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Variation of the inner disk radius during the onset of the 2010 outburst of MAXI J1659–152

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Abstract Low mass black hole binaries are generally transient sources and spend most of their time in the quiescent state. It is believed that the inner accretion flow in the quiescent state is in the form of advection dominated accretion flow and the cold outer accretion disk is truncated far away from the central black hole. During the onset of an outburst, the disk gradually extends towards the central black hole. However, the observational evidence for this general picture is indirect at best. Here we present the results of a study performed to understand the variation of the inner disk radius during the early phase of an outburst. We investigated the variation of the inner disk radius during the 2010 outburst of the black hole candidate MAXI J1659-152 using the method of simultaneous spectral fitting. We found that the inner edge of the disk is truncated at a large radius in the beginning of the outburst when the source was in the hard state. We found a systematic decrease in the inner disk radius as the outburst progressed. We also estimated an upper limit on the mass of the black hole to be $8.1 \pm 2.9\ M_{\odot}$ within the uncertainty of the distance and inclination angle.

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

1 INTRODUCTION

There are about 70 known black hole sources and candidates, and most of them are transient in nature. They occasionally switch to the outburst state and remain most of the time in the quiescent state. The transient nature of black hole binaries can be broadly explained by the hydrogen ionization instability taking place mainly in the cooler outer regions of the accretion disks (see Lasota 2001). Detailed study of these outbursts is important in order to understand the various processes in the vicinity of the black hole. High quality data available from recent missions have provided valuable insights in the overall understanding of outbursts from black hole binaries. However, there are still some key aspects, particularly regarding the nature of the inner accretion disk during the state transitions, which are far from being fully understood. In general, black hole binaries have shown different outburst profiles and durations. The recurrence time between the successive outbursts is also found to differ among transient black hole binaries with multiple outbursts. Despite all these differences, almost all black holes have been observed to follow a Q-shaped track in the hardness-intensity diagram (see Homan et al. 2001; Belloni 2004; Fender et al. 2009). Such diagrams for many black holes show that an outburst starts with the source in the hard state and as the outburst progresses, the source switches to the soft state via an intermediate state called HIMS (see Fender et al. 2009; Done et al. 2007). The source again reaches the hard state when it enters into the quiescence via another intermediate state generally known as SIMS.

Observed properties of the hard and the soft states can be broadly explained in terms of the accretion disk having different inner radii during the two states. According to the truncation model for accretion disk around black hole binaries, the inner disk extends close to the innermost stable circular orbit (ISCO) during the soft states. Thus observations of the soft state provide a good opportunity to measure the spin of the black hole. However, the inner disk radius is truncated at a larger Schwarzschild radius when the source is in the hard state (see Qiao & Liu 2009). Since an outburst starts with the source in the hard state, it is presumed that in the quiescent state too the disk is truncated with the inner accretion flow in the form of a radiatively inefficient advection dominated accretion flow (Narayan & Yi 1994). Thus it is expected that during the onset of the outburst itself, the disk gradually moves in. The observational evidence, showing the changes in the inner disk radii during the very early stages of the outburst, is the best way to verify this concept. Such observations of very early stages are difficult because the outburst can typically only be detected after its luminosity reaches a significant fraction of the peak luminosity. However, with the recent availability of sensitive all sky monitors, it is possible to detect the sources at early stages of the outburst. Even after the early detection of an outburst, rapid follow-up observations, particularly with focusing X-ray telescopes that have energy coverage below 1 keV, are necessary to investigate the accretion behavior during the early progress of the outburst. NASA's *Swift* GRB mission (Gehrels et al. 2004), with its rapid follow-up capability using the X-ray telescope (XRT), is also providing valuable observations for the early stages of X-ray binary outbursts. MAXI J1659–152 is one such black hole binary source which was extensively followed up by *Swift* after the early detection of its 2010 outburst by the MAXI experiment onboard the International Space Station (Matsuoka et al. 2009). In the present work, we have focused on the investigation of the inner disk radius using dense and low-energy coverage by *Swift*/XRT.

