THE X-RAY PROPERTIES OF THE BLACK HOLE TRANSIENT MAXI J1659–152 IN QUIESCENCE

JEROEN HOMAN1, JOEL K. FRIDRIKSSON2, PETER G. JONKER3, DAVID M. RUSSELL4,5, ELENA GALLO6, ERIK KUULKERS7, NANDA REA8, AND DIEGO ALTAMIRANO2

1 Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Cambridge, MA 02139, USA; jeroen@space.mit.edu
2 Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands
3 SRON, Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
4 Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain
5 Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain
6 Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA
7 European Space Astronomy Centre (ESA/ESAC), Science Operations Department, E-2869 Villanueva de la Cañada (Madrid), Spain
8 Institute of Space Sciences (CSIC-IEEC), Campus UAB, Faculty of Science, Torre C5-parell, E-08193 Barcelona, Spain

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ABSTRACT

We present new Chandra X-ray observations of the transient black hole X-ray binary MAXI J1659–152 in quiescence. These observations were made more than one year after the end of the source’s 2010–2011 outburst. We detect the source at a 0.5–10 keV flux of 2 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}, which corresponds to a luminosity of \sim 1.2 \times 10^{31} \text{(d/6 kpc)}^{2} \text{ erg s}^{-1}. This level, while being the lowest at which the source has been detected, is within factors of \sim 2 of the levels seen at the end of the decay of the outburst and soon after a major reflare of the source. The quiescent luminosity of MAXI J1659–152, which is the shortest-orbital-period black hole X-ray binary (\sim 2.4 hr), is lower than that of neutron-star X-ray binaries with similar periods. However, it is higher than the quiescent luminosities found for black hole X-ray binaries with orbital periods \sim 2–4 times longer. This could imply that a minimum quiescent luminosity may exist for black hole X-ray binaries, around orbital periods of \sim 5–10 hr, as predicted by binary-evolution models for the mass transfer rate. Compared to the hard state, we see a clear softening of the power-law spectrum in quiescence, from an index of 1.55(4) to an index of 2.5(4). We constrain the luminosity range in which this softening starts to (0.18–6.2) \times 10^{-3} \text{(d/6 kpc)}^{2} (M/8 M_{\odot}) L_{\text{Edd}}, which is consistent with the ranges inferred for other sources.

Key words: accretion, accretion disks – X-rays: binaries – X-rays: individual (MAXI J1659-152)

Online-only material: color figure

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are systems in which a low-mass donor star transfers mass via Roche-lobe overflow onto a neutron star (NS) or black hole (BH). Many of the LMXBs are transient systems. These transients undergo occasional outbursts during which they typically reach peak luminosities of \textsim 10^{38} \text{ erg s}^{-1}. The soft X-ray luminosity of a quiescent source currently known reaches \textsim 10^{30} \text{ erg s}^{-1} (Chandra et al. 2001). This can clearly be seen in Figure 1. It is important to consider systems with the same \text{P}_{\text{orb}}; at a given \text{P}_{\text{orb}}, BH and NS LMXBs are assumed to have similar quiescent mass accretion rates (Menou et al. 1999). Expected mass transfer rates for quiescent BHs and NSs were calculated by Menou et al. (1999), and they showed that for quiescent LMXBs there should exist a minimum mass transfer rate that stems directly from the existence of a bifurcation orbital period, \text{P}_{\text{bif}}. Below this period the mass transfer is driven by gravitational wave radiation and above it, it is dominated by the nuclear evolution of the secondary star. Specifically, the mass transfer rate increases with decreasing orbital period below \text{P}_{\text{bif}}, while it increases with \text{P}_{\text{orb}} above \text{P}_{\text{bif}}. For a wide range of donor masses, the results of Menou et al. (1999) imply \text{P}_{\text{bif}} \sim 5–10 \text{ hr} for BHs and \text{P}_{\text{bif}} \sim 3–5 \text{ hr} for NSs.

