RXTE Observations of New Black Hole Candidates XTE J1752–223 and MAXI J1659–152

– Timing and Spectral Evolution and BH Masses –

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Abstract

We report the most recent results of our analysis of X-ray monitoring of new Galactic Black Hole (BH) candidates XTE J1752–225 and MAXI J1659–152 performed by Rossi X-ray Timing Explorer (*RXTE*). We investigate various aspects of the RXTE data including energy and power spectra, variability energy distribution and phase lags between soft and hard energy bands. The sources generally show the spectral states and evolution expected from an accreting stellar mass BH. The energy distribution of different variability components show that the aperiodic noise has a spectrum consistently softer with respect to the total rms spectrum, while the spectrum of the quasi-periodic (QPO) features is harder. Particularly interesting behavior is observed in phase lags between variability in soft and hard energy bands. Namely, XTE J1753–223 shows that QPO in the hard band lags the QPO in the soft band. This is opposite to what was previously reported in other bright BH candidates and found in our analysis from MAXI J1659–152. We also report the results of BH mass estimations using the spectral-timing correlation scaling technique. Namely, we obtain the BH masses of 9.5±1.5 and 20±3 solar masses for XTE J1752–223 and MAXI J1659–152 correspondingly.

Key words: accretion—black hole physics—stars: individual — XTE J1752–223, MAXI J1659–152

1. Introduction

During 2009 and 2010 the *Rossi X-ray Timing Explorer (RXTE)* performed extensive monitoring campaigns on the newly discovered galactic black hole candidates XTE J1752–223 (Markwardt et al. 2009, J1752 hereafter) and MAXI J1659–152 (Negoro et al. 2010, J1659 hereafter). General evolution of the discovery outburst of J1752 is reported in Shaposhnikov et al. (2010). Here we present detailed analysis of J1752, including power spectra, variability energy distribution (rms spectra) and time lags. Synergy of these *RXTE* data products provides deep insight into unexplained phenomena related to accreting BHs such as aperiodic and quasi-periodic variability and non-thermal emission.

We also present the evolution of J1659 throughout the discovery outburst. We present the correlation of the spectral index with the frequency of quasi-periodic oscillations (QPO) for this source. The correlation pattern shows clear saturation of the index as the source moves along the transition from hard to soft state. In the framework of the Bulk Motion Comptonization (BMC) scenario this effect is interpreted as a signature of the converging inflow onto a BH horizon (see Shaposhnikov & Titarchuk, 2009, ST09 hereafter, and references therein). J1659 provides further evidence for ubiquity of the index saturation effect in BH candidates. In Shaposhnikov et al. (2010) we showed that the evolution of the variability distribution (rms spectra) during the state transition in J1752 can be explained by changing partial contributions of the thermal Comptonization and BMC in upscattering soft photons. Moreover, in Titarchuk & Shaposhnikov (2010) the behavior of the high energy cutoff observed in XTE J1550-564 was also explained within the BMC framework.

Correlations of the QPO frequency with spectral parameters provide a means to measure BH masses and to estimate source distances. In this Paper we summarize the results of the scaling method for J1752 and J1659. Our results indicate that the BH mass in J1659 may be the highest among the Galactic BH sources measured so far, i.e. about 20 solar masses. Given a possible binary period of 2.4 hours (Kuulkers et al. 2010), this system

