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Thermal emission from the stellar-mass black hole binary XTE J1118+480 in the low/hard state

R. C. Reis,[1]★ J. M. Miller[2] and A. C. Fabian[1]

[1]*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2]*Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA*

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ABSTRACT

We report on the detection of a thermal disc component from the stellar-mass black hole binary XTE J1118+480 in the canonical low/hard state. The presence of a thermal component with a temperature of approximately 0.21 keV in the *Chandra* spectra of XTE J1118+480 is found at more than the 14σ confidence level. Based on this evidence, we argue that the accretion disc in XTE J1118+480 is not truncated far from the central black hole in contrast with previous claims.

Key words: accretion, accretion discs – black hole physics – X-rays: individual: XTE J1118+480.

1 INTRODUCTION

The X-ray spectra of Galactic black hole binaries convey important information on the geometry of the accretion disc surrounding the black hole. These sources have usually been characterized by the relative strength of their soft and hard X-ray emission. In the thermal or high/soft state (HSS; see McClintock & Remillard 2006), the soft spectrum is dominated by thermal emission thought to originate in a standard thin accretion disc extending to the innermost stable circular orbit (ISCO; Shakura & Sunyaev 1973). The presence of a power-law continuum is faint and quasi-periodic oscillations (QPOs) are absent or very weak. In the steep power law or very high state, the thermal disc still dominates the soft X-ray emission but now the power-law component is much more distinguishable and QPOs are observed (Remillard & McClintock 2006). A reflection component (Ross & Fabian 1993; Miller 2007) predominantly around the Fe-$K\alpha$ line emission (6.4–6.97 keV) has also been observed in various systems in these states (Miller et al. 2004; Miniutti, Fabian & Miller 2004; Miller et al. 2008; Reis et al. 2008, 2009). Reflection features in the spectra of these HSS and very high state (VHS) system arise as hard emission, possibly from a corona, irradiates the cooler, optically thick disc below and give rises to fluorescent and recombination emission.

The geometry of the accretion flow in the low/hard state (LHS), however, remains a topic of debate. In the accretion disc corona model for the LHS, the hard X-ray emission originates either in the base of a jet (Merloni & Fabian 2002; Markoff & Nowak 2004; Markoff, Nowak & Wilms 2005) or due to magnetic flares in an accretion disc corona where the X-rays are produced by inverse-Compton scattering of soft photons (Merloni, Di Matteo & Fabian 2000a; Merloni & Fabian 2001). In both these cases, the corona surrounds a thin accretion disc possibly extending close to the ISCO. An alternative model has the accretion flow consisting of a thin disc truncated at large distances from the black hole (Esin, McClintock & Narayan 1997; Esin et al. 2001). In this scenario, the central region is filled with a hot, quasi-spherical advection-dominated accretion flow (ADAF) and the accretion disc temperature should peak in the far-ultraviolet (UV), where interstellar absorption usually complicates its direct detection.

Due to its unusually high Galactic latitude ($b = +62^\circ$) and low interstellar absorption, XTE J1118+480 has been the focus of multiwavelength studies (Hynes et al. 2000; Frontera et al. 2001; Chaty et al. 2003). Dynamical measurements of XTE J1118+480 set a strong constraint on the mass function of $6.1 \pm 0.3\,\mathrm{M}_\odot$ (McClintock et al. 2001; Wagner et al. 2001). Recent studies suggest that the black hole in XTE J1118+480 has a mass of $8.53 \pm 0.60\,\mathrm{M}_\odot$ and an orbital inclination of $68 \pm 2^\circ$ (Gelino et al. 2006). The same authors place the system at a distance of 1.72 ± 0.10 kpc in agreement with that previously suggested by McClintock et al. (2001). However, much higher inclinations have been reported by other studies with Wagner et al. (2001) reporting a value of $81^\circ \pm 2^\circ$, Zurita et al. (2002) constraining it to 71–82° and more recently Khruzina et al. (2005) with $i = 80^{+1}_{-4}{}^\circ$.

