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LETTER

MAXI GSC Observations of a Spectral State Transition in the Black Hole Candidate XTE J1752−223

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Abstract

We present the first results on the black-hole candidate XTE J1752−223 from the Gas Slit Camera (GSC) aboard the Monitor of All-sky X-ray Image (MAXI) on the International Space Station. Including the onset of an outburst reported by the Proportional Counter Array aboard the Rossi X-ray Timing Explorer on 2009 October 23, MAXI / GSC has been monitoring this source approximately 10 times per day with high sensitivity in the 2–20 keV band. XTE J1752−223 was initially in a low / hard state during the first 3 months. An anti-correlated behavior between the 2–4 keV and 4–20 keV bands was observed around 2010 January 20, indicating that the source exhibited a spectral transition to the high / soft state. A transient radio jet may have been ejected when the source was in the intermediate state where the spectrum was roughly explained by a power-law with a photon index of 2.5–3.0. The unusually long period in the initial low / hard state implies a slow variation in the mass-accretion rate, and a dramatic soft X-ray increase may be explained by a sudden appearance of the accretion disk component with a relatively low innermost temperature (0.4–0.7 keV). Such a low temperature might suggest that the maximum accretion rate was just above the critical gas-evaporation rate required for the state transition.

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

1. Introduction

Galactic Black hole candidates (BHCs) are ideal objects for studying how accretion disks and coronae evolve due to changes in the accretion rate, thanks to their high photon statistics and frequent state transitions (see, e.g., McClintock & Remillard 2006 for a review). They are characterized by transient behavior, such as sudden X-ray brightening caused by instabilities originating in the outer accretion disk. During an outburst, which typically lasts a few months, they may go through several distinct spectral states, initial low / hard state (LHS), intermediate or very high state (IMS / VHS), high / soft state (HSS), LHS, and then go back to quiescence. These states are believed to reflect changes in the geometry of the accretion disk and corona (Esin et al. 1997), as well as jets (Markoff et al. 2001; Yuan et al. 2005). BHCs sometimes show powerful radio jets in their outbursts in association with state transitions from the LHS to the HSS. Hence, studying the spectral transition and the disk-jet interaction are important for clarifying the jet production mechanisms (see, e.g., Fender 2006 for a review).

The new X-ray transient XTE J1752−223 was first detected at the 30 mCrab flux level in the 2–10 keV range on

