ENERGY-DEPENDENT POWER SPECTRAL STATES AND ORIGIN OF APERIODIC VARIABILITY IN BLACK HOLE BINARIES

WENFEI YU AND WENDA ZHANG
Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences,
80 Nandan Road, Shanghai 200030, China; wenfei@shao.ac.cn
Received 2012 August 7; accepted 2013 April 23; published 2013 June 5

ABSTRACT
We found that the black hole candidate MAXI J1659−152 showed distinct power spectra, i.e., power-law noise (PLN) versus band-limited noise (BLN) plus quasi-periodic oscillations (QPOs) below and above about 2 keV, respectively, in observations with Swift and the Rossi X-ray Timing Explorer during the 2010 outburst, indicating a high energy cutoff of the PLN and a low energy cutoff of the BLN and QPOs around 2 keV. The emergence of the PLN and the fading of the BLN and QPOs initially took place below 2 keV when the source entered the hard intermediate state and settled in the soft state three weeks later. The evolution was accompanied by the emergence of the disk spectral component and decreases in the amplitudes of variability in the soft and hard X-ray bands. Our results indicate that the PLN is associated with an optically thick disk in both hard and intermediate states, and the power spectral state is independent of the X-ray energy spectral state in a broadband view. We suggest that in the hard or intermediate state, the BLN and QPOs emerge from the innermost hot flow subjected to Comptonization, while the PLN originates from the optically thick disk farther out. The energy cutoffs of the PLN and the BLN or QPOs then follow the temperature of the seed photons from the inner edge of the optically thick disk, while the high frequency cutoff of the PLN follows the orbital frequency of the inner edge of the optically thick disk as well.

Key word: X-rays: binaries
Online-only material: color figures

1. INTRODUCTION
Black hole binaries show well-defined correlated X-ray spectral and variability properties (Remillard & McClintock 2006). According to the observations in 2−60 keV with the Rossi X-ray Timing Explorer (RXTE); e.g., Homan et al. 2001; van der Klis 2006), distinct variability components are shown in the Fourier power spectra. In the soft state, the power spectrum is well described by a power-law noise (PLN) component, with a possible break at around 10 Hz; in the hard state, the power spectrum is dominated by one or more band-limited noise (BLN) components at low frequencies and occasionally has quasi-periodic oscillations (QPOs) at higher frequencies; in the intermediate state, usually seen between the hard state and the soft state in time sequence, the power spectrum is composed of BLN components and QPOs (Belloni et al. 2002), and possibly an additional weak PLN component at low frequency. The overall variability amplitude has been found to be strongly correlated with the fraction of the power-law spectral component (Miyamoto et al. 1994; Muñoz-Darias et al. 2011).

Recent studies show that most of the X-ray variability is associated with the power-law spectral component (van der Klis 2006), as shown by the increase of the fractional rms in relation to the photon energy for BLN components and QPOs (see, e.g., Sobolewska & Życki 2006). However, improved coverage of the soft X-rays down to below 0.5 keV revealed that the disk spectral component can still contribute a fractional rms of a few tens of percent in the hard state in the low frequency Lorentzian component on a timescale of tens of seconds (Wilkinson & Uttley 2009). Miyamoto et al. (1994) analyzed Ginga (≥2 keV) observations of the black hole candidate GS 1124−683. They concluded the evolving power spectra in the soft and intermediate states defined later were with a decomposition of the power spectrum into a BLN and a PLN component, which were attributed to the power-law and the disk blackbody spectral components, respectively. But such an additive picture does not hold when the power-law spectral component is larger than 10% of the total X-ray flux.

The soft-state power spectrum is usually dominated by a PLN component, which was suspected to be the signature of disk accretion (Miyamoto et al. 1994; Cui et al. 1997). Lyubarskii (1997) showed that the PLN can be modeled as an inward propagation of disk fluctuations. Since the PLN remains the same shape in a wide range of frequencies and the variations are thought to originate from the power-law spectral component in the soft state, the likely source responsible for the flux variations at all frequencies in this spectral state is the disk covered by the disk corona (Churazov et al. 2001). On the other hand, the BLN components and the QPOs have been seen only in the hard and intermediate states (or very high state) in which the non-thermal spectral component exists (see, e.g., Homan et al. 2001; Yu et al. 2003). The formation of these components is probably due to the transparency of the high frequency variations in the geometrically thick and optically thin disks, as suggested by Churazov et al. (2001). In summary, we lack direct evidence showing that the PLN in the hard or intermediate states comes from the optically thick disk and the decoupling of the timing components in the energy spectra.