XTE J1118+480 was observed in its LHS by *Chandra* in 2000 as part of a multiwavelength, multiepoch observing campaign. Based on these observation, McClintock et al. (2001) reported an apparent cool thermal component at ≈24 eV which was interpreted as being caused by a truncated accretion disc with $R_{\rm tr} \gtrsim 70 r_{\rm g} (r_{\rm g} = GM/c^2)$, much larger than the expected ISCO. This motivated an ADAF interpretation for the system in XTE J1118+480 which was presented in a later paper by Esin et al. (2001). The cool thermal component reported by McClintock et al. (2001) was in contrast with a previous *ASCA* observation where in an IAU telegram, Yamaoka et al. (2000) detected a blackbody component with a temperature of ≈0.2 keV. This temperature is characteristic of a disc approaching the ISCO in the LHS of X-ray binaries (see e.g. Miller et al. 2006; Miller 2007; Miller et al. 2008; Reis et al. 2008, 2009). In this Letter, we show that a soft thermal disc component with a temperature similar to that

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★E-mail: rcr36@ast.cam.ac.uk

reported by Yamaoka et al. (2000) is clearly present in the *Chandra* 2000 observation and consistent with a disc extending close to the innermost stable circular orbit. In the following sections, we detail our analysis procedure and results.

2 OBSERVATION AND DATA REDUCTION

We analysed the 2000 April 18 *Chandra* and *RXTE* observation of XTE J1118+480 in its LHS. XTE J1118+480 was observed with the *Low-Energy Transmission Grating Spectrometer* (LETGS, Brinkman et al. 2000) and the ACIS-S detector on board *Chandra* for an integrated exposure of 27.2 ks and simultaneously by *RXTE* for a total combined exposure of 3.5 ks (OBS ID 50407-01-02-03 and 50407-01-02-04).[1] The positive and negative first-order *Chandra* LETG spectra were extracted following the Science Threads for Grating Spectroscopy in the CIAO 4.0 data analysis software.[2] The nominal LETGS/ACIS-S energy coverage is between 0.20 and 10 keV (Weisskopf 2004); however, the spectrum is noisier above 7 keV and below ≈0.4 keV. For this reason, we follow the restriction imposed by McClintock et al. (2001) and Miller et al. (2002) and restrict spectral analysis of the LETGS data to the energy range 0.3–7.0 keV.

RXTE data were reduced in the standard way using the HEASOFT v6.6.0 software package. We used the 'Standard 2 mode' data from the *Proportional Counter Array* (PCA) using PCUs 2 and 3 as well as 64 channel data collected with the *High energy X-ray Timing Experiment* (HEXTE) in clusters A and B. For the PCA and HXTE spectra, we restrict our analyses to the 2.8–25 and 20–100 keV energy range, respectively. To account for residual uncertainties in the calibration of PCU 0 and 2, we added a 0.6 per cent systematic error to all energy channel. In the initial analyses of the *Chandra* data, McClintock et al. (2001) used a custom IDL software and a preliminary spectral response, therefore we cannot reproduce their results. Furthermore, the authors do not require a minimum number of counts per energy bin. This differs in this work where we use the latest response software and the FTOOL GRPPHA to require at least 20 counts per energy bin so as to enable the use of χ^2 statistics in all our analyses. All parameters in fits involving different instruments were tied and a normalization constant was introduced. XSPEC v 12.4.0 (Arnaud 1996) was used to analyse all spectra. The quoted errors on all derived model parameters correspond to a 90 per cent confidence level for one parameter of interest ($\Delta\chi^2 = 2.71$ criterion) unless stated otherwise.

3 ANALYSIS AND RESULTS

Anticipating a power law modified by interstellar absorption (PHABS[3] model in XSPEC) to provide a good fit to most of the energy range under consideration, we began by looking at the *RXTE* data in conjunction with *Chandra* data above 3 keV. This low-energy cut off was chosen as we do not expect major contribution from any blackbody component at these energies for a source in the LHS. With the value of the power-law index tied between the *Chandra* and *RXTE* observations, and an equivalent neutral column density fixed at 1.3×10^{20} cm^{-2} as suggested by McClintock et al. (2001), we obtain an excellent fit with $\chi^2/\nu = 578.6/583$ and a photo index of $\Gamma = 1.756 \pm 0.006$ in agreement with that reported by McClintock et al. (2001). Fig. 1 (top panel) shows the data fitted with a power law above 3 keV. By extending the *Chandra* energy range to that of 0.3–7.0 keV, it is clear that this single power law does not provide a good fit to the full energy range and a strong soft excess is seen (Fig. 1, bottom panel) in disagreement with the results presented by McClintock et al. (2001). A single absorbed power law yields an unsatisfactory fit to the full 0.3–100.0 keV energy range, with $\chi^2/\nu = 6698.6/4461$. Allowing the column density to vary between 1.0×10^{20} and 1.3×10^{20} cm^{-2} as per McClintock et al. (2001) marginally improved the fit with $\chi^2/\nu = 6461.4/4460$. Fig. 2 shows the residuals to this fit in the full energy range. Allowing the column density to vary over a wider range[4] (0.67–2.8×10^{20} cm^{-2}) yields a similar unsatisfactory result with $\chi^2/\nu = 6240.7/4460$.