The luminosity difference between quiescent BH and NS LMXBs has been interpreted as evidence for the presence of an event horizon in BH LMXBs (Garcia et al. 2001), although it may also be the result of jet-dominated states in quiescent BH LMXBs (Fender et al. 2003). Interestingly, the lowest-luminosity quiescent source currently known (\text{L}_{\text{X}} < 2.4 \times 10^{30} \text{ erg s}^{-1}) is an NS LMXB, 1H 1905+000 (Jonker et al. 2007). However, this source is likely an ultra-compact with an orbital period less than 80 minutes (Jonker et al. 2006), and therefore falls in a \text{P}_{\text{orb}} range (<4 hr) in which, until recently, no quiescent BH LMXBs had been observed.
Another result of the \textit{Chandra} and \textit{XMM-Newton} observations of quiescent LMXBs concerns the nature of the quiescent accretion flow in BH systems. The quiescent state of BH LMXBs has often been considered a low-luminosity extension of the so-called low-hard state. Indeed, in terms of radio/X-ray flux correlations, which likely trace the evolution of the accretion (in)flow and/or jet outflow, quiescent BH LMXBs appear to follow the main relation seen in the low-hard state (Gallo et al. 2006, 2012). However, recent observations suggest that in terms of X-ray spectral shape, considerable evolution occurs in the accretion flow as some sources approach quiescence (Corbel et al. 2006), with spectral power-law photon indices that are steeper ($\sim 2.2$–2.5) than those seen in the low-hard state ($\sim 1.5$). A recent study of the quiescent spectra of 10 BH LMXBs by Plotkin et al. (2013) suggests that, once these sources reach $L_\text{x} \sim 10^{-5}$, their spectra saturate at power-law indices of $\sim 2.08 \pm 0.07$. Based on their findings, Plotkin et al. (2013) argue that quiescence does not appear to represent a distinct spectral state separated from the low-hard state. Several mechanisms could be responsible for the observed steepening toward quiescence, such as, e.g., a non-linear dependence of mass accretion rate on the inner disk radius, as expected in the presence of outflows (see discussion in Corbel et al. 2006), changes in the properties of a Comptonizing corona (Tomsick et al. 2004; Sobolewska et al. 2011), or the jet’s cooling break shifting through the X-ray band (Plotkin et al. 2013).

In this paper, we present \textit{Chandra} observations of MAXI J1659–152, an X-ray transient that was discovered in 2010 September with the \textit{Swift} Burst Alert Telescope (Mangano et al. 2010). Although it was originally thought to be a gamma-ray burst, optical spectra obtained with the Very Large Telescope/X-shooter (de Ugarte Postigo et al. 2010) and X-ray observations with RXTE (Kalamarck et al. 2010) strongly suggested that MAXI J1659–152 is an LMXB with a BH primary. During an outburst in 2010/2011 that lasted more than nine months, the source was extensively observed with various X-ray (Kalamarck et al. 2011; Muñoz-Darias et al. 2011; Yamaoka et al. 2012), optical/near-infrared (Russell et al. 2010a; Kaur et al. 2012), and radio observatories (van der Horst et al. 2011; Miller-Jones et al. 2011; Paragi et al. 2013). These observations revealed that the source made several state transitions and showed behavior similar to that seen in many other transient BH LMXBs. The distance to MAXI J1659–152 has been estimated using various methods, with a most likely range of 4.5–8.5 kpc (Kennea et al. 2011; Kaur et al. 2012; Kong 2012; Kuulkers et al. 2013; Jonker et al. 2012). Following Jonker et al. (2012), we adopt a distance of 6 kpc in this paper.

\textit{XMM-Newton} and \textit{Swift} observations made during the rise and maximum of the outburst revealed the presence of dips in the X-ray light curves, from which an orbital period of 2.414 ± 0.005 hr was derived (Kuulkers et al. 2013; Kennea et al. 2011). This makes MAXI J1659–152 the BH LMXB with the shortest known orbital period. Such a short orbital period is of particular interest to one of the issues described earlier: the difference between NS and BH quiescent luminosities at low $P_{\text{orb}}$.