MAXI J1659−152, discovered in 2010 by Swift (Kann 2010; Negoro et al. 2010), was initially triggered as a gamma-ray burst (Mangano et al. 2010). Its orbital period is around 2 hr based on its X-ray dips, which makes it the black hole binary with the shortest known orbital period (Kuulkers et al. 2010, 2013). X-ray timing and spectral analysis of the RXTE observations suggest that it is indeed a black hole binary candidate (Kalamkar et al. 2011). It reached 0.2−0.3 crab in the RXTE energy band. Based
on the relation between the peak luminosity of low-mass X-ray binary transient outbursts and the orbital period (Wu et al. 2010), the distance of MAXI J1659−152 should not be large.

A series of monitoring observations of MAXI J1659−152 were performed during the entire outburst period using the Swift X-Ray Telescope (XRT) and RXTE Proportional Counter Array (PCA; Kennea et al. 2011; Muñoz-Darias et al. 2011; Yamaoka et al. 2012; Kuulkers et al. 2013). The XRT power spectra were clearly energy dependent (Kennea et al. 2011). In this paper, we show that during the hard intermediate state, the power spectra corresponded to distinct black hole X-ray power spectral states below and above 2 keV. Furthermore, the emergence of the PLN and the decline of the BLN and the QPO components in the soft X-rays below 2 keV occurred at least several weeks before they were seen in the X-rays above 2 keV during the rising phase of the 2010 outburst. Our results provide strong evidence that the PLN in the hard and intermediate states is of disk origin and that the black hole power spectral state is dependent on the spectral component at which we are looking.

2. OBSERVATION AND DATA ANALYSIS

2.1. Swift XRT and UVOT Data Analysis

There were altogether more than 60 target-of-opportunity Swift observations of MAXI J1659−152 during its 2010 outburst (Kennea et al. 2011; Kuulkers et al. 2013). We focused on the first 38 observations taken in the “Windowed Time” (WT) mode with a frame time of 1.766 ms between MJD 55464 and MJD 55492, corresponding to observation IDs (ObsIDs) 0043492800 to 0031843008, which allows a comparison with the quasi-simultaneous RXTE/PCA observations (Kalamkar et al. 2011; Muñoz-Darias et al. 2011; Yamaoka et al. 2012).

Following the standard approach to eliminate a pile-up effect, we determined the inner radius of the source region by evaluating distributions of grade 0 and grade 0–2 events (see Appendix of Romano et al. 2006 and the pile-up thread1). Annuli with diameters of 20 to 40 pixels were used to evaluate the fraction unaffected by photon pile-up. We chose the smallest-allowed radius in pixels unaffected by pile-up as the inner radius of the source region in order to include as many events as possible. For example, the source region was chosen by excluding the innermost 7 pixels of the ObsID 00434928019.

Our Swift data reduction was performed with HEASOFT 6.11 using the sky coordinate reported in Kennea et al. (2010). Periodic soft X-ray dips were seen in XRT light curves due to absorbers in the disk (Kuulkers et al. 2010, 2013; Kennea et al. 2011), which brought additional low frequency variability. We removed events that lie within 1300 s of the (central) dip times to avoid the effect for even the longest known dips. The XRT spectral files were binned by grppha to ensure a minimum of 20 photons per energy bin. XRT timing analysis was performed with powspec in XRONOS version 5.22. We found that the Leahy normalized Fourier power decreases significantly above 50 Hz and deviates from the expected 2 for a Poisson noise, so we determined the white noise level by averaging the power between 30 Hz and 50 Hz.

2.2. RXTE/PCA Data Analysis

We analyzed the RXTE/PCA pointed observations in the same period. In our PCA spectral analysis, we made use of

\[ \Delta \chi^2 = 1 \]

for the model

\[ \text{powspec} \]

in XRONOS version 5.22. We found that the Leahy normalized Fourier power decreases significantly above 50 Hz and deviates from the expected 2 for a Poisson noise, so we determined the white noise level by averaging the power between 30 Hz and 50 Hz.