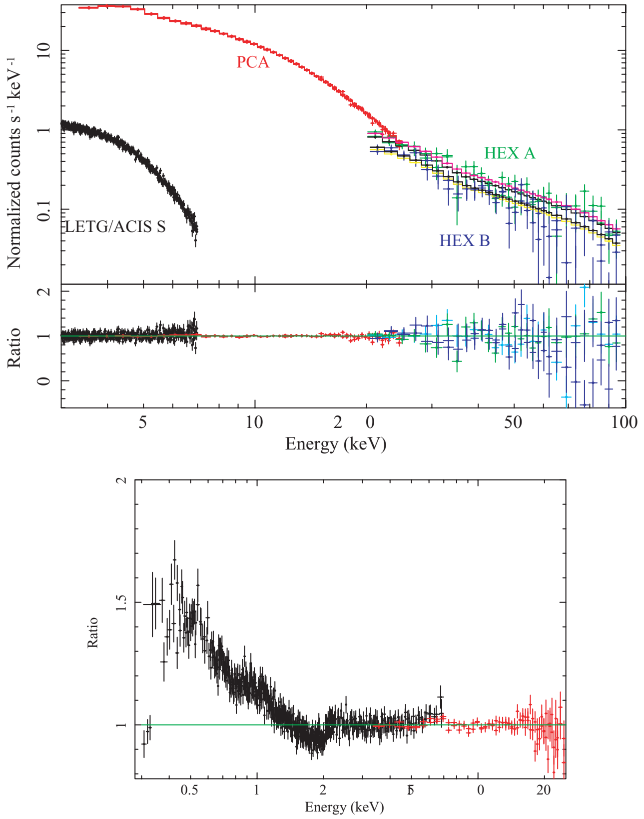

Figure 1. Top panel: *RXTE* and *Chandra* spectra of XTE J1118+480 fitted simultaneously above 3 keV. The data were fitted with a single power-law component modified by absorption in the interstellar medium ($N_{\rm H} = 1.3 \times 10^{20}$ cm^{-2}). Bottom panel: data/model plot for the full energy range 0.3–100 keV (HEXTE data omitted for illustration purposes only) clearly showing the presence of a disc component. The data have been rebinned for plotting purposes only.

To model this soft excess, we initially used the multicolour disc blackbody model DISKBB (Mitsuda et al. 1984; Makishima et al. 1986). The neutral hydrogen column density was constrained to vary between 1.0×10^{20} and 1.3×10^{20} cm^{-2} in accord with the

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[1] In this work, we are only using the two *RXTE* observation that directly overlapped with that of *Chandra*. For a detailed analysis using all of the *RXTE* observation made between 2000 April 13 and May 15 see Miller et al. (2002).

[2] Chandra Interactive Analysis of Observation (CIAO), Fruscione et al. 2006; http://cxc.harvard.edu/ciao/threads/gspec.html.

[3] Using the standard BCMC cross-sections (Balucinska-Church & McCammon 1992) and ANGR abundances (Anders & Grevesse 1989).

[4] The lower and upper limits are derived from maps of infrared (IR) emission (Schlegel, Finkbeiner & Davis 1998) and Ca II absorption features (Dubus et al. 2001), respectively.

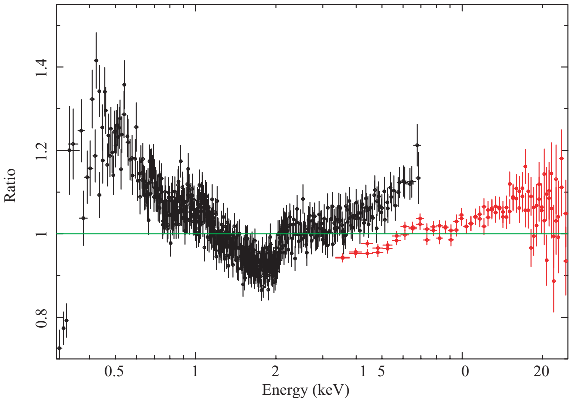

Figure 2. Residuals to a fit with a simple power law over the full 0.3–100.0 keV energy range (HEXTE data omitted for illustration purposes only). It is clear that a simple power law does not provide a possible fit to the full energy range.

