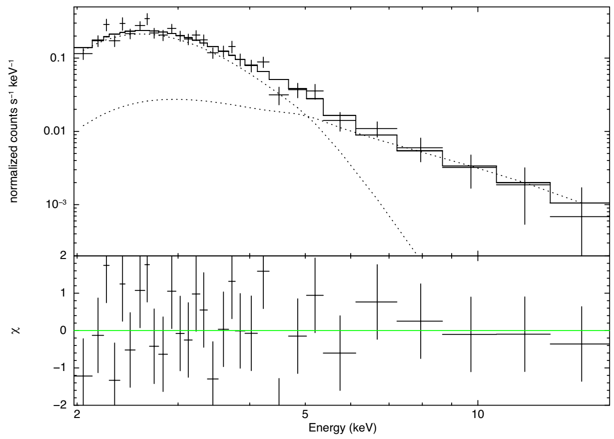

Fig. 4. Representative MAXI/GSC spectra analyzed using the MCD plus power-law model. Bottom panel is the residual between the data and the model.

ponent was found to be not present, only the power law model whose photon index set free was applied.

The typical νF_ν spectra unfolded with the energy response and the residual between the data and the model are shown in the figure 4. Figure 5 plots the evolution of these parameters against time, MCD and power law fluxed, γ, innermost temperature of the accretion disk T_{in} (keV) and innermost radius R_{in} (km)[1] . The MCD was not detected between MJD 55200 and 55214, the photon index and power-law flux was almost constant at ∼1.7 and 1.2×10^{-8} erg s^{-1} cm^{-2}, respectively. The spectrum was dramatically softened on MJD 55215, the MCD component was required for the spectra after MJD 552165 until MJD 55286. We found that the T_{in} decreased from ∼0.7 to ∼0.4 keV, by contrast R_{in} was constant at ∼120 km. Its constancy allows us to identify it with the ISCO in the high/soft state. Furthermore, the value of r_{in} thus estimated is significantly larger than those found in luminous low-mass X-ray binaries (10 km; Mitsuda et al. 1984), the black hole interpretation of XTE J1752—223 (Paper I; Mun oz-Darias et al. 2010) is reinforced. For detailed results and discussions , see Nakahira et al., 2012.

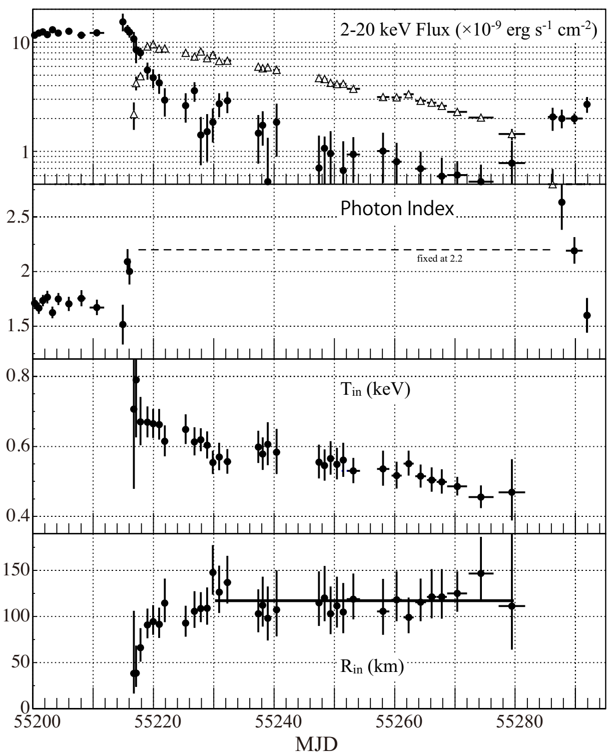

Fig. 5. Evolution of the spectral parameters of XTE J1752—223. From the top, power-law flux, photon index, T_{in} and R_{in} derived with MCD plus power-law model are indicated.

*1 Normalized at inclination angle from out line of sight i=0 and distance from the Earth D=10 kpc

3.3. Spectral Evolution in the Low Hard State

On the period C and D, X-ray observatories except for the MAXI/GSC and Swift/BAT could not observe XTE J1752–223 since the sun located near the source. With the brightness of the source and sensitive energy range of the MAXI/GSC, it is difficult to perform spectral analysis in the Low Hard State using physically-based model such as compps model (not e.g. simple power-law). For simplicity, we just plotted the 4–10 keV MAXI/GSC data and 50–150 keV Swift/BAT data. Each data from scans/snapshots of the MAXI/GSC and the Swift/BAT were averaged for each day. The count vs count plot is shown in figure 6.