3. RESULTS

3.1. Evolution of the X-Ray Spectra and the Variability Amplitudes

Based on the RXTE observations (Muñoz-Darias et al. 2011), the source was in the hard state (before MJD 55467, not covered by the RXTE observations), the hard intermediate state (MJD 55467–55481), the soft intermediate state (MJD 55481–55483), and the soft state (MJD 55484–55490) during a period of nearly four weeks. In Figure 1, we plot the evolution of the spectral and timing properties during the rising phase of its outburst. In our XRT data analysis, we found that the fractional rms variability below 2 keV decreased from 23% to about 5%–8% around MJD 55467–55468, which was accompanied by an increase in the inner disk temperature to above 0.5 keV and in the disk fraction below 2 keV to above 30%. The PLN started to dominate in the energy band below 2 keV about three weeks earlier than in the entire energy band at around MJD 55490. Our analysis of the UVOT data shows that the UVW2 flux reached its peak right before MJD 55468 and then declined. The rise in the UV led the soft X-ray (2–4 keV) rise but lagged the hard X-ray (15–50 keV) rise, suggesting that the UV emission does not entirely belong to the power-law spectral component. The details of our study of the UVOT data are out of the scope of this paper and will be presented elsewhere.

3.2. Distinct Power Spectral States below and above 2 keV

We compared the power spectra in the 0.3–2 keV range seen with the Swift/XRT and in the 2–60 keV range seen with the RXTE/PCA (or in the 2–10 keV range of the XRT when the quasi-simultaneous PCA observations were not available). In order to see the trend clearly, we averaged the corresponding power spectra in nine intervals between MJD 55464–55490, thus determined by similarities of the power spectra. The scheme is shown in the lowest panel of Figure 1. The evolution of the power spectra is shown in Figures 2 and 3, corresponding to the energy ranges 0.3–2.0 keV and 2.0–60.0 keV, respectively.

All of the white-noise-subtracted power spectra were fit with models composed of PLN, zero-centered Lorentzians for BLN components, and Lorentzians for QPOs. The uncertainties of the parameters correspond to $\delta \chi^2 = 1$. In sequence, the power spectra in the energy range 0.3–2.0 keV show a distinct transition from a characteristic hard-state power spectrum dominated

1 http://www.swift.ac.uk/analysis/xrt/pileup.php
The Astrophysical Journal, 770:135 (6pp), 2013 June 20
Yu & Zhang

Figure 1. Evolution of the X-ray intensity as seen with MAXI (2–4 keV) and the BAT (15–50 keV), the disk energy flux fraction in 0.3–2.0 keV and 2.0–10.0 keV, the inner disk temperature and the power-law photon index measured with the XRT (or joint with the RXTE) observations, the fractional rms amplitudes in the 0.3–2.0 keV or the 2.0–60 keV band (integrated in 0.01–20 Hz), and the frequency of the primary QPO. Note that the fractional rms variability declined much faster in 0.3–2.0 keV than in 2.0–60 keV when the disk blackbody temperature increased to above 0.5 keV. We found that the PLN started to dominate the power spectra in the 0.3–2.0 keV band when the disk spectral component increased to above \( \sim 30\% \) (intervals 5 and 6) or \( \sim 50\% \) in 2.0–60 keV (interval 9). In fact, the disk flux fraction in 0.3–2.0 keV should be underestimated since there should be a low energy cutoff of the power-law spectral component to mimic the Comptonization.

(A color version of this figure is available in the online journal.)

Figure 2. Evolution of the average power spectra during the nine time intervals in 0.3–2.0 keV as seen with the Swift/XRT. PLN dominated in interval 5 (see Figure 5(a)).

by BLN and QPOs (see Figure 2, panel 4a XRT) to a characteristic soft-state power spectra showing only PLN at around MJD 55467 (see Figure 2, panel 5a XRT). Note that the transition occurred when the disk blackbody temperature increased from about 0.3 keV to above 0.5 keV.