Table 1. Results of simultaneously fitting the *Chandra* and *RXTE* data with a power law and thermal disc component. It can be seen that statistically we cannot differentiate a model with an inner radius of 6 or $70r_{\rm g}$.

Model	DISKBB	DISKPN	DISKPN
$N_{\rm H}$	$1.30_{-0.02}$	$1.30_{-0.02}$	$1.30_{-0.02}$
$r_{\rm in}(r_{\rm g})$	–	6(f)	70(f)
kT (keV)	0.213 ± 0.005	0.203 ± 0.005	0.216 ± 0.005
N_{MCD}	4900 ± 500	$0.088^{+0.010}_{-0.009}$	0.0038 ± 0.0004
Γ	1.729 ± 0.005	1.729 ± 0.005	1.729 ± 0.005
N_{pl}	0.1919 ± 0.0015	0.1919 ± 0.0015	0.1918 ± 0.0015
χ^2/ν	4133.8/4456	4135.6/4456	4136.7/4456

Notes. All fits contain an inverse edge with an energy of 2.09 ± 0.01 keV and $\tau = -0.08 \pm 0.01$ as described in the text. The various models are described in XSPEC as PHABS × (power law + DISKPN) or DISKBB. Error refers to the 90 per cent confidence range. The normalization of each component is referred to as N. The column density $N_{\rm H}$ is in units of $(10^{20}\,{\rm cm}^{-2})$.

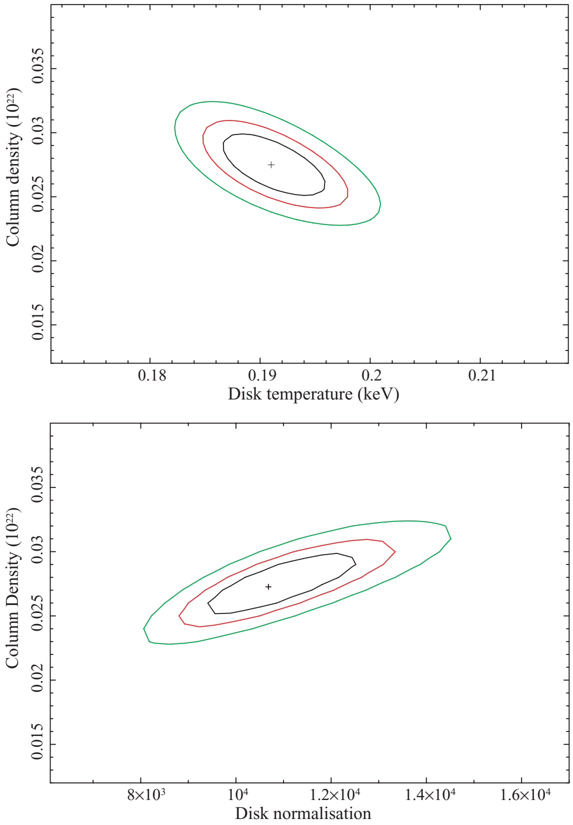

Figure 3. Contour plot of hydrogen column density versus (top panel) disc temperature and (bottom panel) disc normalization for XTE J1118+480. The 68, 90 and 99 per cent confidence range for two parameters of interest are shown in black, red and green, respectively. It can be seen that even when the column density is allowed to vary over its full parameter space the disc temperature remains greater than 0.18 keV at the 99 per cent confidence level.