MAXI J1659–152 was already observed with \textit{Chandra} during the initial decay of its outburst, a subsequent three-month reflare, and soon after the source appeared to have reached quiescence. The results of these observations were reported by Jonker et al. (2012). They found the source in a quiescent state during most of their observations. The minimum quiescent luminosity of MAXI J1659–152 was determined from two observations taken shortly after the reflare; it falls at the high end of what is expected for its orbital period (assuming a distance of 6 kpc), although it is still fainter than quiescent NS LMXBs with similar $P_{\text{orb}}$ values. One explanation for this higher than expected luminosity could be that at the time of the last \textit{Chandra} observations the source still had not reached its minimum quiescent luminosity. The new \textit{Chandra} observations presented here were made about a year after the source had entered quiescence. They allow us to test whether the quiescent luminosity reported by Jonker et al. (2012) was close to a minimum luminosity, or if the source had declined even further. We also present a more detailed study of the spectral softening in MAXI J1659–152.

2. OBSERVATIONS AND DATA ANALYSIS

MAXI J1659–152 has been observed eight times with \textit{Chandra}. A log of the observations can be found in Table 1. All observations were made with the back-illuminated S3 CCD chip of the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The first six observations were already analyzed by Jonker et al. (2012). Two new observations, made in 2012 July, were added to the analysis presented in this work. Observations 6–8 were made in VFAINT mode, which allows for better background cleaning, while the others were made in FAINT mode. All observations were analyzed using CIAO 4.4, CALDB 4.5.5.1, and ACIS Extract version 2012nov1 (Broos et al. 2010). As a first step, the \texttt{chandra\_repro} script was run to reprocess the data from all the observations. The data were checked for episodes of enhanced background, but none were found. Images in the 0.5–7.0 keV band were extracted for each observation to search for extended emission. Further analysis was performed with the help of ACIS Extract.

Source spectra were extracted from near-circular polygon-shaped regions modeled on the \textit{Chandra} ACIS point-spread function (PSF). The source extraction regions had a PSF enclosed energy fraction of $\sim 0.97$ (for a photon energy of $\sim 1.5$ keV) and a radius of $\sim 1.9$, except for the extraction region for observation 4, which had an enclosed energy fraction of $\sim 0.98$ and a radius of $\sim 2.7$ (due to the higher count rate). For the background extraction regions, we used annuli centered around the source, with inner radii of $\sim 4\arcsec$ ($22\arcsec$ for observation 4) and outer radii of $24\arcsec$–$25\arcsec$ ($45\arcsec$ for observation 4). A circular region with a radius of $\sim 4\arcsec$ centered around the source to the northeast of MAXI J1659–152 (CXOU J165902.6–151518;
The raw data were smoothed using a Gaussian kernel with a 2-pixel radius. With the exception of the faint uncataloged source CXOU J165902.6–151518, no additional nearby sources were detected. The spectra were fitted in the 0.3–7 keV range with XSPEC 12.7.1 (Arnaud 1996). Given the low number of source counts, per spectrum (as low as 10), we used the C statistic (Cash 1979), modified to account for the subtraction of background counts, per spectrum. Following Jonker et al. (2012), all spectra (with the abundances set to wilm and the cross sections set to vern. Because of high count rates (see Table 1), for observation 4 we also added the pile-up model of Davis (2001).

The spectra were fitted with an absorbed power law (tbabs*pegpwrlw in XSPEC), with the abundances set to wilm and the cross sections set to vern. Because of high count rates (see Table 1), for observation 4 we also added the pile-up model of Davis (2001).

The spectra were fitted in the 0.3–7.0 keV range with XSPEC 12.7.1 (Arnaud 1996). Given the low number of source counts per spectrum (as low as 10), we used the C statistic (Cash 1979), modified to account for the subtraction of background counts, the so-called W statistic. The spectra were grouped to at least one photon per spectral bin. Following Jonker et al. (2012), all spectra (with the abundances set to wilm and the cross sections set to vern. Because of high count rates (see Table 1), for observation 4 we also added the pile-up model of Davis (2001).

The $N_H$ was first determined from fits to the spectrum of observation 4, which had the highest number of counts, and subsequently it was fixed in all spectral fits. We obtained a value of $0.33(2)\times10^{22}$ atoms cm$^{-2}$, which is somewhat higher than the value of $0.23\times10^{22}$ atoms cm$^{-2}$ used by Jonker et al. (2012; see also Kennea et al. 2011).

To put to our Chandra observations in the context of the full outburst decay, we also constructed a 0.3–10 keV light curve from archival Swift/XRT observations, using the online Swift/XRT data products generator (Evans et al. 2009). For our Chandra observations, corresponding Swift/XRT 0.3–10 keV count rates were calculated from our Chandra spectra, by simulating Swift/XRT spectra based on the best-fit model parameters and using Swift/XRT response files.