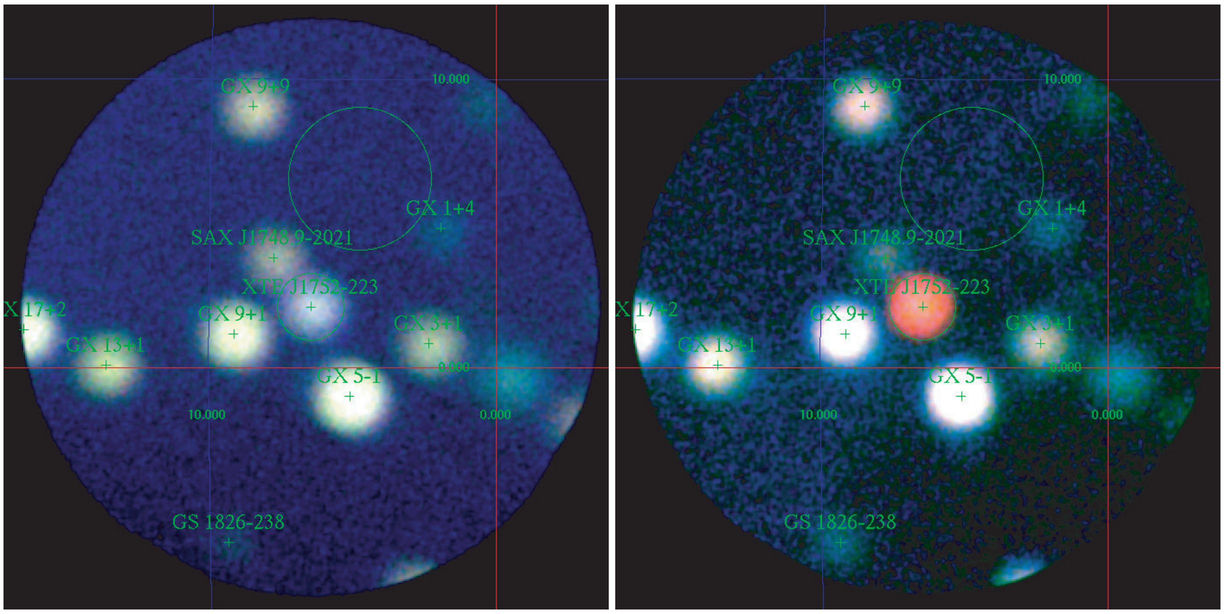

Fig. 1. MAXI / GSC false-color images during the period of December 20 to January 19 (upper panel) and January 20 to February 28 (lower panel). Red: 2–4 keV, Green: 4–10 keV, Blue: 10–20 keV. 10° radius area from XTE J1752−223 is extracted, and the source clearly reddens because of the spectral transition. There are many bright X-ray sources near XTE J1752−223 with a few hundreds of mCrab such as GX 9+1 and GX 3+1. Source and background regions used for the light curve analysis are shown by green circles on both images.

2009 October 23 during 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 be (RA, Dec) = $(17^{\mathrm{h}}52^{\mathrm{m}}15.^{\mathrm{s}}14, -22.^{\circ}20'33.''8)$ with a $5''$ uncertainty by follow-up Swift X-Ray Telescope (XRT) localization (Markwardt et al. 2009b). The energy spectrum is consistent with a power-law with a photon index of 1.38 ± 0.01, and the power spectrum shows band-limited noise with a total rms of $\sim$30%, suggesting that the source was in a typical LHS (Shaposhnikov et al. 2009; Muñoz-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 2010 February 11 (Brocksopp et al. 2010a, 2010b); however, the BH mass, inclination angle and the distance have not yet been determined.

Since 2009 August 3, 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). MAXI / GSC also observed a rapid spectral softening on 2010 January 22 due to a spectral transition from the LHS to the HSS (Negoro et al. 2010). The MAXI initial results are described in Matsuoka et al. (2010) and Ueno et al. (2010).

In this paper, we report on MAXI GSC observations of XTE J1752−223 during its outburst since 2009 October. In the observation and result section, we demonstrate MAXI's spectral performance for such a bright source. Finally, we discuss the origin of the rather unusual behavior of XTE J1752−223 in the light curve and spectral hardness.

2. Observations and Results

MAXI carries two scientific instruments: the GSC and the Solid State Camera (SSC). GSC consists of twelve one-dimensional position-sensitive proportional counters operated in the 2–20 keV range, while SSC is composed of 32 X-ray CCD cameras with an energy range of 0.5–12 keV. GSC observes two different directions (horizontal and zenithal direction) with an instantaneous field of view of 3° × 160°, each covered by six cameras. It covers 70% of the whole sky in every orbit 32 times per day at maximum. Both instruments have been working properly in orbit, but four out of the twelve GSC cameras have been turned off due to discharges in the proportional counters. See Matsuoka et al. (2009) for more details concerning MAXI. In this paper, we use only the GSC data, which offer a larger sky coverage and effective area than those of SSC.

Figure 1 shows two 1-month integrated X-ray sky images with a radius of 10° centered on XTE J1752−223 in the 2–20 keV band. These false-color images are produced by superposing red (2–4 keV), green (4–10 keV), and blue (10–20 keV) images. Data from all of the counters were combined, and two images were made for two separate periods (from 2009 December 20, to 2010 January 19, and 2010 January 20 to