MAXI J1659−152 was detected both by *Swift*/BAT (Mangano et al. 2010) and MAXI (Negoro et al. 2010) when it entered its discovery outburst on 2010 September 25. The source remained in the outburst state for about one and a half months. Various properties of this source during the outburst have been extensively reported by Muñoz-Darias et al. (2011), Kennea et al. (2011), Kalamkar et al. (2011) and Yamaoka et al. (2012) using the observations with both *Swift* and *RXTE* missions. Muñoz-Darias et al. (2011) carried out a spectral and timing analysis using energy and power density spectra obtained from *RXTE*/PCA. They found the inner disk radius to be constant at about 40 km during the peak of the outburst with a possible decrease towards the later stages of the outburst, assuming an orbital inclination of 70°. Kennea et al. (2011) studied *Swift* observations of the source and found that the inner radius of the disk was decreasing as the outburst proceeded. Kennea et al. (2011) also suggested the inclination of the source to be in the range 60°–75° owing to the absence of eclipses and the presence of dips in the light curves.

Here we report our reanalysis of *Swift* observations of MAXI J1659–152 carried out using the method of simultaneous fitting of multiple observations while tying the geometry dependent parameters (such as black hole mass, binary inclination, distance, etc.) which are not expected to change across various observations (Rao & Vadawale 2012). This method is expected to provide a better estimate of the process dependent parameters such as disk radius, temperature and accretion rate because the uncertainty in the geometry dependent parameters is removed to a large extent. We find that the source was in the hard state during initial observations and the accretion disk was truncated at a large radius. We show that the inner disk radius systematically decreases as the outburst progresses and the spectrum becomes softer and ultimately it reaches the ISCO during the peak of the outburst. This is possibly the first observational confirmation of the general picture of black hole binary outburst evolution that demonstrates it starts in the hard state with a truncated accretion disk and then the disk radius gradually decreases to the ISCO.

Section 2 of this paper provides the details of the observations used and the data reduction steps followed in the present study. We have described details of the analysis and the results obtained from it in Section 3 which is followed by the discussion in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The 2010 outburst of MAXI J1659–152 was extensively recorded by *Swift*. A total of 39 observations with *Swift*/XRT are available from NASA's public archive HEASARC. All XRT observations are in windowed timing mode except an observation taken on MJD 55466 (ObsID 00434928004) which is in photon counting mode. For the present work we have analyzed data from 38 observations acquired by *Swift*/XRT taken in windowed timing mode. The basic data reduction was carried out using the task XRTPIPELINE with the standard filtering and screening criteria for all the observations using R.A. (=$16^{\rm h}59^{\rm m}01.679^{\rm s}$) and Dec (=$15^\circ 15' 28.54''$) positions, as determined from the UVOT images by Kennea et al. (2011). The first few observations are long pointed observations with multiple pointings. The spectra were generated from individual pointings for all of the observations resulting in a total of 80 spectra from 38 observations. The source and background spectra were extracted using a circular region with a 20 pixel radius. The count rate for a few observations is above 150 count $\rm s^{-1}$, suggesting that these might be affected by a moderate pile-up. However, the count rate is below 300 count $\rm s^{-1}$ for all the cases and hence the effect of pile-up can be removed by ignoring one brightest pixel from the extraction region as suggested by Romano et al. (2006). Hence, we re-extracted the source spectra for all these observations after removing the brightest pixel. The ancillary response files were generated using the task `XRTMKARF`, corrected for hot columns and bad pixels along with PSF correction. The RMF files, necessary to fit the spectrum in `XSPEC`, were from `CALDB` as obtained from the task `XRTMKARF`. The spectra were grouped to obtain a minimum of 20 counts in each bin. The XRT spectra were extracted covering an energy range of 0.7–9 keV. Also, the energy range of 1.7–2.5 keV was ignored in all XRT spectra because of the presence of large residuals in almost all the spectra.