Two phenomena were seen at that point. One was the disk fraction exceeding \( \sim 30\% \) in the 0.3–2.0 keV range (the actual disk fraction should be higher because the power-law model should have a low energy cutoff to mimic Comptonization). The PLN became insignificant at energies somewhere above 2 keV. In one observation around MJD 55467–55468 (ObsID 00434928005), the PLN in the 0.3–2.0 keV range was about five times larger than that seen in the quasi-simultaneous RXTE/PCA observation (ObsID 95358-01-02-00) in 2–60 keV (Figure 4). In order to determine the energy at which the PLN cuts off, we obtained the power spectrum of the XRT data in the 2–4 keV range. We found that if we use a model composed of the PLN and several Lorentzians for the BLN and QPO components, which were fixed at the frequencies of the BLN and QPO components seen in the 2–60 keV PCA data, the best-fit model gives the amplitude of the 2–4 keV PLN (although itself has only a 1\( \sigma \) significance) as 30% lower than the amplitude of the PLN in the 0.3–2.0 keV range (Figure 5). Therefore, the PLN component should have a high energy cutoff at around 2–4 keV. How high can the energy cutoff of the PLN be? We could only place a 1\( \sigma \) upper limit on the PLN in 2.0–4.0 keV, which is weaker than that measured in 0.3–2.0 keV but is still considered to be comparable to the 10% level (0.01–20 Hz range) in the 0.3–2.0 keV band. We found that the average XRT photon energy in the 0.3–2.0 keV and the 2.0–4.0 keV XRT bands were 1.3 keV and 2.8 keV, respectively. Both energies are in the energy range of the disk blackbody spectral component with significant contribution to the energy spectrum. The XRT observation therefore put the PLN cutoff energy to roughly 2.8 keV.
The RXTE/PCA observation puts an additional constraint on the PLN cutoff energy. We found that the 2–60 keV RXTE/PCA observation showed a PLN of about five times lower than that seen in the 0.3–2.0 keV with the Swift/XRT. Based on our study of the XRT power spectra in the two energy bands 0.3–2.0 keV and 2.0–4.0 keV, it is likely that only some low energy photons contribute to the PLN (not all of the 2–60 keV photons). We can then estimate the high energy cutoff of the PLN based on the assumption that only part of the photons contribute to the PLN. We studied the PCA energy spectrum and found that 20% of the PCA photons were below 3.5 keV, 40% were below 4.7 keV, and 50% had energies less than 7.4 keV. Therefore, assuming the PLN energy spectrum is a step function (between 10% rms at low energies, as in 0.3–2.0 keV, and 0% rms above a cutoff energy), if only the photons below 3.5 keV contribute to the PLN at the same amplitude level as seen in 0.3–2.0 keV with the XRT, the overall amplitude of the PLN in the 2–60 keV PCA band would be five times lower than that seen in 0.3–2.0 keV, as we observed with the PCA. This will put a constraint on the PLN cutoff energy at 3.5 keV (note that the PCA energy resolution is poor so the cutoff energy should be approximate);
The Astrophysical Journal, 770:135 (6pp), 2013 June 20

Yu & Zhang

Figure 6. Distinct average power spectra below and above 2 keV seen simultaneously during MJD 55467–55474 (intervals 5 and 6). The power spectrum below 2 keV obtained with the Swift/XRT (in red) shows a single PLN component with a likely cutoff at about 1 Hz, while the corresponding power spectrum above 2 keV obtained with the RXTE/PCA (in blue) mainly consists of BLN and QPOs above 1 Hz. Solid lines represent the best-fit models, in which the power-law index of the PLN was allowed to vary between −0.8 and −1.2. The dashed lines represent BLN or QPO components as well as the power-law component for the average power spectrum above 2 keV obtained with the RXTE/PCA. Note that the QPO frequency evolved dramatically in the 6 day interval, which led to multiple peaks in the average power spectrum in the hard X-ray band. The best-fit PLN component in 2–60 keV (blue dashed line) has a much lower amplitude than that in the 0.3–2.0 keV range (red line). The simultaneous power spectra indicate a strong energy dependence of the PLN and the BLN or QPO components.

(A color version of this figure is available in the online journal.)

if the soft photons contribute to the PLN at half of the amplitude as in the 0.3–2.0 keV XRT band, the highest energy photon contribution to the PLN would reach 4.7 keV, but the cutoff energy should be lower than 3.5 keV (in this case 40% of the PCA photons with the lowest energies contribute to the PLN). This is a very conservative estimate since the PLN in 2–4 keV in the XRT probably has an amplitude comparable to that seen in 0.3–2.0 keV. At 4.7 keV in the XRT energy spectrum, we found that the disk blackbody component in a disk blackbody plus power-law model contributed 10% of the total photon counts, while at around 1.3 keV the disk blackbody component contributed 30% of the total photon counts. So the PLN energy spectrum does look more like a disk blackbody than a steep power law, with a high energy cutoff that is consistent with the disk spectral component.