### 3. RESULTS

All the 0.5–7 keV band images were visually inspected for possible features close to MAXI J1659–152 that could be related to jet outflows, such as those detected in XTE J1550–564 (Corbel et al. 2003), H 1743–322 (Corbel et al. 2005), and possibly XTE J1752–223 (Ratti et al. 2012). None could be seen. We also created a combined image from seven of the eight observations to increase sensitivity; observation 4 was excluded from this because of the prominent read-out streak. The total exposure time for the resulting image, which is shown in Figure 2, is $\sim219$ ks. Again, no obvious jet-related structures could be identified.

Table 1 lists the results of our spectral fits. Since they had similar count rates, the spectra of observations 3 and 5–8 were fitted simultaneously with their power-law indices tied, as the power-law indices would otherwise be poorly constrained; the normalizations were left free to vary independently. The unabsorbed 0.5–10 keV fluxes measured during the two new Chandra observations (7 and 8) of MAXI J1659–152 are $1.7(9)\times10^{-15}$ erg s$^{-1}$ cm$^{-2}$ and $3.7(12)\times10^{-15}$ erg s$^{-1}$ cm$^{-2}$. Since observations 7 and 8 were taken only a few days apart, we also made a fit with the normalizations of the power-law component tied, which resulted in a flux of $2.8(8)\times10^{-15}$ erg s$^{-1}$ cm$^{-2}$. We find power-law indices between $1.5$ and $2.5$. There appears to be a correlation between the slope of the power law and the flux, as can be seen from Table 1 and Figure 3; the power law steepens as the flux decreases. A fit to the spectral index versus flux relation in Figure 3 with a constant index is significantly worse ($\chi^2$/dof = 14.1/3) than one with a power-law ($\chi^2$/dof = 1.00/2). We note that the power-law indices reported here are somewhat higher than the values reported in Jonker et al. (2012), although they are consistent at the 1σ level individually. This is likely the result of our much smaller source extraction regions ($\sim2''$ instead of 10'') and the higher $N_H$ value that we used in our fits.

9 http://www.swift.ac.uk/user_objects/
In Figure 4, we show the combined Swift and Chandra light curve of MAXI J1659–152. The Chandra data are shown in red. The dashed horizontal line shows the count rate level corresponding to the average flux in the last two Chandra observations. Around day 200, MAXI J1659–152 showed an initial decline toward quiescence. This decline was rapid, with an exponential decay time scale of 5.3 ± 0.3 days (fitted to the first three Chandra observations, plus the Swift observation near day 200). The best-fit exponential decay is shown as a gray diagonal line. The source had nearly reached the quiescent level at the time of the third Chandra observation. However, shortly thereafter it showed a nearly 90 day reflare (Yang & Wijmans 2011), during which the flux went up by a factor of ∼3000. The second decay was rapid as well; a fit to the two Swift data points before the fifth Chandra observation yields an exponential decay time scale of 4.8 ± 0.9 days, hence the e-folding times are consistent with being the same.

4. DISCUSSION

We have presented an analysis of Chandra observations of MAXI J1659–152. Two new observations were analyzed in addition to the earlier six presented in Jonker et al. (2012) and Plotkin et al. (2013). These 2 observations were made more than 320 days after the end of the reflare that was observed at the end of the outburst of MAXI J1659–152 (see Figure 4). While the flux of observations 7/8 is the lowest value observed in the quiescent state of MAXI J1659–152, it is consistent (within 1σ errors) with the value measured in observation 5, which was taken close to the end of the reflare. The flux of observation 6 was also within a factor of two of the flux seen in observations 7/8. The five lowest fluxes seen with Chandra (obs. 3, 5, 6, 7+8) all fall within a factor of ∼2.5 of each other. Combined with the fact that these fluxes were measured over a time span of ∼430 days, this suggests that this flux range (2.8(8)–7(3) × 10^{-15} erg s^{-1} cm^{-2}) represents a relatively stable (within a factor of ∼2.5) minimum quiescent flux for MAXI J1659–152.