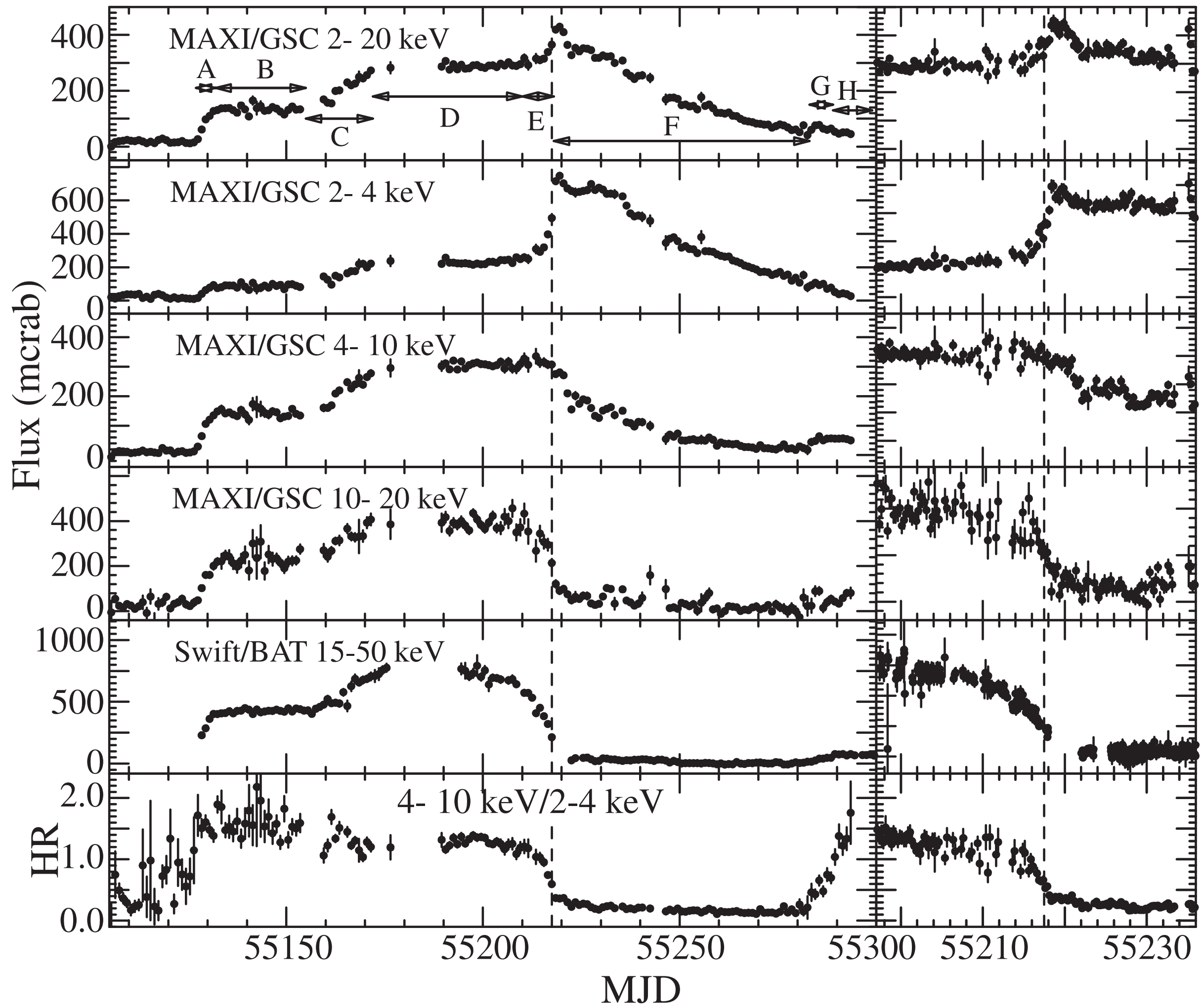

Fig. 2. MAXI light curve of XTE J1752−223 in four energy ranges (2–20, 2–4, 4–10, and 10–20 keV from the top to the fourth panel) in comparison with Swift / BAT (15–50 keV: the fifth panel). The hardness ratio between the 2–4 keV and the 4–10 keV bands is shown in the bottom panel. Right panel: The period in the left panel when the plasma ejection was detected (January 21 as shown by the dashed line) is expanded.

2010 February 28). XTE J1752−223 is clearly detected in both GSC images. Because of its location near the Galactic Center $(l, b) = (6.^\circ42, 2.^\circ11)$, many bright X-ray sources, such as GX 9+1, GX 5−1, and GX 3+1, are visible in this field. The point spread function (PSF) of the MAXI / GSC is estimated to be about $2.^\circ0$ (FWHM) in this energy range. The position of XTE J1752−223, determined by GSC, is consistent with the Swift / XRT localization.