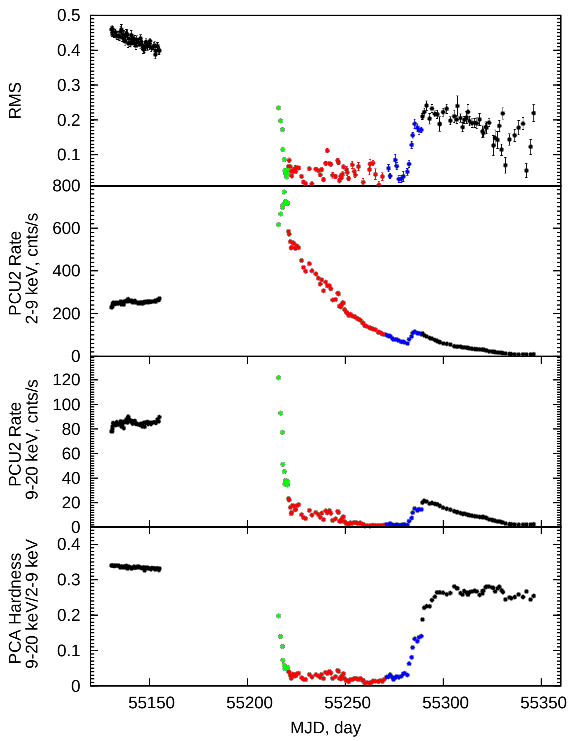

Fig. 1. J1752 outburst evolution. From top to bottom: Total rms variability (0.01-64.0 Hz) in the whole PCA range (i.e. no channel selection made), PCA lightcurves in 2-9 keV and 9-20 keV energy ranges and the spectral hardness versus time.

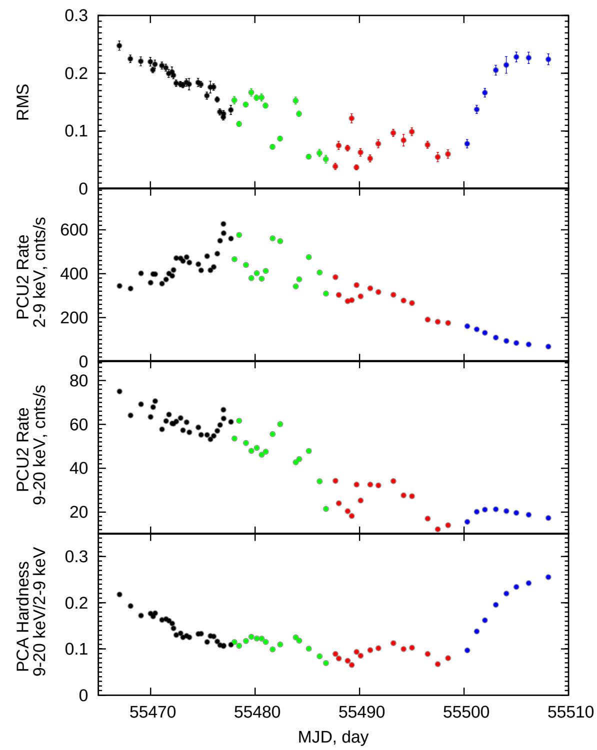

Fig. 2. The same as Figure 1 for J1659 outburst evolution.

may present a very exotic ultra-compact BH binary.

In the next section we briefly describe the discovery and the *RXTE* observations of J1752 and J1659. In Section 3 we present a general discussion of the spectral evolution of the outbursts. In the Section 4 we present a detailed analysis of the J1752 using the Fourier techniques, i.e. power spectra Fourier resolved (rms) spectra and time lags. In Section 5 we present the correlations between the QPO and the spectral parameters in J1659 and summarize the BH mass measurements using the correlation scaling method. Conclusions follow in Section 6.

2. Sources, Observations and Data Analysis

2.1. Discovery of J1752 and J1659

J1752 was discovered during the *RXTE*/PCA Galactic Bulge Scans performed on October 23, 2009 17:52 UT. The outburst lasted for about 8 months and exhibited a uniquely long rise low-hard state (LHS), transition to the high-soft state (HSS) and reverse transition to the decay LHS (see Shaposhnikov et al. (2010) for complete details).

Swift/BAT had triggered on an unidentified source on September 25, 2010 08:05:05 UT which was preliminary identified as Gamma-ray burst (Mangano et al. 2010). *MAXI* detection and observations provided correct identification as a Galactic X-ray transient (Negoro et al. 2010). *RXTE* pointed observations started on September 28, 2010 00:43 UT and revealed phenomenology consistent with the source being a new BH candidate (Kalamkar et al. 2010a).

