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XTE J1752-223: A broad band X-ray spectral investigation combined with timing studies

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We report on X-ray monitoring observations of the transient black hole candidate (BHC) XTE J1752-223 with the Rossi X-ray Timing Explorer (RXTE). The source was discovered on 2009 October 23 and during its low/hard state (LHS), which lasted for at least 25 days, all timing and spectral properties were similar to those of Cyg X-1 during its canonical hard state. The combined PCA/HEXTE spectra were well fitted by an absorbed broken power law with high energy cut off. When RXTE observations were resumed, after an observational gap due to solar constrains, the source was in the hard intermediate state (HIMS), showing type C QPOs. The source evolved through the soft intermediate state, characterized by a 5 – 10% rms variability and type B QPOs, into the high soft state. In the following it showed several transitions between these states. The combined PCA/HEXTE spectra were well fitted by an absorbed disk black body plus broken power law. After a further 59 days XTE J1752-223 passed through another HIMS at lower luminosity into the LHS. We discuss the different states, including a discussion of the variability diagram, and present the results of our combine spectral (PCA/HEXTE) and timing investigations. In addition, we will discuss the results of our spectral studies in which we combined RXTE and Swift data.

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1. Introduction

Black hole X-ray transients (BHTs) represent the majority of the black hole binary (BHB) population known so far. Most of the time BHTs stay in quiescence. Only during outburst BHTs show a characteristic evolution of their spectral and temporal properties. This led to the definition of different states: the outburst begins and ends in the so-called low/hard state (LHS), while in between it evolves to the high/soft state (HSS). Although this general behaviour is widely agreed on, the exact definition of the states and especially of the transition between these states are still under debate. In this work we follow the classification of [1] (see however [6] for an alternative classification and [7] for a comparison).

XTE J1752-223 was discovered by the Rossi X-ray timing explorer (RXTE) on 2009 October 23 [5] at a 2 to 10 keV flux of 30 mCrab. Showing significant similarities with the typical properties of a BHT during the low hard state (LHS) as well as detections of an optical and a radio counterpart triggered a daily monitoring by RXTE to follow up the outburst evolution. An overview paper, including spectral and time variability studies, based on RXTE Proportional Counter Array (PCA) data, was presented by [11]. A two day long RXTE observation taken in the early phase of the outburst was analysed by [8]. A study of combined PCA and High Energy X-ray Timing Experiment (HETXE) data was presented by [12]. For the results obtained from MAXI GSC and *Swift* see [10] and [2], respectively.

2. Observations and data analysis

We investigated 206 RXTE observations, including data obtained by the HEXTE (20 – 200 keV) on board RXTE, to present a comprehensive spectral-timing study of XTE J1752-223 [12]. The observations were taken between 2009 October 26 and 2010 July 3 and cover the whole outburst. In this paper we added Swift X-ray telescope (XRT) data where present to cover also the 0.5 to 5 keV range. Swift XRT observations were taken between 2009 October 25 and 2010 July 29. For about 1/4 of the RXTE observations there are Swift XRT observations available, which were taken within less than 24 hours either before or after the RXTE observation. We always correlated RXTE and Swift XRT observations which were located closest to each other in time.

For our timing analysis, we used PCA channels 0 – 35 (2 – 15 keV) only. The PCA Standard 2 mode (STD2; 129 channels covering the 2 – 60 keV range) was used for spectral analysis. Energy spectra were extracted from PCA and HEXTE data using the standard RXTE software within HEASOFT V. 6.9. From the PCA only Proportional Counter Unit 2 (PCU2) data were used. From HEXTE we used Cluster B data for observations taking before 2009 December 14. For later observations the “on source” spectrum was obtained from Cluster A, while the background spectrum was estimated using Cluster B data.[1] To account for residual uncertainties in the instrument calibration a systematic error of 0.6 and 1 per cent was added to the PCA and HEXTE data, respectively. Nevertheless there are still additional residuals in the HEXTE spectra obtained after 2009 December 14. We will address this point in more detail in Sect. 4.