We calculated the net source counts by subtracting the background from the on-source data. To avoid source contamination from the nearby bright sources GX 9+1 ($2.^\circ82$ away) and SAX J1748.9−2021 in the globular cluster NGC 6440 (Patruno et al. 2010; $2.^\circ13$ away), we carefully selected the source and background regions as circles of $1.^\circ17$ and $2.^\circ48$ radius, respectively (see figure 1). The extracted source counts were normalized by dividing by the total exposure (in units of $cm^2\,s$) obtained with a time integral of the collimator effective area. The Crab Nebula was analyzed in the same way, and the count rates of XTE J1752−223 were normallized by the Crab unit (1.30, 1.25, and 0.32 counts $cm^{-2}\,s^{-1}$ in the 2–4, 4–10, and 10–20 keV range). The thus-obtained 1-day averaged light curve of XTE J1752−223 is shown in figure 2. GSC scans were performed approximately 10 times per day. A data gap from December 7th to 23th was due to a solar avoidance limitation (the current solar protection is set at above 4° from the Sun).

The X-ray light curve shows the following notable features. There are two initial plateau phases that lasted for ~ 25 d and ~ 40 d, 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 rising phases A and C were about 5 d and 15 d, respectively. Another notable feature is an anti-correlated behavior around the peak. The 2–4 keV flux rapidly increased after 2010 January 20 (MJD: 55216), while fluxes in the other two bands and the Swift / BAT 15–50 keV

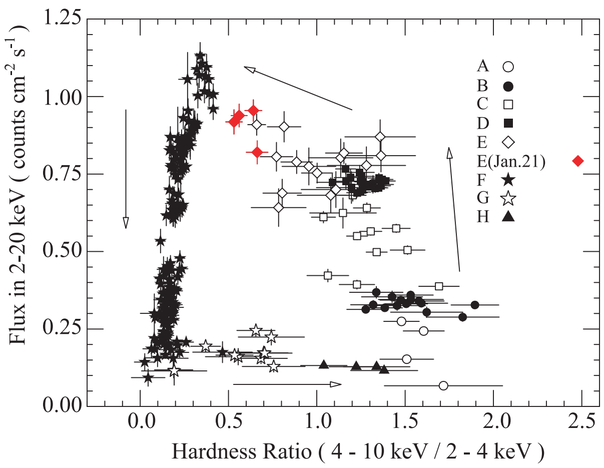

Fig. 3. Hardness–intensity diagram during the outburst of XTE J1752−223. Data points during the six phases (A to H) are shown by the different symbols; 6 hr of integrations were used in Phase E, F, and G, while one-day integrations were used for the other phases. The spectral evolution generally moves in the direction shown by the arrows. Filled diamonds show the data when increased radio emissions, presumably jets, were detected on 2010 January 21.

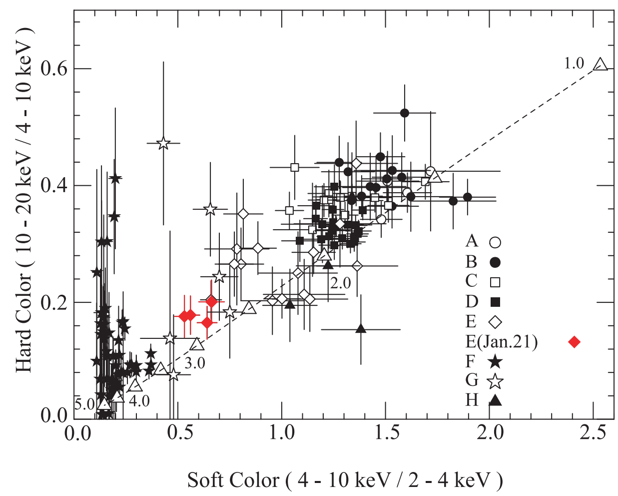

Fig. 4. Color–color diagram during the outburst of XTE J1752−223. The same symbols are used in figure 3. The dashed line represents the spectral shapes of an absorbed power-law with a photon index ranging from 1.0 to 5.0. The open triangles correspond to photon indices from 1.0 to 5.0 (0.5 step), from upper-right to lower-left.

flux decreased (Phase E for $\sim$9 d). 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$90 d for the source to complete the transition after the onset of an outburst. The 2–20 keV flux reached a peak on 2010 January 23 (MJD: 55219) at about the 430 mCrab level, and then gradually decreased (Phase F). The emissions during Phase F were dominated by the soft bands ($<$4 keV) (see also the lower panel of figure 1). Around March 28 (MJD: 55283), hard X-rays and the hardness ratio again increased (Phase G and H). The outburst had continued at the time of writing this paper (the end of 2010 May), and the current duration for the outburst is about 210 d.