most likely range reported by McClintock et al. (2001). This resulted in a much improved overall fit with $\chi^2/\nu = 4244.6/4458$ and an F-test value of 1164.14 (1048.23 when $N_{\rm H}$ is allowed to vary over a wider range) over the fit without DISKBB. With a disc normalization of 5800 ± 400 (1σ confidence level), the presence of this thermal disc is thus effectively confirmed at more than the 14σ level. The best fit resulted in an effective disc temperature of 0.203 ± 0.005 keV. This is in agreement with the value reported by Yamaoka et al. (2000) where a blackbody component with a temperature of 0.2 ± 0.1 keV was found in an *ASCA* observation of XTE J1118+480. However, there appears to be an instrumental artefact at an energy of approximately 2 keV (see bottom panel of Figs 1 and 2) consistent with an edge due to the Iridium coating of the detector. Following Miller et al. (2002), we modelled this using an inverse edge at an energy of ≈2 keV ($\tau < -0.1$). This further improved the quality of the fit with $\chi^2/\nu = 4133.8/4456$. The various parameters for this fit are shown in Table 1.[5] In order to investigate any degeneracy between the thermal components (disc normalization and temperature) and the column density, we explored their *full* parameter space using the 'contour' command in XSPEC with all parameters free to vary. Fig. 3 shows the 68, 90 and 99 per cent contour for two parameters of interest. With the column density allowed to vary over its full parameter space, the best-fitting value approaches $2.7 \times 10^{20}\,{\rm cm}^{-2}$, significantly higher than the range suggested by McClintock et al. (2001). However, the disc temperature remains above ~0.18 keV at the 99 per cent confidence level (Fig. 3).

Having shown above that the presence of a disc component is required at more than the 14σ level, we investigated the possibility of constraining the innermost radius of emission. To do this, we used the XSPEC model DISKPN (Gierlinski et al. 1999) which is a modified version of DISKBB where the torque-free inner boundary condition is taken into account. This model has three parameters: the maximum colour temperature of the disc ($T_{\rm col}$) in units of keV, the inner disc radius, $r_{\rm in}$, and the normalization which is defined as $m^2 \cos i / d^2 \beta^4$, where m is the mass of the black hole in solar masses, d is the distance to the source in kpc and β is the colour correction factor. We performed a fit on the full energy range with the inner radius, $r_{\rm in}$ fixed at both the value expected for a disc extending down to the innermost stable circular orbit of a non-spinning black hole ($6r_{\rm g}$) and that of the truncated disc predicted by McClintock et al. (2001) of $70r_{\rm g}$. Table 1 summarizes our results and Fig. 4 shows

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[5] A possible feature around 6.4 keV in the *RXTE* spectra can be seen in Fig. 2. Adding a Gaussian at 6.4 keV corresponding to iron fluorescence emission improves the fit to $\chi^2/\nu = 4075.6/4454$. This broad line (1 keV) has an equivalent width of approximately 100 eV. Replacing the Gaussian with a LAOR line results in a further improvement to the fit with $\chi^2/\nu = 4043.9/4453$ and an inner radius characteristic of a maximally rotating black hole ($r_{\rm in} \sim 1.6r_{\rm g}$).

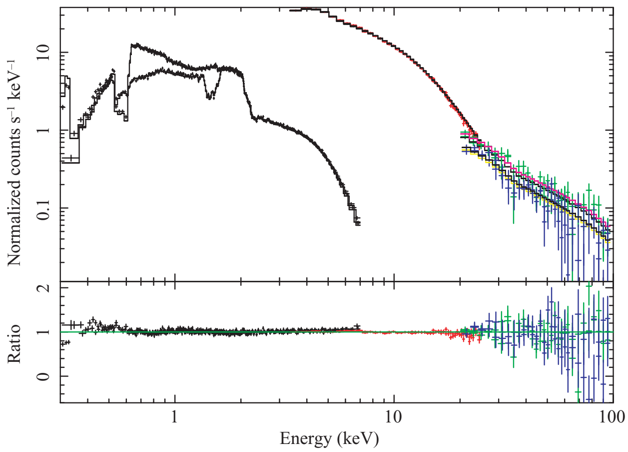

Figure 4. *RXTE* and *Chandra* spectra of XTE J1118+480 fitted simultaneously for the full energy range. The data were fitted with a single power-law component modified by absorption in the interstellar medium and a multi-colour disc blackbody with a temperature of ≈0.21 keV. The data have been rebinned for plotting purposes only.