2.2. Observations

RXTE have covered both outbursts with the intensive daily monitoring programs. During the first half of the outburst from J1659, a very frequent, 2-3 per day observation strategy was utilized revealing rich timing phenomenology. Unfortunately, the *RXTE* observations during both campaigns were not continuous due to the Sun observational constrains. Specifically, a significant part of the LHS and IS in J1752 were not observed beginning from MJD 55155 until MJD 55215. For the same reason, the latest part of the J1659 outburst starting from MJD 55508 was not covered by *RXTE* pointing observations. Fortunately, most of the soft-to-hard transition was observed, allowing study of the QPO evolution study and subsequent BH mass measurement (see Section 5). Individual observations used for analysis presented in Figures 3-6 are taken on the following dates: (J1752) 944044-01-01-00 on 2009-10-26 14:52 UT, 94331-01-06-00 on 2010-01-19 21:36 UT, 94331-01-06-01 on 2010-01-20 22:48 UT, 94331-01-06-02 on 2010-01-21 20:52 UT, 95360-01-01-00 on 2010-01-22 18:57 UT, 95360-01-01-02 on 2010-01-24 16:04 UT, (J1659) 95358-01-02-00 on 2010-09-28 00:43 UT and 95108-01-22-00 on 2010-10-10 03:36 UT.

2.3. Data analysis

First we perform a standard spectral analysis by extracting deadtime and background normalized PCA spectra using the Standard2 data mode, providing 16 sec time resolution spectra in 129 energy channels. For spectral analysis we utilized the data from PCU2 only. We fit the spectra in the 3-45 keV energy range in XSPEC (Arnaud 1996) with a Generic Comptonization model (XSPEC BMC model) modified by interstellar absorption and, in most cases of the rising phase LHS and IS observations, by a high energy cutoff component. Also, a gaussian at $\sim$ 6.4 keV with a width of 0.5-1.5 keV was added to account for possible contribution of the iron K_α emission line.

Next, to study the variability content of the source emission we calculate the Fourier Power Density Spectra (PDS) for all observation using high time resolution data modes in the whole PCA range. The PDSs were then integrated to get the total root-mean-square (rms) variability and fitted using a sum of Lorentzians to find QPO frequencies.

We also investigated the energy distribution of the variability power (rms spectra) in different frequency ranges using Fourier Resolved spectroscopy (Revnivtsev et al. 1999). We calculate the phase lags between different energy bands. Phase lags are calculated as an argument of a cross-spectrum between lightcurves in two different energy bands. For presentation, the phase lags shown throughout the manuscript are normalized to 2π, The time lags are obtained by dividing the phase lags by the frequency. A positive lag means that the harder variability lags that at softer energies.

3. Evolution

We present the evolution of J1752 and J1659 throughout the outbursts in Figures 1 and 2 respectively. The top panels show evolution of the fractional rms variability, source fluxes in energy ranges of 2-9 keV and 9-20 keV, inferred from our spectral model, and their ratio, commonly referred to as a hardness ratio. Data for the LHS and the HSS are plotted in black and red, while rise and decay IS are shown in green and blue correspondingly.

There are number of differences in the outburst behavior between J1752 and J1659. First, as it was already mentioned, the J1659 outburst was about 5 times shorter than the event form J1752. J1659 have not shown a long hard state. In fact, after 3 days after the discovery the source was already in the hard IS, showing a 1.6 Hz QPO. The state transition episodes in J1752 are dynamically much shorter than the LHS and HSS stages from the same source and faster than those observed in J1659. In fact, the IS episodes in J1659 seem to be a part of a gradual source evolution. Furthermore, the lowest hardness value achieved by J1659 (0.06$\sim$0.07, see the bottom panel in Fig. 2) is 10 times higher than that shown by J1752. In fact, the power law component during the second half of the HSS in J1752 became so weak that the spectrum could be considered completely thermal. In opposite, in J1659 the power law remained relatively strong throughout the entire event.