The other phenomenon associated with the transition between intervals 4 and 5 is that the BLN and QPOs disappeared in the soft band 0.3–2.0 keV, indicating a low energy cutoff in the BLN and QPOs, while the power spectra in the energy range above 2.0 keV showed characteristic BLN and QPOs in the hard or the intermediate state up to MJD 55486 (Figure 3, panels 4b–8b XRT). We know that in interval 8 the source transited to the soft state for a while (Muñoz-Darias et al. 2011). Therefore, in the X-rays above 2 keV, the transition of the power spectrum to PLN took place nearly three weeks after it occurred in 0.3–2.0 keV.

We have also investigated the relative strength of the BLN and PLN in the soft X-ray band 0.3–2.0 keV. For the power spectrum in the soft band in each interval (5–9), we fixed the PLN slope to a power-law index of −1 and the width of the zero-centered Lorentzian to the width of the BLN component obtained with the simultaneous 2–60 keV RXTE power spectrum. The normalizations of the PLN and BLN were relaxed. We found that there was no need to include a BLN component in the fits, and therefore we can only put upper limits on potential BLN variability amplitudes in the 0.3–2.0 keV range. In the end, we found that the amplitude of the PLN was always more than two times the BLN upper limit, which ranged from 1.1% to 3.6%. The amplitude of the BLN components rose sharply above about 2 keV to more than 10% (intervals 5–7). This demonstrates that distinct power spectral states were seen in 0.3–2.0 keV and above 2.0 keV (2–60 keV PCA band), as shown in panels 5a and 6a of Figure 2 or panels 5b and 6b of Figure 3, indicating a transition of the power spectral state across the soft and hard bands around MJD 55470—the energy boundary that divides the X-ray spectrum into disk-dominated and power-law-dominated regimes. In Figure 6, we plot the average power spectra corresponding to intervals 5 and 6. It suggests a frequency cutoff of the PLN seen in the 0.3–2.0 keV energy range at around 1 Hz, overlapping with the frequencies of the BLN and the QPOs seen at above 2 keV in the PCA band. We found that the deficiency of the PLN power above 1 Hz has nothing to do with the subtraction of the white-noise level. Both the energy cutoffs (∼2–3.5 keV) of the PLN and BLN components and the possible frequency cutoff (∼1 Hz) of the PLN imply that the PLN and the BLN plus QPOs were almost separated in energy and in frequency during those observations.

4. CONCLUSION AND DISCUSSION

The relatively slow evolution of MAXI J1659–152 between the spectral and timing states provided us an opportunity to focus on how the spectral content of the timing components evolves in black hole transients. With the help of both Swift/XRT and RXTE/PCA, we were able to look at the energy dependence of the power spectra in much more detail. Although an energy–frequency two-dimensional spectral space was not mapped out by the observations, the observations provided an important picture of the energy dependence of the properties of black hole power-spectral states.

In the conventional picture of black hole spectral states, there is a tight correlation between the energy spectra and the power spectra shape (Homan et al. 2001; Remillard & McClintock 2006). This is incorrect when we extend the power spectral study to soft energies. We found that MAXI J1659–152 showed the PLN in the soft X-ray energy band to be dominated by the thermal spectral component when it transited from the hard state to the intermediate state, while at the same time displaying typical BLN and QPOs in the hard X-ray energy band dominated by the power-law spectral component. Therefore, we found distinct power spectral states, i.e., PLN versus BLN plus QPOs, coexisted below and above a certain cutoff energy estimated in the range 2–3.5 keV, suggesting that the conventional perception of black hole states is primarily a hard X-ray view based on the RXTE/PCA band, and a broadband or even a multi-wavelength view is needed to better understand black hole power-spectral states.

