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

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ABSTRACT

We report on the detection of a thermal-disk 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 disk in XTE J1118+480 is not truncated far from the central black hole in contrast with previous claims.

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

1 INTRODUCTION

The X-ray spectra of Galactic black hole binaries convey important information on the geometry of the accretion disk surrounding the black hole. These sources have usually been characterised 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 disk extending to the innermost stable circular orbit (ISCO; Shakura & Sunyaev 1973). The presence of a powerlaw continuum is faint and quasi-periodic oscillations (QPOs) are absent or very weak. In the steep power law or very high state the thermal disk still dominates the soft X-ray emission. However, now the power law component is much more distinguishable 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-Kα line emission (6.4–6.97 keV) has also been observed in various systems in these states (Miniutti et al. 2004; Miller et al. 2004, 2008; Reis et al. 2008, 2009). Reflection features in the spectra of these HSS and VHS systems arise as hard emission, possibly from a corona, irradiates the cooler, optically thick disk below and gives rise 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 disk 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 disk corona where the X-rays are produced by inverse Compton scattering of soft photons (Merloni, Di Matteo & Fabian 2000; Merloni & Fabian 2001). In both these cases the corona surrounds a thin accretion disk possibly extending close to the ISCO. An alternative model has the accretion flow consisting of a thin disk truncated at large distances from the black hole (Esin et al. 1997, 2006). The same authors place the system at a distance of 81 ± 72 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° ± 2°, Zurita et al. (2002) constraining it to 71–82° and more recently Khruzina et al. (2005) with i = 80°±1° degrees.

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 disk with \( R_{\text{tr}} \gtrsim 70 \text{rg} \) \((r_{\text{g}} = GM/c^2)\), 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 \( \approx 0.2 \) keV. This temperature is characteristic of a disk approaching the ISCO in the low/hard state of X-ray binaries (see e.g. Miller et al. 2006; Miller 2007; Miller et al. 2008; Reis et al. 2008, 2009). In this paper we show that a softthermal disk component with a temperature similar to that reported by Yamaoka et al. (2000) is clearly present in the Chandra 2000 observation and is consistent with a disk 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 low/hard state. 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). 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. The nominal LETGS/ACIS-S energy coverage is between 0.20–10 keV (Weisskopf 2004), however the spectrum is noisier above 7 keV and below \( \approx 0.4 \) 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 cluster A and B. For the PCA and HEXTE 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 P CU 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 the present 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 \( \chi^2 \) statistics in all our analyses. All parameters in fits involving different instruments were tied and a normalisation 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.

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 13 April and 15 May see Miller et al. (2002).

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

\[ \chi^2 = \sum \frac{(y_i - \bar{y})^2}{\sigma_i^2} \]

\[ \chi^2/\nu = \frac{\chi^2}{N - M} \]

\[ M = N - \text{red} \]

\[ \text{red} = \frac{\chi^2}{N} \]

\[ \text{red} = \frac{1}{\chi^2/\nu} \]

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

4 The lower and upper limits are derived from maps of IR emission (Schlegel et al. 1998) and Ca II absorption features (Dubus et al. 2001) respectively.