3 SPECTRAL ANALYSIS AND RESULTS

The spectrum of a black hole binary broadly consists of two components: a multi-temperature accretion disk component and a Comptonized component of radiation coming from the corona. The disk component is typically fitted with a multi-temperature disk blackbody model `DISKBB`. The model, `DISKBB`, is an old model (Mitsuda et al. 1984; Makishima et al. 1986) that calculates the accretion disk spectrum by ignoring the zero-stress inner boundary condition. It has two parameters, viz. the temperature at the inner disk radius and the normalization, which represents a combination of the inner disk radius $R_{\rm in}$ and two geometry dependent parameters, orbital inclination and distance to the source. Thus, estimation of the inner disk radius using `DISKBB` requires an accurate knowledge of both the distance and orbital inclination, which are not generally available for newly discovered sources. `DISKPN` is an alternate model describing a multi-temperature disk (Gierliński et al. 1999). It calculates the disk spectrum by considering the pseudo-Newtonian potential, which provides a more accurate description of the gravitational potential in the vicinity of the black hole. An important aspect of `DISKPN`, particularly in the context of the present work, is that it considers the inner disk radius to be an independent parameter in the units of gravitational radius, $R_{\rm g}$. It should be noted that there are other, fully relativistic, and hence more accurate, disk models such as `KERRBB` available in `XSPEC`. However, such models always assume the accretion disk extends to the ISCO and thus cannot be used to model the spectrum of a truncated disk. Hence, we use `DISKPN` to model the multi-color accretion disk component in our spectral analysis. The normalization of `DISKPN` presents a combination of geometry dependent parameters (apart from the color correction factor, which is typically assumed to be 1.7 in literature). Utilizing this feature of `DISKPN`, we fit multiple spectra simultaneously while tying their normalization. This results in an independent estimate of the inner radius for each spectrum and a better constraint on the normalization. The second major constituent of the black hole binary spectrum, the Comptonized component, is typically fitted with a `POWERLAW` as an approximation. However, this results in an underestimation of the disk flux at lower energies because of the low energy divergence of `POWERLAW`. Therefore, we use an alternate model, `SIMPL`, which represents the Comptonization process more accurately (Steiner et al. 2009). Thus we fit all the spectra with the model `PHABS`⊗(`SIMPL`⊗`DISKPN`). As expected, the fitting of an individual spectrum results in a rather poor constraint on the parameters with a large range in the normalization. Simultaneous fitting of all 80 spectra is not practically possible. Therefore, we made 10 groups from the 80 spectra such that a group has 10 spectra. In order to have a link between groups, we kept the first two spectra of a group same as the last two spectra of the previous group. Each group was fitted with the same model with the normalization tied for all the spectra. In this way, a good constraint on `DISKPN` normalization could be found.

From the above fits, we obtained 10 values of `DISKPN` normalization (N) from the spectral fitting of 10 groups and the minimum and the maximum values of N were 2.33×10^{-3} and 3.26×10^{-2} respectively. The spectral fitting in groups was not able to calculate the error for a few groups. Therefore, the maximum and minimum values of N were frozen in the spectral fitting of individual spectra. We show the parameters (with error bars) obtained from the fitting of individual spectra with frozen normalization in Figure 1. We also show the parameters obtained from the groups in all the panels. We can see from the figure that the points obtained from the fitting of individual spectra and fitting in groups match very well. All the error bars correspond to a confidence range of 90%. The reduced χ^2 values for all the 80 spectra are below 1.26 in both cases when the `DISKPN` normalization in the individual spectra was frozen at the minimum and the maximum values obtained from simultaneous fitting of spectra in groups. The variation in energy flux of the source is shown in panel A. Panel C shows the variation of the inner disk radius in units of gravitational radius for the maximum and minimum values for normalization of `DISKPN`. It is clear from the figure that the inner disk radius is at a larger distance in the beginning and it gradually decreases with time towards the black hole. This is consistent with the result shown by Done & Zycki (1999) where they demonstrated that the disk was truncated at a few tens of Schwarzschild radii during the hard state of Cyg X-1. Zdziarski et al. (2004) also reported that the inner disk was observed to have a larger radius in the hard states than in the soft states for two outbursts of GX 339-4.