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. A color–color diagram is also shown in figure 4. A line is plotted for a power-law spectral model with a photon index (Γ) ranging from 1.0 to 5.0 modified by the absorption (equivalent hydrogen column density $N_{\rm H} = 0.72 \times 10^{22}$ cm^{-2}; Muñoz-Darias et al. 2010). Note that the current GSC energy response gives systematic uncertainties of about 0.5×10^{22} cm^{-2} and 0.1 in $N_{\rm H}$ and Γ, respectively. As the outburst proceeds, the Γ continuously varies from $\sim$1.5 to $\sim$5.0. The spectral shapes during Phases B + D and F is approximated by a power-law with photon indices of 1.5–2.0 and above 3.5, respectively. These estimated photon indices are roughly consistent with typical values found from BHCs in the LHS (Phase B + D) and the HSS (Phase F). The power-law index in Phase E shows an intermediate value (2.0–3.0) between those seen in LHS and HSS. An RXTE-pointed observation carried out on 2010 January 19 (MJD: 55215) during Phase E shows that the source was at least in the IMS (Shaposhnikov 2010). Detailed spectral parameters and their evolution in this outburst will be reported in a forthcoming paper (K. Yamaoka et al. 2010, in preparation).

3. Discussions

We have presented the first results on the black-hole candidate XTE J1752−223 in the current outburst from the MAXI / GSC on ISS. Judging from the light curve and spectral hardness, we have found that the source was initially in the LHS with two long plateau phases (B and D). After a long stay ($\sim$90 d) in the LHS, it exhibited a spectral transition via the IMS (Phase E) into the HSS at around 2010 January 22 (Phase F). The source came back to the LHS at around 2010 April 3 (Phase H), and the source flux is gradually declining toward the quiescent state.

It should be noted that a relatively high level of radio emission was detected by the Australia Telescope Compact Array (ATCA) on 2010 January 21 (Brocksopp et al. 2010a), just corresponding to the beginning of the spectral transition from the LHS to the HSS. The GSC spectrum on this date is roughly represented by a power-law with a photon index of 2.5–3.0 (see figure 4), suggesting that the source was probably in the IMS. Later, two separate radio sources were identified with high-resolution imaging by the European VLBI Network (e-EVN) (Brocksopp et al. 2010b). If we interpret it as being plasma ejection, it is consistent with the scenario that large-scale jets are produced in association with the spectral transition from the LHS to the HSS. Another important result is that the luminosities during the transition from the HSS to the LHS, and from the LHS to the HSS were not the same: the hard-to-soft transition occurred at a 2–20 keV flux higher by a factor of about 7 than that at the soft-to-hard transition. Such hysteresis behavior was first noticed for GS 1124−68 and GX 339−4 (Miyamoto et al. 1995), and has been well established for many BHCs. This means that the spectral transition is not controlled by the mass-accretion rate alone, but depends on its history. Most of the BHCs show a rapid flux rise within a few days, which causes a near-instantaneous spectral transition (Gierliński & Newton 2006), and then their fluxes decay with an e-folding time of several ten days into quiescence (some BHCs show a secondary flare). It is known that the spectral state begins with the initial LHS, and then evolves through the VHS / IMS, HSS, and LHS during an outburst. However, about 8 BHCs, such as XTE J1118+480 and GRO J0422+32, remained in the LHS throughout their previous outbursts (Brocksopp et al. 2001). The very long duration of the initial LHS in XTE J1752−223 and the two long plateau phases are rather uncommon for the BHC outbursts. Meyer-Hofmeister (Meyer-Hofmeister 2004) points out that systems with short orbital periods, like XTE J1118+480 (4.1 hr) and GRO J0422+32 (5.1 hr), tend to have low peak luminosities in their outbursts (and hence do not show state transition) because smaller accretion disks have less accumulated matter. The long LHS observed in XTE J1752−223 might be related to a short orbital period. From our observations, however, XTE J1752−223 also resembles GX 339−4, which remained in the LHS for a long period before a transition into the HSS (McClintock & Remillard 2006). GX 339−4 has a relatively long orbital period (1.7 d) among BHCs categorized in low-mass X-ray binaries, indicating a larger accretion-disk size. In this case, the unusually long duration of the LHS before the state transition would result from a gradual change in the accretion rate. It is still unclear what causes the slow increase of the accretion rate, in contrast to other X-ray novae. Therefore, determining the orbital period of XTE J1752−223 should be important to clarify the nature of the long LHS period.