The simultaneous emergence of the PLN and the thermal disk spectral component from below 2 keV provides strong evidence that in the hard or intermediate state, the PLN is from the approaching disk flow. The disappearance of the BLN and QPOs and the decrease in the overall variability amplitude started in the soft X-ray band below 2 keV as well, which indicates that the photons responsible for the BLN and the QPOs emerged
from regions other than the optically thick disk. A reasonable interpretation is that the photons responsible for the BLN and the QPOs originated from the innermost disk flow, which were upscattered in the corona. This could naturally contribute to some hard lag at low frequencies in the black hole hard state, but may not be the major cause of the lag, which has been suggested to come from the propagation of the low frequency variability into the hot coronal flow (Uttley et al. 2011). The separation of the simultaneous PLN and BLN (or the QPOs) in energy and in frequency might be set up by the inner disk edge disrupted by the hot coronal flow. Comptonization of the soft seed photons originated from the inner edge of the optically thick disk. Because they were upscattered to higher energies, these photons did not contribute to the PLN seen in the soft X-rays, but did, contribute to the BLN and QPOs, leading to a high frequency cutoff of the PLN at the BLN or QPO frequencies. We might have seen such a cutoff at around 1 Hz where the BLN and the QPOs peaked (see Figure 6). The PLN in the intermediate state should evolve into the PLN seen in the soft state, which is probably accompanied by the formation of a disk corona which is needed to explain the energy spectrum in the soft state (Churazov et al. 2001).

In summary, MAXI J1659−152 has provided the best example of an isolation rather than a coupling among the power spectral components in the energy spectrum, which reveals clues to the origin of the aperiodic variability in black hole binaries. The observations provided the evidence that the PLN is of disk origin and the BLN and QPOs are of coronal origin, which has been known for years but has lacked direct evidence. Our work also suggests that there might be links in the characteristic frequency and in the (seed) photons between the PLN and the BLN (or QPOs). This is a very important topic to explore in the future since our current power spectral modeling is based on the superposition of noise components and QPOs on some mathematical forms (PLN and Lorentzians). Justifications of the mathematical forms for the noise and QPO components as well as the simple superposition method are necessary for physical modeling of the black hole power spectrum.

We thank the Swift operation team for scheduling the TOO observations and a large international team for requesting the TOO observations that we analyzed in this paper. We also thank the anonymous referee for useful suggestions, which helped to improve this work significantly. We acknowledge the use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. This work is supported by the National Basic Research Program of China (973 project 2009CB824800) and the National Natural Science Foundation of China (10833002, 11073043).

REFERENCES

Belloni, T. M., Psaltis, D., & van der Klis, M. 2002, ApJ, 572, 392
Churazov, E., Gilfanov, M., & Revnivtsev, M. 2001, MNRAS, 321, 759
Cui, W., Heindl, W. A., Rothschild, R. E., et al. 1997, ApJL, 474, L57
Homan, J., Wijnands, R., van der Klis, M., et al. 2001, ApJS, 132, 377
Kalamkar, M., Homan, J., Ahumirano, D., et al. 2011, ApJL, 731, L2
Kann, D. A. 2010, GCN, 11299, 1
Kennea, J. A., Krimm, H., Mangano, V., et al. 2010, ATel, 2877, 1
Kennea, J. A., Romano, P., Mangano, V., et al. 2011, ApJ, 736, 22
Kuulkers, E., Ibarra, A., Pollock, A., et al. 2010, ATel, 2912, 1
Kuulkers, E., Kouveliotou, C., Belloni, T., et al. 2013, A&A, 552, A32
Lyubarskii, Y. E. 1997, MNRAS, 292, 679
Mangano, V., Hoversten, E. A., Markwardt, C. B., et al. 2010, GCN, 11296, 1
Miyamoto, S., Kitamoto, S., Iga, S., Hayashida, K., & Terada, K. 1994, ApJ, 435, 398
Muñoz-Darias, T., Motta, S., Stiele, H., & Belloni, T. M. 2011, MNRAS, 415, 292
Negoro, H., Yamaoka, K., Nakahira, S., et al. 2010, ATel, 2873, 1
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Romano, P., Campana, S., Chincarini, G., et al. 2006, A&A, 456, 917
Sobolewska, M. A., & Zycki, P. T. 2006, MNRAS, 370, 405
Uttley, P., Wilkinson, T., Cassatella, P., et al. 2011, MNRAS, 414, L60
van der Klis, M. 2006, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 39
Wilkinson, T., & Uttley, P. 2009, MNRAS, 397, 666
Wu, Y. X., Yu, W., Li, T. P., Maccarone, T. J., & Li, X. D. 2010, ApJ, 718, 620
Yamaoka, K., Allured, R., Kaaret, P., et al. 2012, PASJ, 64, 32
Yu, W., Klein-Wolt, M., Fender, R., & van der Klis, M. 2003, ApJL, 589, L33