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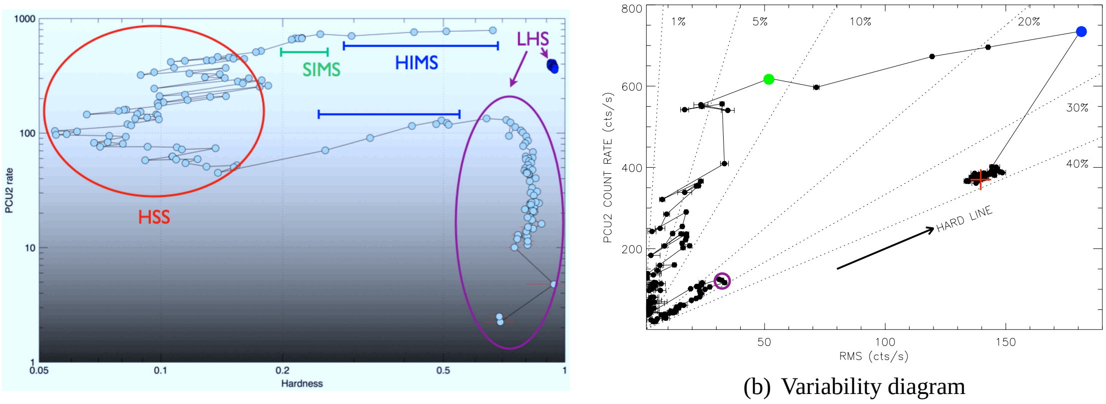
[1] This was necessary as Cluster B stopped “rocking” on 2009 December 14 and observes now in “off source” position only. Cluster A has been “staring” in “on source” position since 2006 October 20.



(a) Hardness intensity diagram

(b) Variability diagram

Figure 1: The hardness intensity diagram is shown in (a). The different states (following the classification of [1]) through which XTE J1752-223 evolves are indicated (see Sect. 5). The rms-intensity diagram (b) gives the PCU2 count rate depending on the total rms. The LHS is located close to the line indicating a fractional rms of 40%. The first observation is marked by a red cross. The onset of the HIMS is given by a blue dot, of the SIMS by a green dot. The onset of the LHS at lower luminosity is marked in violet.

The XRT data analysis and extraction of the spectra were done with the tools provided by the UK Swift Science Data Centre in Leicester [see 3]. All XRT observations were performed in window timing (WT) mode.

3. Timing investigations

Figure 1(a) shows the hardness intensity diagram (HID), which gives the PCU2 count rate depending on the hardness. XTE J1752-223 starts in the upper right corner (dark blue dots in Fig. 1(a)) and evolves in counter clockwise direction, describing the standard q-shaped pattern in the HID.

The rms-intensity diagram (RID), which gives the PCU2 count rate depending on the total rms, is shown in Fig. 1(b). It was introduced, based on GX 339-4 data, in [9]. This diagram allows to constrain different states without needing any spectral information. More information on the different states is given in Sect. 5.

4. Spectral investigations

We performed a broad-band spectral analysis by combining PCA (3 – 20 keV), HEXTE (20 – 200 keV), and – if available – *Swift*/XRT (0.5 – 5 keV) data. We ignored the 1.5 – 2.3 keV range in the XRT data, as it contained strong residuals, which are a known feature in WT mode observations that are affected by pile-up. The spectral fitting was done with ISIS V. 1.6.1 [4].

In a first step we fitted the PCA/HEXTE spectra, as described in [12], using an absorbed broken power law with a high energy cut-off. To account for the iron line at 6.4 keV a Gaussian centered at that energy was added. From day 2 onwards until day 68 an additional disc blackbody model was needed, representing the emission of the soft X-ray disc surrounding the black hole. The foreground absorption was fixed at $N_{\rm H}= 0.72\times10^{22}$ cm^{-2} [8].