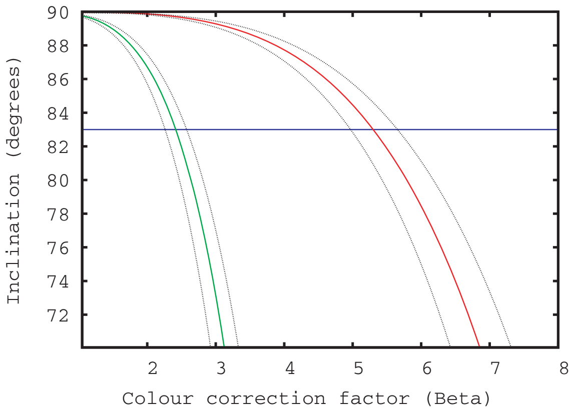

Figure 5. Inclination versus colour correction factor (β). The red and green curves are for a disc with inner radius of 70 and 6$r_{\rm g}$, respectively. The dashed black lines show the error range. The upper limit for the inclination in XTE J1118+480 is shown by the solid blue line.

the best-fitting spectra with the multicolour disc blackbody having an inner radius fixed at 6$r_{\rm g}$.

It can be seen from Table 1 that models with and without a truncated disc give equally satisfactory fits. In order to differentiate between these two models, we have to consider the physical significance of their respective parameters. The mass and distance to the black hole in XTE J1118+480 has recently been estimated at 8.53 ± 0.60 M$_\odot$ and 1.72 ± 0.1 kpc, respectively (Gelino et al. 2006). The inclination of the system, however, remains highly uncertain with various studies placing an upper limit of ≈ 83° (Wagner et al. 2001; Zurita et al. 2002; Khruzina et al. 2005). Using these values in conjunction with the values obtained for the normalization of the DISKPN models in Table 1, we see in Fig. 5 that for a disc truncated at 70$r_{\rm g}$, the inclination lies below 83° only when the colour correction factor $\beta \gtrsim 5$. For the disc extending to 6$r_{\rm g}$, the colour correction factor, β only needs to be greater than ≈2.2 in order for the derived inclination to lie below 83°. It was shown in Merloni, Fabian & Ross (2000b) that the colour correction factor β, which need not be constant, varies between $1.7 < \beta < 3$. With this limitation on β, it is highly unlikely that the disc in XTE J1118+480 is truncated at 70$r_{\rm g}$ and could even extend within 6$r_{\rm g}$ indicating the presence of a rotating Kerr black hole.

4 DISCUSSION

A thermal component with a temperature of approximately 0.21 keV in the *Chandra* spectra of XTE J1118+480 has been found at more than the 14σ confidence level. This component has already been reported in a previous observation of the source with *ASCA* (Yamaoka et al. 2000) but has none the less been overlooked in previous analyses of the *Chandra* observation. Previous claims that the accretion disc in XTE J1118+480 is truncated at a radius greater than 70$r_{\rm g}$ are based on the lack of evidence for this soft thermal component.

In the previous section, we have shown that a disc truncated at both 6 and 70$r_{\rm g}$ gives equally satisfactory fits to the current data. However, based on the current upper limit on the inclination of the system (≈83°), the model containing a disc truncated at 70$r_{\rm g}$ seems unphysical. Furthermore, with a disc temperature of ≈0.21 keV, it is likely that the disc in XTE J1118+480 is *not* truncated far from the black hole. This temperature is broadly consistent with the $L_x \propto T^4$ relation expected for a geometrically stable blackbody. For XTE J1118+480 at a distance of ≈1.8 kpc and a mass of ≈8 M$_\odot$, we obtain a blackbody radius extending to <6$r_{\rm g}$. Similar results have been presented for the black hole candidate XTE J1817−330 (Rykoff et al. 2007), where the authors have followed the evolution of the system from the high-soft state through to the LHS and found that the disc did not recede after the state transition. Contrary to this interpretation, Gierlinski, Done & Page 2008 suggested that irradiation of a truncated accretion disc by Comptonized photons could lead to a disc radius underestimated by a factor of 2–3. It must be noted, however, that the prescription of this model, specially in the case of XTE J1817−330, requires that the irradiation somehow reproduces the $L_x \propto T^4$ relation expected for a simple blackbody observed by Rykoff et al. (2007). Furthermore, in spectra where we observe both a broad Fe-$K\alpha$ line and the disc continuum, the shape of the broad line argues strongly against a recessed disc, as is the case for the black hole binary GX 339−4 in its LHS (Miller et al. 2006; Reis et al. 2008). However, it must be noted that in both the present work on XTE J1118+480 and that of Rykoff et al. (2007) on XTE J1817−330, $L_x/L_{\rm Edd} \gtrsim 0.001$ which prompts the question of whether this could be a bright phase of the LHS. It is still possible that an advective flow take over at some point below $L_x/L_{\rm Edd} \sim 0.001$.