The average flux of observations 7/8 translates into a 0.5–10 keV luminosity of 1.2(3) × 10^{31} (d/6 kpc)^2 erg s^{-1}, where the distance d is likely in the range 4.5–8.5 kpc (see Section 1). In Figure 1, we show the quiescent luminosities of NS (stars) and BH LMXBs (circles) as a function of P_{orb}. MAXI J1659–152 is shown as an open circle. As can be seen from this figure, there is a clear correlation between the quiescent luminosities of BH LMXBs and their P_{orb}, although there is substantial scatter. The quiescent luminosity of MAXI J1659–152 is relatively high compared to some of the systems in the P_{orb} range of 4.2–8.3 hr. This would still be true had we assumed a distance of 4.5 kpc, which would imply a luminosity of 6.8 × 10^{30} erg s^{-1}. As mentioned in Section 1, the mechanism that drives the mass accretion in quiescence is expected to switch from gravitational-wave losses to evolution of the secondary star around a P_{orb} of ∼5–10 hr in BH LMXBs, depending on the mass of the secondary (Menou et al. 1999). As a result, the lowest quiescent BH luminosities are expected to be found in systems with a P_{orb} around 5–10 hr. Based on the data presented in their paper, Gallo et al. (2008) already suggested that such a minimum may exist at a limiting luminosity of a few times 10^{30} erg s^{-1}. Although the number of systems with P_{orb} of a few hours is still very small, the relatively high quiescent luminosity of MAXI J1659–152, the shortest P_{orb} system, may be a further sign of the existence of a minimum quiescent luminosity for BH LMXBs, in a range consistent with that implied (P_{orb} ∼ 5–10 hr) by the work of Menou et al. (1999).

Additional support for the existence of a minimum quiescent luminosity for BH LMXBs may come from Swift J1357.2–0933, a very faint X-ray transient discovered in early 2011 (Krimm et al. 2011). This system likely contains a BH (Armas Padilla et al. 2013) and has a short orbital period of 2.8 hr (Corral-Santana et al. 2013). A Swift/XRT observation at the end of the outburst, when the source was returning to or had returned to quiescence, yielded an upper limit on the 0.5–10 keV luminosity of 2 × 10^{31} erg s^{-1} (Armas Padilla et al. 2013), for a distance of 1.5 kpc (Rau et al. 2011). Swift J1357.2–0933 is shown as the gray data point in Figure 1. This upper limit is close to the quiescent luminosity of MAXI J1659–152, and about a decade higher than one would expect based on extrapolating the general trend seen for BH systems above P_{orb} = 4 hr.

Figure 3 shows a steepening of the spectrum as the flux decreases. This has previously been seen in other sources (Corbel et al. 2006; Plotkin et al. 2013), but our observations of MAXI J1659–152 present one of the clearest examples of spectral softening as a source recedes into quiescence. Our Chandra observations of MAXI J1659–152 allow us to set constraints on the luminosity level at which this softening
starts. In observation 4, which showed the highest luminosity of our observations, the power-law index was found to be 1.55(4), which is consistent with the indices seen in the hard state at the end of the outburst of MAXI J1659–152 (Yamaoka et al. 2012). In the second brightest observation (nr.,1), the index was already significantly higher at 1.87(12). It is therefore likely that in MAXI J1659–152 the spectral softening started between 0.5–10 keV fluxes of $4.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (obs.,1) and $1.4 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ (obs.,4). This corresponds to fractional Eddington luminosities of $(0.18–6.2) \times 10^{-3} (d/6	ext{kpc})^2 (M/8 M_\odot)$. For XTE J1550–564 Corbel et al. (2006) report an average power-law index of 2.25(8) in the 0.5–10 keV flux range of $(7.94–10)^{-14}$ erg s$^{-1}$ cm$^{-2}$. For a distance of 4.38 kpc and a BH mass of 9.1 $M_\odot$ (Orosz et al. 2011), this implies that the softening in XTE J1550–564 must have started above a fractional Eddington luminosity of $\sim 1.8 \times 10^{-6}$. In H 1743–322 an index of 2.2(6) was measured by Corbel et al. (2006) at a 0.5–10 keV flux of $5.0(7) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. For a distance of 8.5 kpc (Steiner et al. 2012), this implies that the softening must have started above a fractional Eddington luminosity of $4.2 \times 10^{-6} (M/8 M_\odot)$. Combining Chandra data from 10 quiescent BHs (including the ones discussed above), Plotkin et al. (2013) find that softening is already ongoing around $3 \times 10^{-5} L_{\text{Edd}}$ and plateaus around $3 \times 10^{-6} L_{\text{Edd}}$, similar to the range we find for MAXI J1659–152.