4 DISCUSSION

It is well known that a typical outburst of a black hole binary system undergoes different spectral states during its evolution. These spectral states are generally understood in terms of an interplay between the direct X-ray emission from the accretion disk and its reprocessing by the Compton cloud surrounding the inner region of the disk. In the soft state, the accretion disk is believed to extend to the ISCO and the overall spectrum is dominated by the disk component. In the hard state, the accretion disk is believed to be truncated well before ISCO and the overall spectrum is dominated by the Comptonized component. Our finding that the accretion disk is truncated at the beginning of the outburst and the inner disk radius gradually reduces as the outburst progresses is consistent with this general understanding of the outburst as well as the spectral states of black hole binaries. This confirmation of the general picture has become particularly important because recently there have been a few reports contradicting the general picture of hard states (Miller et al. 2012; Reis et al. 2012, 2010; Hiemstra et al. 2011), where the hard state spectrum is modeled using models dominated by the reflection component, thus implicitly assuming the presence of the disk close to the black hole. In fact, some reports (Miller et al. 2013) model the spectrum with the power law and reflection component and completely ignoring the disk component, which would be physically inappropriate. Thus our present results reinforce the general understanding that the accretion disk is truncated in the hard state. The exact values of the inner disk radius corresponding to the minimum and the maximum

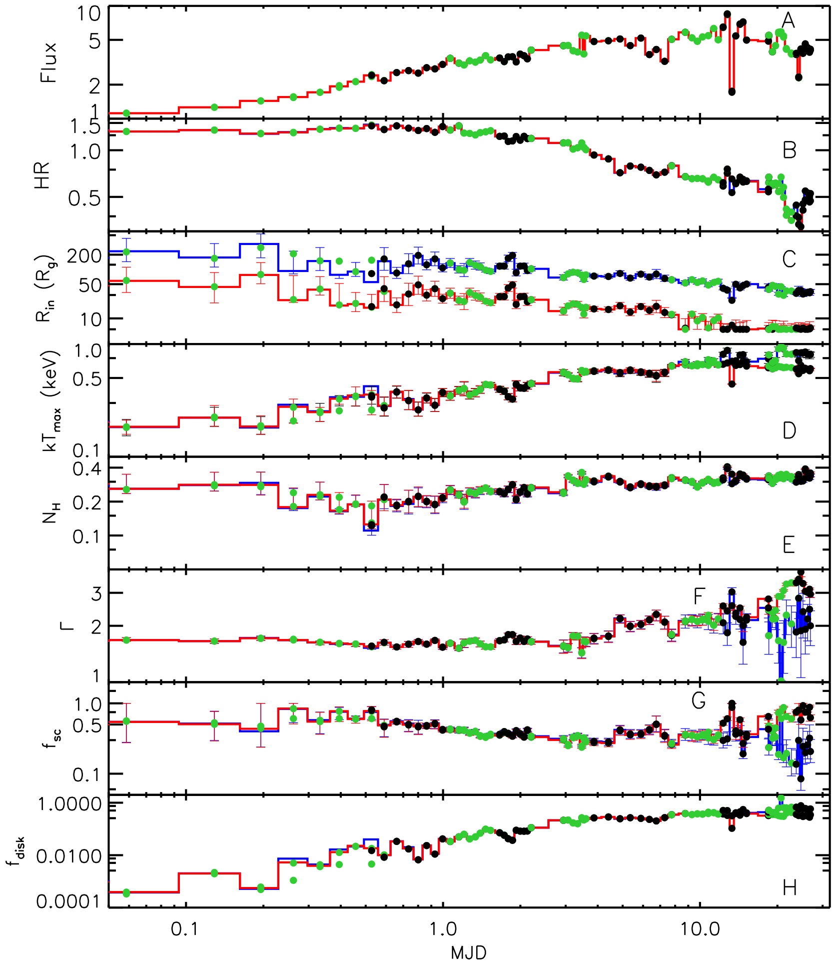

Fig. 1 A multi-panel plot showing the variation of the parameters with time, where MJD 55464.4 is taken as a reference. Red and blue solid lines correspond to the parameters obtained by freezing the normalization of `DISKPN` to its maximum and minimum values respectively. The parameters obtained from the fitting in groups have been overplotted with filled circles. Green and black circles have been used alternatively to differentiate parameters used for neighboring groups. See text for details.