4. PDS, Rms Spectra and Time Lags

In this Section we focus on the variability properties of both sources during an initial hard-to-soft state transition. We present detailed analysis of different power spectral components including rms spectra and time lags. The main feature of PDS during state transition is the low frequency QPO with centroid frequency evolving from below 0.1 Hz to 10 Hz as a source moves from LHS to HSS. Usually, QPOs are observed on top of broadband variability which has a broken power law shape roughly constant at low frequencies (also known as flat-top noise or white red noise). The nature of these variability components is still in debate. It is essential to study all observational aspect of X-ray data to solve the puzzle of variability in BH sources.

In Figures 3, 4 and 5 we show three different type of *RXTE* data products based on Fourier analysis: PDS, rms spectra and times lags. Figures 3 and 4 show the results for six observations of J1752 covering the range of spectral states from the extreme LHS (panels A in Fig. 3) through the hard IS showing Type C QPOs (panels B,C and D) to the soft IS showing type B and A QPOs (Fig. 4). The first observation therefore belongs to the start of LHS (black points in Fig. 1), while the rest of the observations belong to the hard-to-soft IS (green data points in Fig. 1).

The following important observations can be made in regard to the evolution shown on the Figures 3 and 4. As the total variability drops from $\sim$ 50 % in the LHS to below 10 % at the end of IS (see Shaposhnikov et al. 2010) the rms spectra evolves from constant to decreasing with energy at the start of the IS to the increasing with energy during the soft IS (see Fig. 4). Rms spectra of the QPO are consistently harder than both the the total rms spectra and the rms spectra of the broad-band noise.