3 ANALYSIS AND RESULTS

Anticipating a power-law modified by interstellar absorption (PHABS 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 cutoff was chosen as we do not expect major contribution from any black-body 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 \( 1.3 \times 10^{20} \) 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). Figure 1 (Top) shows the data fitted with a powerlaw above 3 keV. By extending the Chandra energy range to that of 0.3–7.0 keV it is clear that this single powerlaw does not provide a good fit to the full energy range and a strong soft excess is seen (Fig. 1 bottom) in disagreement with the results presented by McClintock et al. (2001). A single absorbed-powerlaw 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 1.0–1.3 \( \times 10^{20} \) cm\(^{-2} \) as per McClintock et al. (2001) marginally improved the fit with \( \chi^2/\nu = 6461.4/4460 \). Figure 2 shows the residuals to this fit in the full energy range. Allowing the column density to vary over a wider range \( (0.67–2.8 \times 10^{20} \text{cm}^{-2}) \) yields a similar unsatisfactory result with \( \chi^2/\nu = 6240.7/4460 \).
To model this soft excess we initially used the multicolour disk blackbody model DISKBB (Mitsuda et al. 1984 ; Makishima et al. 1986). The neutral hydrogen column density was constrained to vary between $1.0-1.3 \times 10^{20} \text{cm}^{-2}$ in accord with the 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 $N_{\text{H}}$ is allowed to vary over a wider range) over the fit without DISKBB. With a disk normalisation of $5800 \pm 400$ (1σ confidence level) the presence of this thermal disk is thus effectively confirmed at more than the 14σ level. The best fit resulted in an effective disk temperature of $2.7 \pm 0.005$ keV. This is in agreement with the value reported by Yamaoka et al. (2000) where a black-body component with a temperature of $0.2 \pm 0.1$ keV was found in an ASCA observation of XTE J1118+480. However, there appears to be an instrumental artifact at an energy of approximately 2 keV (see bottom panel of Fig. 1 and Fig. 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 $\approx 2$ 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. In order to investigate any degeneracy between the thermal components (disk normalisation 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 fit value approaches 2.7 keV at the 99 per cent confidence level (Fig. 3).

Having shown above that the presence of a disk 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 disk ($T_{\text{col}}$) in units of keV, the inner disk radius, $r_{\text{in}}$, and the normalisation which is defined as $m^2 \cos \iota / d^2 \beta^3$, where $m$ is the mass of the black hole in solar masses, $d$ is the distance to the source in kpc and $\beta$ is the colour correction factor. We performed a fit on the full energy range with the inner radius, $r_{\text{in}}$, fixed at both the value expected for a disk extending down to the innermost stable circular orbit of a non-spinning black hole ($6r_g$) and that of the truncated disk predicted by McClintock et al. (2001) of $70r_g$. Table 1 summarises our results and Fig. 4 shows the best fit spectra with the multicolour disk blackbody having an inner radius fixed at $70r_g$.

Notes.- All fits contain an inverse edge with an energy of $2.09 \pm 0.01$ keV and $\tau = -0.08 \pm 0.01$ as described in the text. The various models are described in XSPEC as PHABS x (PL + DISKPN) or DISKBB. Error refers to the 90 per cent confidence range. The normalisation of each component is referred to as $N$. The column density $N_{\text{H}}$ is in units of ($10^{20} \text{cm}^{-2}$).
tiate 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 \(\approx 83^\circ\) (Wagner et al. 2001; Zurita et al. 2002; Khruzina et al. 2005). Using these values in conjunction with the values obtained for the normalisation of the DISKPN models in Table 1 we see in Fig. 5 that for a disk truncated at 70\(r_g\), the inclination lies below 83° only when the colour correction factor \(\beta \gtrsim 5\). For the disk extending to 6\(r_g\), the colour correction factor, \(\beta\) only needs to be greater than \(\approx 2.2\) in order for the derived inclination to lie below 83 degrees. It was shown in Merloni, Fabian \& Ross (2000) that the colour correction factor \(\beta\), which need not be constant, varies between 1.7 < \(\beta\) < 3. With this limitation on \(\beta\) it is highly unlikely that the disk in XTE J1118+480 is truncated at 70\(r_g\) and could even extend within 6\(r_g\) 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 14\(\sigma\) confidence level. This component has already been reported in a previous observation of the source with ASCA (Yamaoka et al. 2000) but has nonetheless been overlooked in previous analyses of the Chandra observation. Previous claims that the accretion disk in XTE J1118+480 is truncated at a radius greater than 70\(r_g\) is based on the lack of evidence for this soft thermal component.