`DISKPN` normalization differ as expected. Therefore, the inner disk radius for the minimum and maximum normalization is shown in separate panels in Figure 2. It is clear from Figure 2 that the inner disk radius decreases in both cases where the minimum and maximum `DISKPN` normalizations are applied. Since the values corresponding to the maximum `DISKPN` normalization are smaller, the inner disk radius reaches the minimum value of $6R_{\rm g}$ as allowed by the model `DISKPN`, towards the later stages of the outburst as shown in the plot. Since the model `DISKPN` uses the Schwarzschild metric, it does not allow the $R_{\rm in}$ to go below $6R_{\rm g}$. The dotted horizontal line in panel B of Figure 2 and the case shown in panel C of Figure 1 correspond to the inner disk radius of $6R_{\rm g}$.

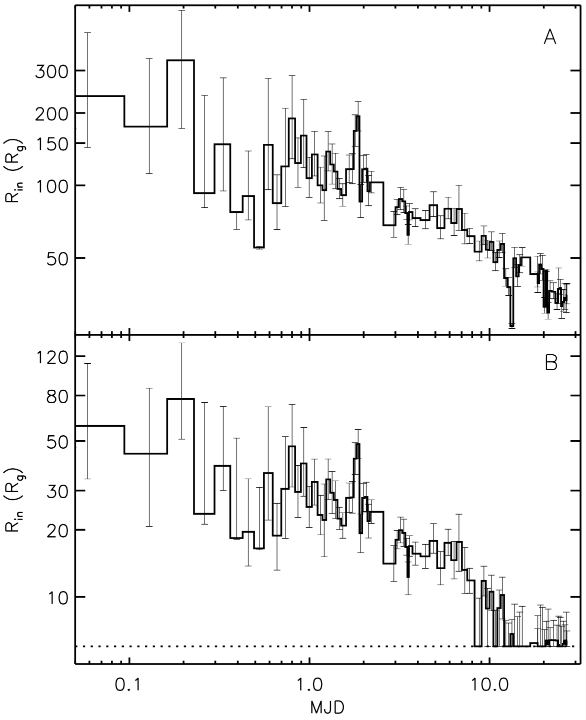

Fig. 2 The figure shows the variation of the inner disk radius, $R_{\rm in}$, with time in units of $R_{\rm g}$. MJD 55464.4 is taken as a reference. Panels A and B show the plots corresponding to the minimum and the maximum `DISKPN` normalization respectively. A dotted horizontal line at $6R_{\rm g}$ is drawn in panel B which is the minimum value allowed by the model `DISKPN`.

Panel A in Figure 1 gives absorbed total energy flux in units of 10^{-9} erg s^{-1} cm^{-2}. Panel B shows hardness ratio, HR, defined as the ratio of energy flux in the energy range 5–12 keV to the energy flux in 2–5 keV. Panels C and D in Figure 1 show the variation of the inner disk radius $R_{\rm in}$ and the maximum temperature $kT_{\rm max}$ respectively. It is clear from the plot that the maximum temperature of the blackbody component of radiation from the accretion disk was low at the beginning of the outburst and the inner edge of the disk was relatively far from the black hole. The maximum temperature increased slowly as the outburst progressed. However, during all the *Swift* observations the $kT_{\rm max}$ was found to be in the range 0.11–0.97 keV (including error bars).

We noticed small variations in $N_{\rm H}$ values during the outburst. However, the value is close to 0.3×10^{22} cm^{-2} most of the time. The variation in $N_{\rm H}$ is shown in panel E of Figure 1 in units of 10^{22} cm^{-2}. The power law index is small and the spectrum is hard at the beginning of the outburst and it softens as the outburst progresses. The power law index for the maximum normalization shows significant softening in the spectra towards the end of the plot, in contrast to the minimum normalization. The power law index is also well constrained, corresponding to the maximum normalization. This, along with the values of the inner disk radii, shows that the spectral parameters corresponding to the maximum normalization are more physical. The variation in power law index is shown in panel F of Figure 1. Panel G of Figure 1 shows the scattering fraction which is obtained from the model component SIMPL. The scattering fraction gives the fraction of seed photons coming from the disk which are Compton up-scattered in the corona (Steiner et al. 2009).