Let us explain the overall picture of the light curve of the XTE J1752−223 outburst. We never assume the generally accepted disk-truncation scenario in the LHS, though some other scenarios have been proposed for the LHS, e.g., Liu et al. 2007, where the innermost radius of the disk ($R_{\rm in}$) is basically determined by the balance between the accretion rate and the gas evaporation rate (Meyer et al. 2000; Liu et al. 2002; Done et al. 2007). In this scenario, the LHS is the state where the accretion disk is truncated at a larger radius than the Innermost Stable Circular Orbit (ISCO = 3 Schwarzschild radii for a non-rotating BH), due to a low accretion rate. As the accretion rate increases (then begins in an outer part of the accretion disk), $R_{\rm in}$ decreases. When the radius decreases, the corona around the disk cools down via efficient inverse Compton scattering of the soft disk photons, and exhibits softer X-ray spectra. Thus, the two phases in the LHS (B and D) can be interpreted with a slightly higher accretion rate in Phase D than that in Phase B. Furthermore, when the accretion rate eventually exceeds a critical rate required for the state transition, the gas evaporation will not be strong enough to truncate the disk. Thus, $R_{\rm in}$ reaches the ISCO, and intense thermal radiation from the accretion disk, i.e., an ultra-soft component, appears in soft X-rays (Phase F in the HSS). The disk truncation scenario does not predict any time evolution of $R_{\rm in}$ during the HSS. As can be seen in the light curve with a very smooth decay during the HSS, the local accretion rate smoothly decreases with time. When it falls below the critical rate again, the source comes back to the LHS (Phase H).

The significant increase mainly in the 2–4 keV band suggests that the disk innermost temperature ($kT_{\rm in}$) is relatively low. Preliminary fits of the MAXI / GSC data with the disk blackbody model (Mitsuda et al. 1984) during Phase F revealed that $kT_{\rm in}$ was 0.4–0.7 keV, including a systematic uncertainty of 0.1 keV. The Swift / XRT observation taken on 2010 February 4 also showed that the blackbody temperature is about 0.5 keV (Curran et al. 2010). This temperature is lower than those of other BHCs, such as GRO J1655−40 and XTE J1550−564, whose $kT_{\rm in}$ in the HSS exceeds 1 keV (Gierliński & Done 2004). The variation of $kT_{\rm in}$ is determined by how much the accretion rate exceeds the critical rate, and hence a low $kT_{\rm in}$ indicates that the accretion rate in the HSS is just above the critical rate. It is known that the spectral transition from the LHS to the HSS will occur at around 10%–20% Eddington luminosity, but with large uncertainties (Wu et al. 2010). The $kT_{\rm in}$ for the Schwarzschild BH can be estimated to be $\approx 1.2\,{\rm keV}\ (M/10\,M_{\odot})^{-1/4}(\eta/1.0)^{1/4}(h/1.7)$ (e.g., Makishima et al. 2000), where h is the spectral hardening factor (Shimura & Takahara 1995), η is the Eddington ratio ($L/L_{\rm E}$), and M is the mass of the central object. Assuming that the maximum $kT_{\rm in}$ is 0.6–0.7 keV and η is 0.1–0.2, the black-hole mass can be roughly estimated at 8.6–32 $M_{\odot}$. The GSC flux in the 2–10 keV range at the outburst peak (2010 January 23) was $9.7 \times 10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}$ with a $\sim 20\%$ absolute flux uncertainty. Assuming that (1) the 2–10 keV flux is 21%–28% of the bolometric flux based on the disk blackbody model, and that (2) the Eddington luminosity is $1.5 \times 10^{38}\ (M/M_{\odot})\,{\rm erg\,s^{-1}}$, the distance to the source can be estimated as being 5–10 kpc.

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[1] ⟨http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/⟩.

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