Data points shown by the color red, green, blue, magenta and cyan corresponds to the period A (MJD55127–55131), B (MJD55132–55154), C (MJD55155–55174), D (MJD55175–55207) and E (MJD55208–55219), respectively. Periods A and B with a dashed-line which passes through the origin, means the unchanged spectrum. By contrast, the plots in the period C move away from the line, it implies a change of photon index or cut-off energy. Swift/BAT count rate above 50 keV from latter D through E decreased significantly. Since photon indices from MJD=55200 to 55214 derived with MAXI/GSC are constant at Γ=1.7, the variation until former E could be regarded as a decay of electron plasma temperature.

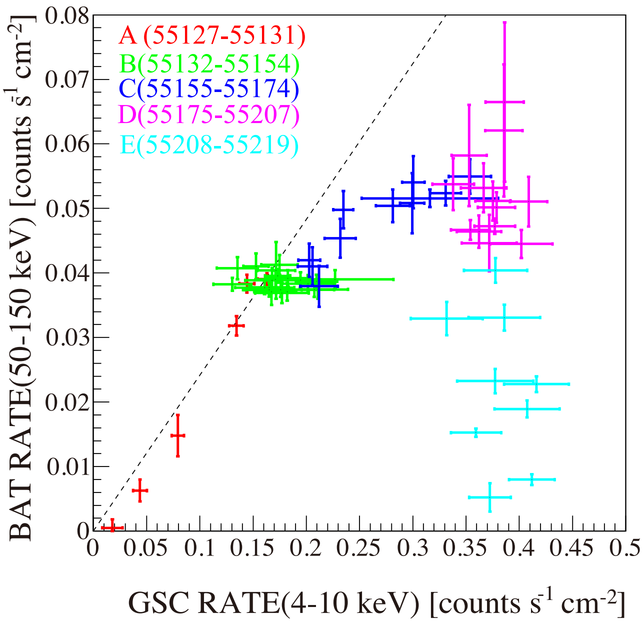

Fig. 6. GSC 4-10 keV count vs BAT 15-50 keV count diagram for XTE J1752–223 Data points in each periods are shown in different color.

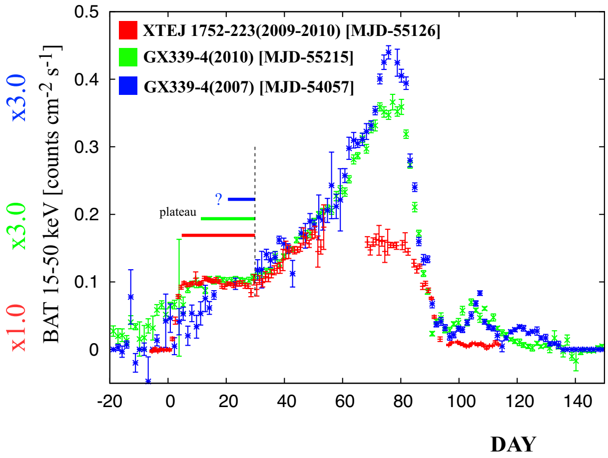

Fig. 7. Modified Swift/BAT light curves from XTE J1752-223 and GX 339-4(2007, 2010) are shown. GX 339-4 rates were trebled, and were shifted to their fast-decay periods are to be matched. After of the plateau, their slopes of increasing part and length to the HSS transition harmonized.

4. conclusion

Using data obtained by the MAXI/GSC, the Swift/XRT, and Suzaku, we have performed X-ray spectral analysis of the black hole candidate XTE J1752—223 in the high/soft state. As commonly seen in BHCs, the innermost radius remained constant in this state during the continuous observation with the MAXI/GSC. The results using the MCD plus power-law model were consistent between the three observatories. The constancy and the large value of relatively R_{in} implies us that XTE J1752–223 is a black hole X-ray binary. In the low/hard state, we performed joint analysis in combination of the MAXI/GSC and the Swift/BAT. Although it showed no spectral change in the lower luminosity, it indicated spectral variation in the higher luminosity. It may due to the variation of cut-off energy which comes from the change of the density or the electron temperature of optically thin plasma, as seen in GX 339–4 (e.g. Motta et al., 2009). Additionally, the light curve of XTE J1752–223 may resembles GX 339–4. When the 15-50 keV Swift/BAT is thrice and shifted, the growth rate and time scale after the plateau period agrees (figure 7).

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