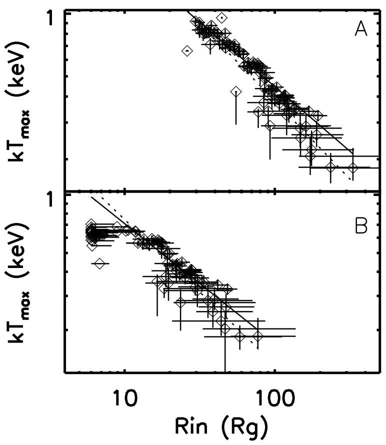

Fig. 3 The figure shows the variation of $kT_{\rm max}$ and $R_{\rm in}$ as obtained from spectral fits when `DISKPN` normalization was frozen at the minimum (*panel A*) and the maximum values (*panel B*). The solid and the dotted lines are the best-fit and standard results respectively.

We studied the ratio of unabsorbed energy flux from the disk to the unabsorbed total energy flux in the energy range 2–10 keV and the plot is shown in panel H of Figure 1. It can be seen that all the observations show consistent behavior of increasing disk fraction as the outburst progresses. It should be noted that one observation (ObsId 00434928028 on MJD 55485) shows a peculiar behavior of disk fraction corresponding to the minimum normalization > 1, which is a fitting artifact. This happens because the *Swift*/XRT spectrum alone is not able to properly constrain the power law giving the best fit power law index of $\Gamma \sim 1$ which is unphysical. We have verified this by simultaneously fitting this particular spectrum with the nearest *RXTE*/PCA spectrum, where the simultaneous fit gives the power law index of $\Gamma \sim 2.2$ and the proper disk fraction (< 1). However, we have included here the values obtained from the *Swift*/XRT spectrum only because the *RXTE* observations are not available for the full duration of the *Swift* observations. We also studied the hardness ratio defined above and show the values in panel B of Figure 1. It is clear from the plot that the spectrum was hard in the beginning of the outburst and then it slowly softened. The softening of the source continued until the end of *Swift* coverage. The hardness ratio and the inner disk radius seem to be correlated and the correlation coefficient is 0.71 and 0.74 for the minimum and maximum normalization respectively. This is consistent with the general understanding that as the disk region increases with decreasing inner disk radius, the fraction of soft photons coming from the disk increases thereby making the hardness ratio small. Also, the correlation coefficients between disk-to-total flux ratio and the hardness ratio are –0.83 and –0.92 for the minimum and maximum normalizations respectively.

A sharp variation in almost all the parameters is observed between MJD 55477 and 55478. This is because of an observation with ObsID 00434928018. The count rate for this observation is only 42.49 cts s^{-1}. This may be one of the extended dips observed in this source. We studied the variation of the maximum blackbody temperature and the inner disk radius from individual fitting of spectra with normalization frozen at the minimum and maximum normalizations.

Figure 3 shows the plots obtained between $kT_{\rm max}$ and $R_{\rm in}$ for the maximum and the minimum normalizations. We fitted the plot and found the best fit to be $kT_{\rm max} = (7.75{\pm}0.93)\ R_{\rm in}^{-0.62\pm0.03}$ keV for the minimum normalization and $kT_{\rm max} = (2.96 \pm 0.38)\ R_{\rm in}^{-0.62\pm0.04}$ keV for the maximum normalization. We ignored the values of $R_{\rm in}$ where the lower bound is not constrained, to find the best fit corresponding to the maximum normalization. This result is comparable to the result given by

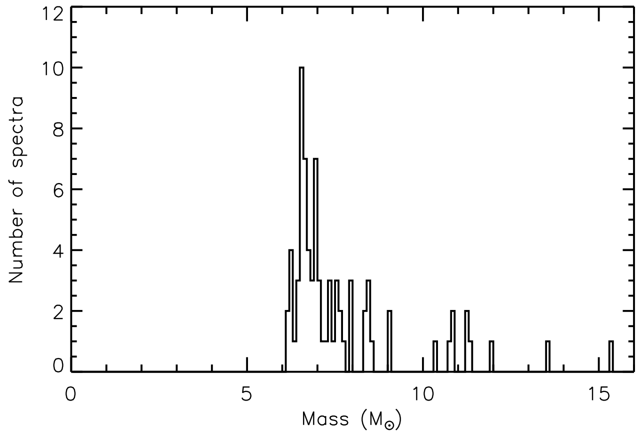

Fig. 4 Histogram of the black hole mass obtained from 79 spectra.