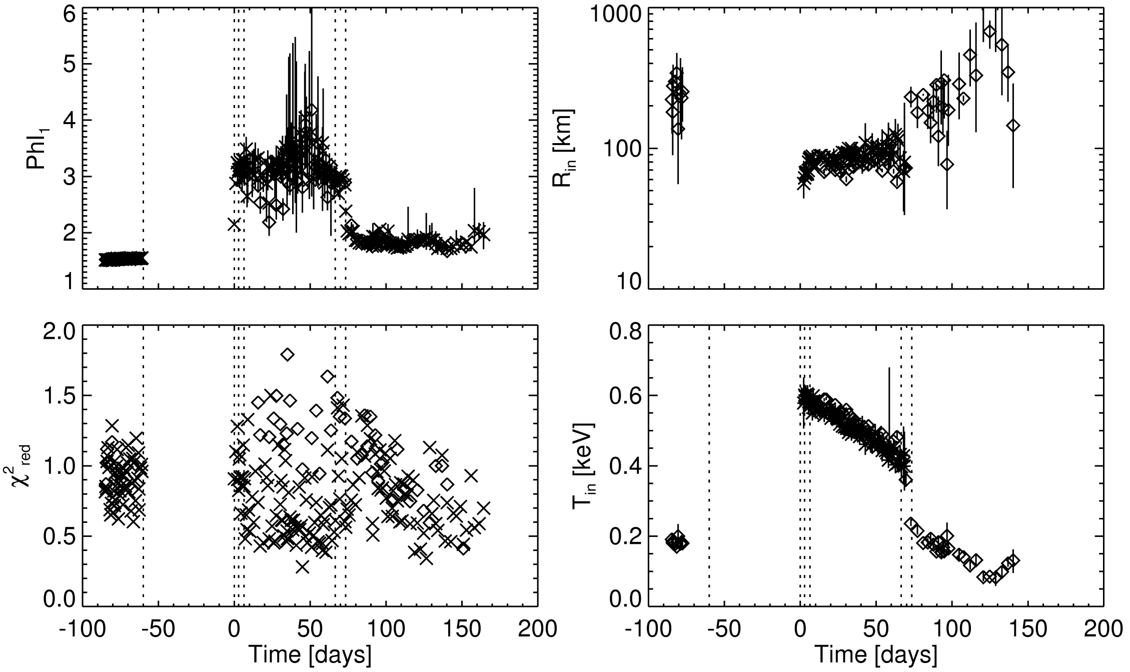


Figure 2: Temporal evolution of selected spectral parameters. Given are the evolution of reduced chi^2 (lower left panel), photon index below break energy (upper left panel), inner disk temperature (lower right panel), and inner disk radius (upper righty panel). Values obtained from PCA/HEXTE data are denoted by "X", those from XRT/PCA/HEXTE data by "$\Diamond$". The vertical dashed lines indicate times of (main) state transitions; from left to right: LHS, observation gap, HIMS, SIMS, HSS, HIMS, LHS (see also Sect.5). T= 0 corresponds to 2010-01-19 21:34:08.757 UTC; MJD 55215.8987.

As already mentioned in Sect. 2, all HEXTE observations taken after day 0 are affected by additional residuals, which are related to the fact that HEXTE detectors have stopped rocking. To take these residuals into account, we allowed the strength of the HEXTE background to be renormable (`corback` command in ISIS) and added three additional gaussians at the position of the strongest residuals (at ~63 keV, ~53 keV, and ~40 keV). Nevertheless, some spectral fits still yielded unacceptable high values of $\chi^2_{\rm red}$ or totally un-physical parameter values. For these observations, we decided to model the HEXTE background during fitting, using a sophisticated model that takes known residual lines into account.

The combined XRT/PCA/HEXTE spectra were fitted with the same model, but this time the disc blackbody component was always added and the foreground absorption was free.

The temporal evolution of $\chi^2_{\rm red}$ as well as of selected spectral parameters is given in Fig. 2. To derive the inner disc radius a distance of 3.5 kpc [11] and an inclination of 70° [8] were assumed. The behaviour of spectral parameters during different states is presented in Sect. 5.

5. The different states and their timing and spectral properties:

- For the first 29 days (dark blue dots in Fig. 1(a); about 50 observations) the count rate was rather constant. During this time the source was in the low/hard state (LHS), showing rms variability of ~40% (see Fig. 1(b), [8]). The spectral components are almost constant during this state (see also Fig. 2): fold energy (cut-off) ≈145 keV, break energy ≈10 keV, photon index below break (PhI_1) ≈1.53, photon index above break (PhI_2) ≈1.28, inner disc temperature (T_{in}) ≈0.18 keV, inner disc radius (R_{in}) ≈242 km, $N_{\mathrm{H}} \approx 0.77 \times 10^{22}$ cm^{-2}. Furthermore they are very similar to those of Cyg-X1 [8].

- After that XTE J1752-223 was not observable with RXTE for a further 60 days due to solar constrains. For *Swift* this gap was even longer (93 days).
- When the source was observed again with RXTE its count rate has increased and the source was in the hard intermediate state (HIMS). During this observation and the following two observations the source showed type C QPOs (quasi periodic oscillations) at 2.2 Hz, 4.1 Hz and 5.5 Hz, respectively, while the rms variability decreased from 25% to 18% (see Fig. 1(b)). The spectrum was softer than in the LHS, with $\mathrm{PhI}_1 \sim 2.8$ and $\mathrm{PhI}_2 \sim 2.0$. The high energy cut-off is no longer well constraint.
- XTE J1752-223 evolved further through the soft intermediate state (SIMS), showing type A/B QPOs, and an rms variability of less than 10%. In the following the source showed a main transition to the high/soft state (HSS) as well as several secondary transitions between the SIMS and HSS. A detailed discussion of these transitions will be given in a forthcoming paper. When the source was observed again with Swift R_{in} has reduced to ∼75 km and T_{in} increased to ∼0.6 keV. During the HSS R_{in} increased slightly, while T_{in} decreased continuously.
- After a further 59 days XTE J1752-223 passed through another HIMS at lower luminosity. During this transition T_{in} as well as PhI_1 decreased rapidly.
- Finally the source entered into the LHS again at lower luminosity. The spectral components are rather similar to those at the beginning of the outburst, apart from the fold energy, which cannot be well constraint. This is partly due to the source being fainter, but even more due to the large uncertainties in the HEXTE spectra.
- In total XTE J1752-223 was for more than about 300 days in outburst and evolved through all canonical BHCs states, before it fated into quiescence again.

Acknowledgments

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