In the LHS hard time lags are associated with the ape-

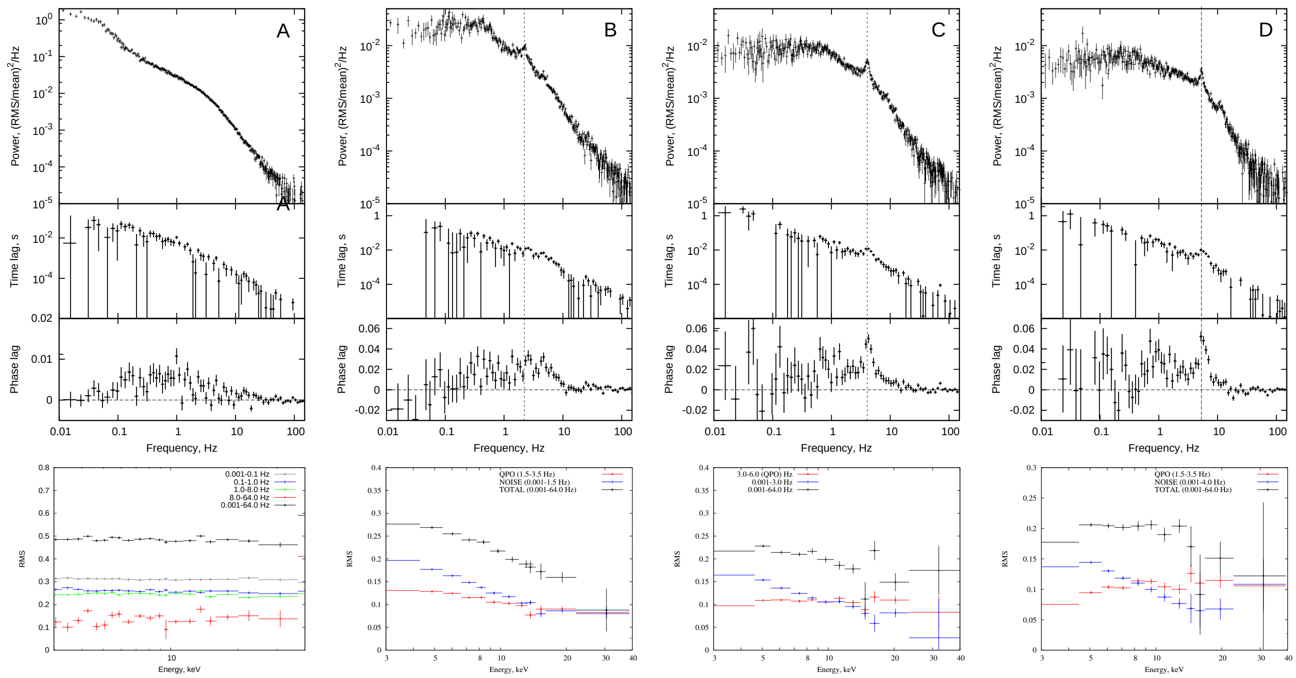

Fig. 3. Fourier analysis of four $RXTE$ data sets during the LHS and the IS in J1752. From left to right diagrams present analysis of the following $RXTE$ observations: 94044-07-01-00 (combined with -000 and -010 data subsets) , 94331-01-06-00, 94331-01-06-01 and 94331-01-06-02. The top diagrams show the power spectra, time and phase lags from top to bottom. The phase lags are calculated between the lightcurves corresponding to 1.5-5 keV and 10-12 keV energy ranges. The lower figures show the energy dependence of rms variability in frequency bands related to the aperiodic and QPO variability.

riodic variability (see Muñoz-Darias et al. 2010 for the detailed time lag analysis during extreme LHS in J1752), while the time lags during the transition in QPO have become more pronounced and stay positive throughout almost the entire transition episode. Only for the Type-A QPO observation (Fig. 4, right panels) the time lags become negative. This is opposite to what was observed in XTE J1859-226 (Casella et al. 2004) and XTE J1550-564 (Remillard et al. 1999) where the lags at the Type C QPO frequencies are negative for the most part of the transition. We note that in these observations QPO lags appear to be affected by the negative lags introduced by the broad band noise component. Therefore, it is not conclusive that the intrinsic lags in the QPO are negative and our analysis of J1752 data show clearly that at least in this source the Type C QPO time lags are positive. In Figure 5 we plot the maximum time lag observed near QPO versus its frequency. The decreasing trend in the time lag is apparent as the transition progresses. These observations can be qualitatively understood in terms of Comptonization process. Naturally, if QPO is a quasi-regular process in the Compton Corona, then the time lag is the delay the hard photon should experience with respect to the softer "seed" component as they up-scattered in the corona. As the corona collapses, as expected in a standard state transition scenario, the time delay should decrease (e.g. Nowak et al. 1999). In fact, observations of both QPO frequency increase and time delay decrease during state transition in J1752 are signatures of the collapsing corona.

The negative time lags in the 95360-01-01-02 observation can be related to a possible jet/outflow expected during this stage (Fender et al. 2009). As the Compton corona becomes compact, the jet/outlow provides means for the hard photons to be downscattered in energy and delayed with respect to the hard emission. While no major radio event during IS in J1752 is reported so far, the radio brightness of XTE J1859-226 and XTE J1550-564 during transitions analyzed by Casella et al. and Remillard et al (see Fender et al. and references therein for details on radio observations of the galactic BHCs) is consistent with negative hard lags being produced by the downscattering in a jet or outflow. Note the hard rms spectrum of the Type A QPO (right bottom panel in Fig. 4). Negative time lags indicate that the intrinsic spectrum of the matter involving in the QPO oscillations may be even harder.