Kennea et al. (2011), though they fitted individual spectra separately with `DISKBB` and we fitted with `DISKPN` with normalization frozen at certain values in all the spectra, in order to tie the geometry dependent parameters. The results deviate from the standard result of $T_{\mathrm{max}} \propto R_{\mathrm{in}}^{-0.75}$. This deviation can be attributed to variation in the accretion rate as the outburst progresses.

We made an attempt to estimate the mass of the black hole using the maximum and the minimum values of normalization. We estimated the mass of the black hole with the following expression, which is taken from Gierliński et al. (1999),

$$M = \left[\frac{N}{(1 - f_{\mathrm{sc}})} \frac{D^2 f_{\mathrm{col}}^4}{\cos i} \right]^{1/2} , \tag{1}$$

where M is mass in solar units, N is normalization obtained from the disk component `DISKPN`, f_{sc} is scattering fraction obtained from the Comptonization component `SIMPL`, D is distance in kpc, f_{col} is the spectral hardening factor and i is inclination in degrees. The fitted value of normalization can be used to estimate the black hole mass because inclination and distance are relatively well constrained for MAXI J1659–152. The inclination angle is constrained in the range 60°–75° based on the presence of dips and absence of eclipses in the light curves of the source (e.g. Kennea et al. 2011; van der Horst et al. 2013; Kuulkers et al. 2013). A number of distance estimates are available for the source which are in good agreement with most of the estimates close to 6 kpc (Kennea et al. 2011; Kaur et al. 2012; Jonker et al. 2012). Since the scattering fraction f_{sc} is different for all 80 spectra, we obtain a total of 80 values for the mass assuming a distance of 6.0 kpc, inclination angle of 70° and the canonical value of 1.7 for the spectral hardening factor. A histogram of 79 out of these 80 mass values is shown in Figure 4. We ignored one observation (ObsID 00434928018) for the mass estimation because the scattering fraction for this observation was very high ($\sim$ 1), resulting in a very high value of mass. We calculated the black hole mass to be 7.9±2.4 $M_\odot$ using a weighted average of these values. If we consider the uncertainty in distance (within 5 to 6 kpc), inclination angle (within 65° to 75°) and spectral hardening factor (within 1.6 to 1.8), the average mass comes out to be 8.1 ± 2.9 $M_\odot$. It should be noted that these estimates are obtained using the maximum normalization from our simultaneous fitting. For the minimum normalization, all the values of mass are found to be lower than 3 $M_\odot$ and hence are ignored. This mass estimate, therefore, can be considered to be an absolute upper limit for the black hole in MAXI J1659–152.

5 CONCLUSIONS

We carried out a detailed spectral analysis of the 2010 outburst of the black hole candidate MAXI J1659–152 with a different spectral model. The outburst lasted for almost one and a half months and has been studied by many authors. We fitted spectra of the outburst with a more physical model that included `DISKPN` and `SIMPL`. The normalization of `DISKPN` was frozen at certain values obtained from simultaneous fitting of spectra in groups. We found an upper limit on the mass of the black hole to be 8.1±2.9 $M_{\odot}$. We studied the variation of the inner disk radius during the outburst using a simultaneous fitting method. We have observed a very systematic variation in the inner disk radius as the outburst progressed. The disk was initially found to be truncated at a larger radius of about a few hundred Schwarzschild radii when the source was in the early stages of the outburst. This, probably, is the first observational evidence of an accretion disk closing-in as the outburst progresses. We see the result as a supporting evidence for the truncation model amongst the growing evidence against the truncation model.

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