In the previous section we have shown that a disk truncated at both 6 and 70\(r_g\) gives equally satisfactory fits to the current data. However, based on the current upper limit on the inclination of the system (\(\approx 83^\circ\)), the model containing a disk truncated at 70\(r_g\) seems unphysical. Furthermore, with a disk temperature of \(\approx 0.21\) keV it is likely that the disk 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 \(\approx 1.8\) kpc and a mass of \(\approx 8\) M\(_\odot\) we obtain a blackbody radius extending to \(< 6r_g\). 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 low/hard state and found that the disk did not recede after the state transition. Contrary to this interpretation, Gierlinski et al. (2008) suggested that irradiation of a truncated accretion disk by Comptonized photons could allow a disk 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 black body observed by Rykoff et al. (2007). Furthermore, in spectra where we observe both a broad Fe-K\(\alpha\) line as well as the disk continuum, the shape of the broad line argues strongly against a recessed disk, as is the case for the black hole binary GX 339-4 in its low/hard state (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, \(L_x / L_{\text{Edd}} \gtrsim 0.001\) which prompts the question of whether this could be a bright phase of the low/hard state. It is still possible that an advective flow take over at some point below \(L_x / L_{\text{Edd}} \approx 0.001\).

The temperature of this putative disk is very tightly constrained to approximately 0.21 keV and is 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 disk based on a colour temperature of 0.21 keV. The radial dependence of the effective temperature of an accretion disk is found to be \(T^{ef}(r) = T_{\text{col}}/\beta = (3GMf/8\pi\sigma\tau R^3)^{1/4}\) (Frank, King \& Raine 1992), where \(f = 1 - (R_{in}/R)^{1/2}\) and \(M = 4\pi D^2F_\alpha \cos i / c^2\). With \(F_\alpha = F_{\alpha}/10^3\) ergs cm\(^{-2}\) s\(^{-1}\) ≈ 5, \(r = R/r_g\), \(m = M/M_\odot\) and \(d = D / \text{kpc}\), we obtain \(T^{ef}(r) \approx 1.34(d^2\cos i / \text{cm}^2)^{1/4}(f/r_g)^{1/4}\). Assuming a Schwarzschild 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 degrees and \(\beta < 3\) results in an upper limit for the disk radius of \(\approx 16r_g\). Note that this value is obtained in the extreme case of \(\beta = 3\). Lowering \(\beta\) to 2.4 results in a decrease in the upper limit of the disk radius of \(\approx 10r_g\). We further note that the presence of a broad fluorescence line in the RXTE data corroborates the existence of a dense disc extending close to the black hole.

If the disk does indeed extend close to the ISCO in XTE J1118+480, it is plausible that the broadband spectral energy distribution (SED) observed in various multiwavelength cam-
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. 2001) or magnetic flares in the inner part of the accretion flow (Merloni, Di Matteo & Fabian 2000). The strong UV hump observed in this system would thus not be exclusively due to viscous dissipation from a cold, truncated accretion disk. Another possibility would thus not be exclusively due to viscous dissipation (Di Matteo & Fabian 2000). The strong UV hump observed in this system extending close to the ISCO. A thermal disk 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 disk corona possibly extending close to the ISCO could explain the broadband SED in XTE J1118+480. Our results further support the notion that the broadband SED in XTE J1118+480 is caused by inverse Compton scattering of soft photons in a corona embedding a thin accretion disk 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 low/hard state. A thermal disk 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 disk extending close to the radius of marginal stability. The presence of a disk 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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REFERENCES