Similarly to the analysis presented above for J1752, in Figure 6 we present the timing analysis of two observations of J1659. Hard lags seen in the first observation performed on Sept. 28, 2010 are similar to the J1752 observation 94331-01-06-00 (Panel B in Fig. 3). Time

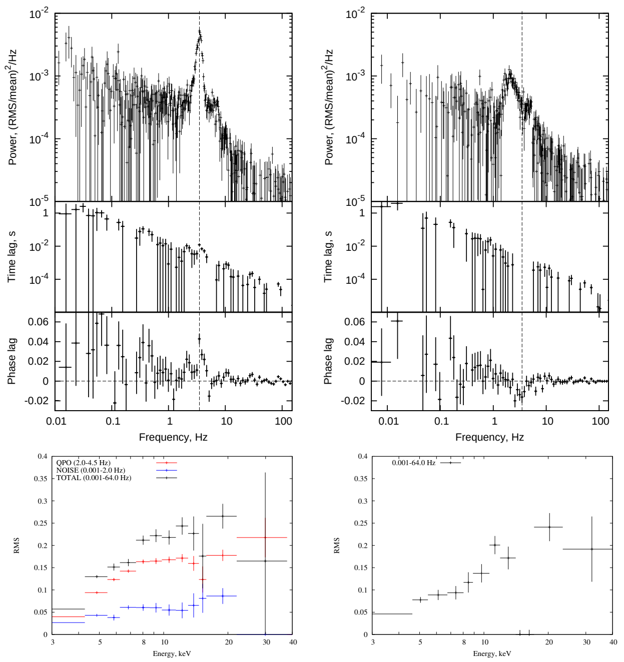

Fig. 4. Same as Figure 3 for J1752 observations 95360-01-01-00 (left panels) and 95360-01-01-02 (right panels) which belong to the soft IS episode.

lags are positive and follow approximately a power law distribution with frequency. There is no apparent contribution from the QPO at 1.7 Hz. The total rms spectra show variability increasing from 20 % at 3 keV to 25 % at 7 keV and then leveling off at higher energies. Separate rms spectra for the QPO and noise show different shapes. The QPO rms distribution increases towards 10 keV and then saturates, similar to the total rms. Oppositely, the noise rms spectrum shows a soft distribution at energies below 10 keV and then breaks to get harder above this energy. The second J1659 observation shown in Figure 6 was taken later on Oct. 10 and shows a Type C QPO at 6.3 Hz . Notably, the rms spectra are similar to that shown by the J1752 observation 95360-01-01-02 showing Type A QPO. The time lag associated with the QPO is clearly negative. The source behavior in radio wavelengths reported by van der Horst et al. (2010) agrees with the downscattering in the open jet scenario proposed above (however, one should keep in mind the radio quenching on Oct. 8) .

5. BH Masses in XTE J1752–223 and MAXI J1659–152

We use the mass determination method based on the scaling between spectral index and QPO frequency. Combined with the information on the spectrum normalization, the method also can constrain the distance to the source, albeit with some systematic uncertainty due to the unknown geometrical factor (see ST09). BH

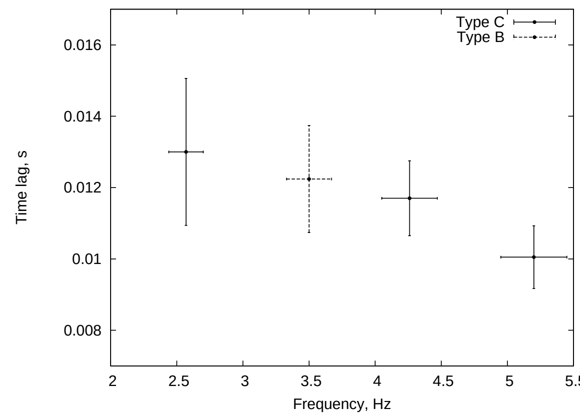

Fig. 5. The QPO time lag versus the QPO frequency. The time lag is decreasing as the QPO frequency increases. This is consistent with the lags being introduced by Comptonization in shrinking corona.