The temperature of this putative disc is very tightly constrained to approximately 0.21 keV and independent of the MCD model used (Table 1). Using the measured X-ray flux of the system (non-absorbed flux in the 0.1–200 keV range) and estimates of its distance and mass (McClintock et al. 2001; Gelino et al. 2006), we can make an estimate on the upper limit on the radius of the accretion disc based on a colour temperature of 0.21 keV. The radial dependence of the effective temperature of an accretion disc is found to be $T^{\rm eff}_{(R)} = T_{\rm col}/\beta = (3GM\dot{M}f/8\pi\sigma_T R^3)^{1/4}$ (Frank, King & Raine 1992), where $f = 1 - (R_{\rm in}/R)^{1/2}$ and $\dot{M} = 4\pi D^2 F_x \cos i/\epsilon c^2$. With F = $F_x/10^9$ erg cm^{-2} s^{-1} ≈ 5, r = R/r$_{\rm g}$, m = M/M$_\odot$ and d = D/kpc, we obtain $T^{\rm eff}_{\rm (r)} \approx 1.34\,({\rm d}^2 \cos i/\epsilon {\rm m}^2)^{1/4}(f/{\rm r}^3)^{1/4}$. Assuming a Schwarzchild black hole with an efficiency of 6 per cent, mass of 8.5 M$_\odot$ and a distance of 1.72 kpc, as well an upper limit on the inclination of 83° and $\beta < 3$ results in an upper limit for the disc radius of ≈16 $r_{\rm g}$. Note that this value is obtained in the extreme case of $\beta = 3$. Lowering β to 2.4 results in a decrease in the upper limit of the disc radius of ≈10$r_{\rm g}$. We further note that the presence of a broad fluorescence line in the *RXTE* data corroborates the existence of dense disc extending close to the black hole.

If the disc does indeed extend close to the ISCO in XTE J1118+480, it is plausible that the broad-band spectral energy distribution (SED) observed in various multiwavelength campaign (Hynes et al. 2000; Frontera et al. 2001; Chaty et al. 2003) is mostly due to optically thin synchrotron emission such as that originating in the innermost part of a jet (Markoff et al. 2005) or magnetic flares in the inner part of the accretion flow (Merloni et al. 2000a). The strong UV hump observed in this system would thus not be exclusively due to viscous dissipation from a cold, truncated accretion disc. Another possibility would be that this optical-UV emission is dominated by reprocessed hard X-ray emission (King & Ritter 1998) as is likely for XTE J1817−330 (Rykoff et al. 2007). However, based on fast X-ray and optical variability, Kanbach et al. (2001) argued against reprocessing and favoured synchrotron emission as the source of the optical and UV emission in XTE J1118+480. This view was further strengthened by Hynes et al. (2003, 2006) who, on the basis of the rapid X-ray, UV, optical and infrared variability, argue that the SED in XTE J1118+480 is mostly dominated by synchrotron emission possibly originating at the base of a jet. The same authors also argued that a cold, thermal disc component cannot satisfactorily model the IR variability (Hynes et al. 2006). Noting the presence of simultaneous QPO in both the optical and X-ray light curves of XTE J1118+480, Merloni, Di Matteo & Fabian (2000a) suggested that magnetic flares in an accretion disc corona possibly extending close to the ISCO could explain the broad-band SED in XTE J1118+480. Our results further support the notion that the broad-band SED in XTE J1118+480 is caused by inverse-Compton scattering of soft photons in a corona embedding a thin accretion disc extending close to the ISCO.

5 CONCLUSIONS

We have studied the *Chandra* observation of the stellar-mass black hole binary XTE J1118+480 in the canonical LHS. A thermal disc emission with a temperature of approximately 0.21 keV is found at greater than the 14σ level. For XTE J1118+480, this thermal emission most likely originates from an accretion disc extending close to the radius of marginal stability. The presence of a disc component in the *Chandra* spectra of XTE J1118+480 has been overlooked in previous analysis, which resulted in XTE J1118+480 becoming the archetype for ADAF scenarios. In light of our analysis, this picture needs to be reconsidered.

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