There are also various reports of softening of X-ray spectra toward quiescence based on RXTE data (see, e.g., Tomsick et al. 2001; Wu & Gu 2008; Dincer et al. 2008; Russell et al. 2010b; Sobolewska et al. 2011). These authors report that softening already starts at luminosities of $\sim 10^{-2} L_{\text{Edd}}$, which is much higher than the luminosity range implied by MAXI J1659–152. However, in several of these works (Tomsick et al. 2001; Russell et al. 2010b; Sobolewska et al. 2011) the spectra were not corrected for Galactic ridge emission, which provides a natural explanation for the observed softening; the Galactic ridge emission can be fitted with a power law with an index of $\sim 2.14$ (Revnivtsev 2003), and an even higher index when an absorbed power law is used. Simulations that we performed suggest that a ridge contribution of as little as 5% can already result in detectable softening in a typical RXTE observation. In other works (Wu & Gu 2008; Dincer et al. 2008), attempts were made to correct the spectra for the Galactic ridge emission. We inspected Swift/XRT archival data of GRO J1655–40 (Homan et al. 2005), GX 339–4, and H 1743–322 (both this work), taken around the same time as the RXTE data, or covering the same luminosity range; these data show no evidence for spectral softening occurring around $10^{-2} L_{\text{Edd}}$. Moreover, at a few times $10^{-4} L_{\text{Edd}}$, Wu & Gu (2008) find a range of indices (with RXTE) that is substantially higher ($\sim 1.7–2.5$) than the average index found at a few times $10^{-5} L_{\text{Edd}}$ with Chandra ($\sim 1.7 \pm 0.1$; Plotkin et al. 2013). We therefore suspect that the reports of spectral softening based on RXTE data may not be reliable and they should therefore be regarded with some caution.

As mentioned in Section 1, the softening of spectra in quiescence can be explained by a variety of models. Quiescent spectra are generally not of sufficient quality for accurate spectral modeling (beyond a simple power law) and it is therefore difficult to test (and distinguish between) competing models for quiescent accretion flows. However, the observed softening (and its relation with luminosity) can possibly be used for this purpose. For example, Ball et al. (2001) showed that for convection-dominated accretion flows the softening in quiescence is expected to occur at luminosities below $\sim 10^{-7} L_{\text{Edd}}$, whereas our work shows that softening already starts at luminosities $\sim 20–600$ times higher.

The outburst light curve in Figure 4 shows that MAXI J1659–152 had almost reached quiescence around day $\sim 220$. However, a major reflare, during which the luminosity increased by a factor of $\sim 3000$, occurred soon after. While reflare (or secondary maxima) near the end of an outburst are not uncommon (see, e.g., Chen et al. 1993; Tomsick et al. 2004; Russell et al. 2012), the magnitude of this reflare appears to be unusually high. This may be partly due to fact that the secondary maximum is well separated from the main outburst by a brief period of near-quiescence, whereas in other systems it occurred during (the decay of) the main outburst phase. Given the short orbital period of the system, it is possible that the secondary had undergone substantial X-ray heating of its outer layers, possibly resulting in a temporary increase in the mass transfer rate (see, e.g., Augusteijn et al. 1993).

Finally, during its outburst, MAXI J1659–152 showed spectral and timing signatures (Kalamkar et al. 2011) that suggested that the source had crossed the so-called “jet line” (Fender et al. 2009) during its transition from the hard state to softer spectral states. Such crossings have been associated with major ejection events, which are observed in the radio, but also on occasion in X-rays. Although the outburst of MAXI J1659–152 has been monitored densely in radio, no radio flares were observed around the time at which MAXI J1659–152 crossed the jet line (Paragi et al. 2013). Our deep Chandra images of MAXI J1659–152 do not reveal any indications for a major ejection event in X-rays either.

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