mass for J1752 of 9.5±1.0 $M_\odot$ obtained by scaling was reported by Shaposhnikov et al. 2010. Here we apply scaling to J1659. The QPO-index correlation observed during the initial hard-to-soft transition has saturated at the index of 2.3. We were unable to find a scalable reference pattern as all available rising transitions either have index saturation values exceeding 2.4 or level off below 2.2. We therefore use the decay data as the decay transitions are usually scalable. By scaling the correlations observed in J1659 during the outburst decay to the 2003 data from GX 339-4 we obtain scaling coefficients $s_\nu = \nu_{GX339-4}/\nu_{J1659} = 1.62 \pm 0.03$ and $s_N = N_{GX339-4}/N_{J1659} = 1.08 \pm 0.03$. Using the BH mass and distance of GX 339-4 of $M_{GX339-4}/M_\odot = 12.3 \pm 1.4$ and $d_{GX339-4} = 5.8 \pm 0.7$ kpc, obtained by ST09, we infer the parameters for J1659 as $M_{J1659}/M_\odot = 20 \pm 3$ and $d_{J1659} = 7.6 \pm 1.1$ kpc. Here we assumed the geometrical factor of unity. Due to the fact that dips were observed in J1659 by *Swift* (Kuulkers et al. 2010) J1659 is probably has a high inclination. Therefore the distance to J1659 given above should be considered an upper limit. The BH mass in J1659 presented above exclude any possibility other than the source being an astrophysical BH.

In Figure 8 we show the Index-QPO frequency correlation for the hard-to-soft transition in J1659. The correlation is marked by a clear index saturation for high frequency values. This effect is proposed as a signature of a BH, based on observation of a large set of galactic BH sources as well as theoretical arguments (ST09). The index saturation seen in J1659 is in fact one of the most pronounced among galactic BH candidates. Kalamkar et al. (2010b) classified J1659 as a BH candidate using an empirical argument based on the similarity with other BH sources. The index-QPO saturation in J1659 is physically motivated evidence that J1659 is, in fact, a

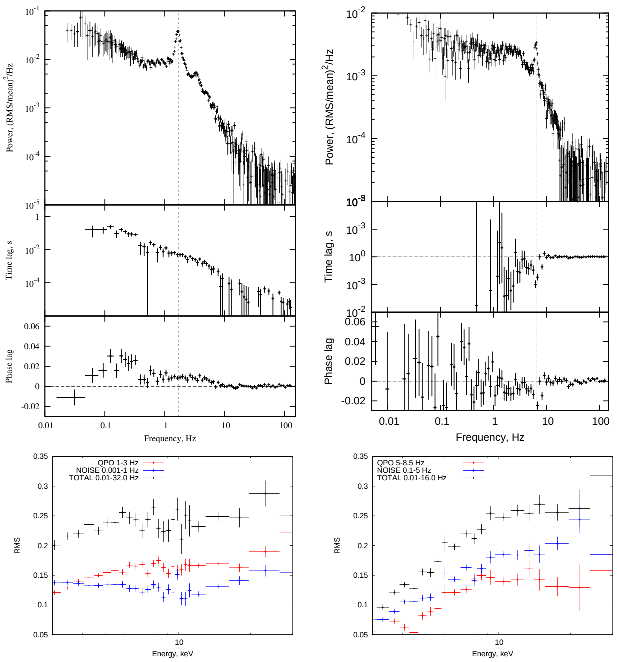

Fig. 6. Same as Figure 3 for J1659 observations 95358-01-02-00 (left panels, the first *RXTE* observation of the source) and 95108-01-22-00 (right panels) both taken when the source was in the hard IS state.

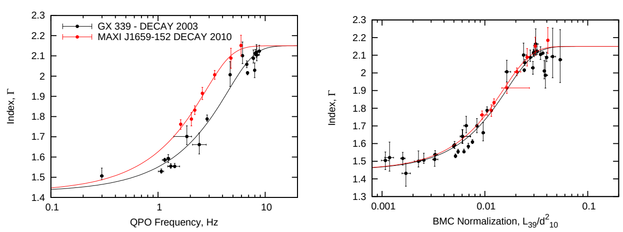

Fig. 7. BH mass determination in J1659 with scaling method. We use the GX 339-4 data for the decay stage of the 2003 outburst (see ST09). On the left: Index versus QPO frequency. On the right: index versus the BMC model normalization.

BH. The BH mass of 20 solar masses along with possible period of ∼2.5 hours makes J1659 the shortest period X-ray binary harboring the heaviest BH. If confirmed, these results may have strong implications to the evolutionary scenarios of binary stars (see e.g. de Mink, for the discussion of the role of rotational mixing in producing such a heavy and compact binaries).

6. Conclusions

We present detailed comprehensive analysis of *RXTE* data collected during the discovery outbursts from new galactic BH binaries XTE J1752–223 and MAXI J1659–152. We show that the hard time lags observed at the QPO frequency during the hard IS are related to delay during upscattering in Compton Corona, while negative lags observed later on, during the soft IS, may be explained by downscattering in a jet or outflow.

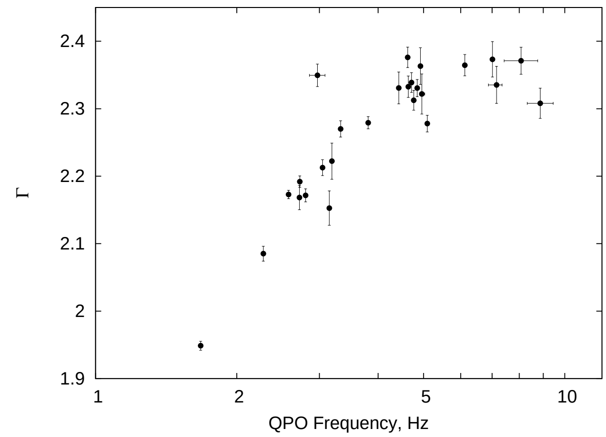

Fig. 8. The Index - QPO frequency correlations during the hard IS of J1659.

We also reportth BH mass determination in the two sources. While the BH in J1752 is close to the most other BHs with a mass of about 9.5 $M_{\odot}$, J1659 has BH mass of 20 $M_{\odot}$, making it the heaviest stellar mass BH in the Galaxy.

References

Arnaud, K.A., 1996,ASP Conf. Series volume 101, 17

Belloni, T. 2005, AIP Conference, 797, 197 (astro-ph/0504185)

Casella, P., Belloni, T., Homan, J., & Stella, L. 2004, A&A, 426, 587

de Mink, S. E., Cantiello, M., Langer, N., & Pols, O. R. 2010, AIP Conference Series, 1314, 291

Fender, R. P., Homan, J., & Belloni, T. M. 2009, MNRAS, 396, 1370

Jahoda, K., et al. 2006, ApJS, 163, 401

Kalamkar, M., et al. 2010a, ATel 2881

Kalamkar, M., et al. 2010b, astro-ph/1012.4330

Kuulkers, E., et al. 2010, Atel 2912

Mangano, V., et al. 2010 GCN #11296

Markwardt C.B., et al. 2009, Atel. 2258

Muñoz-Darias, T., et al. 2010, MNRAS, 404, L94

Negoro, H. et al. 2010, Atel. 2873

Nowak, M. A., et al. 1999, ApJ, 510, 874

Remillard, R. A., et al. 1999, ApJ, 517, L127

Remillard, R. A., McClintock, J. E. 2006, ARA&A, 44, 49

Revnivtsev, M., Gilfanov, M., & Churazov, E. 1999, A&A, 347, L23

Shaposhnikov, N., & Titarchuk, L. 2009, ApJ, 699, 453

Titarchuk, L., & Shaposhnikov, N. 2010, ApJ, 724, 2, 1147

van der Horst, A.J., et al. 2010, Atel 2918