Anders E. & Grevesse, N., 1989, GeCoA, 53, 197A
Arnould K.A., 1996, ASPC, 101, 17A
Balucinska-Church, M. & McCammon D., 1992, ApJ, 400, 699B
Brinkman B. C., et al., 2000, SPIE, 4012, 81B
Chaty S., Haswell C. A., Malzac J., Hynes R. I., Shrader C. R., Cui W., 2003, MNRAS, 346, 689
Dubus, G., Kim, R. S. J., Menou, K., Szkody, P., Bowen, D. V., 2001, ApJ, 553, 307
Esin A. A., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
Esin A. A., McClintock J. E., Drake J. J., Garcia M. R., Haswell C. A., Hynes R. I., Muno M. P., 2001, ApJ, 555, 483
Frank J., King A., Raine D., 1992, Accretion Power in Astrophysics (2nd ed.; Cambridge Univ. Press)
Frontera F., Zdziarski A. A., Amati L., Mikolajewska J., Belloni T., Del Sordo S., et al., 2001, ApJ, 561, 1006
Fruscione et al. 2006, SPIE Proc. 6270, 62701V, D.R. Silvia & R.E. Doxsey, eds.
Gelino D. M., Balman S., Kiziloglu U., Yilmaz A., Kalemcu E., Tomskick J. A., 2006, ApJ, 642, 438G
Gierlinski M., Zdziarski A.A., Poutanen J., Coppi P. S., Ebisawa K., Johnson W. N., 1999, MNRAS, 309, 496
Gierlinski M., Done C., & Page K., 2008, MNRAS, 388, 753
Hynes R. I., Mauche C. W., Haswell C. A., Shrader C. R., Cui W., Chaty S., 2000, ApJ, 539, L37
Hynes R. I., Haswell C. A., Cui W., Shrader C. R., O'Brien K., Chaty S., et al., 2003, MNRAS, 345, 292
Hynes R. I., Robinson E. L., Pearson K. J., Gelino D. M., Cui W., et al., 2006, ApJ, 651, 401
Kanbach G., Straubmeier C., Spruit H. C., Belloni, T., 2001, Nature, 414, 180
King A. R., & Ritter H., 1998, MNRAS, 293, L42
Khruzina T. S., Cherepashchuk A. M., Bisikalo D. V., Boyarchuk A. A., Kuznetsov O. A., 2005, AREP, 49, 79
Markoff S., Nowak M. A., 2004, ApJ, 609, 972
Markoff S., Nowak, M. A., & Wilms J., 2005, ApJ, 635, 1203
Makishima et al., 1986, ApJ 308, 635
McClintock J.E., Haswell C. A., Garcia M. R., Drake J. J., Hynes R. I., Marshall H. L., Muno M. P., et al., 2001, ApJ, 555, 477
McClintock J.E., & Remillard R.A. 2006 Black hole binaries (Compact stellar X-ray sources), 157-213
Merloni A., Di Matteo T., Fabian, A. C., 2000, MNRAS, 318, L15
Merloni A., Fabian, A. C., Ross, R. R., 2000, MNRAS, 313, 193
Merloni A., Fabian, A. C., 2001, MNRAS, 332, 165
Merloni A., Fabian, A. C., 2002, MNRAS, 321, 549
Miller J.M., Ballantyne D. R., Fabian A. C., Lewin W., H., G., 2002, MNRAS, 335, 865
Miller J.M. et al., 2004, ApJ, 606, L131
Miller J.M., Homan J., Steeghs D., Rupen M., Hunstead R.W., Wijnands R., Charles P.A., & Fabian A.C., 2006, ApJ, 653, 525
Miller, J. M., 2007, ARA&A, 45, 441
Miller J.M., Reynolds C.S., Fabian A.C., Cackett E.M., Miniutti G., Raymond J. Steeghs D., Reis R.C., Homan J., 2008, ApJ, 679L, 113
Miniutti G., Fabian A.C., Miller J.M., 2004, MNRAS, 351, 466
Mitsuda K., Inoue H., Koyama K., Makishima K., Matsuoka M., Ogawara Y., Suzuki K., et al., 1984, PASJ, 36, 741
Reis R. C., Fabian A. C., Ross R. R., Miniutti G., Miller J. M., and Reynolds C., 2008, MNRAS, 689R
Reis R. C., Fabian A. C., Ross R. R., Miller J. M., 2009, MNRAS in press, MN-08-1287-MJR2
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Ross R.R., & Fabian A.C., 1993, MNRAS, 261, 74
Rykoff E. S., Miller J. M., Steeghs D., Torres M. A. P., 2007, ApJ, 666, 1129
Schlegel, D. J., Finkbeiner, D. P., Davis, M., 1998, ApJ, 500, 525
Shakura N. I. and Sunyaev R. A., 1973, A&A, 24, 337
Wagner R. M., Foltz C. B., Shahbaz T., Casares J., Charles P. A., Starfield S. G., Hewett P., 2001, ApJ, 556, 42
Weisskopf, M. C., 2004, SPIE. 5488, 25W
Yamaoka K., Ueda Y., Dotani T., Durouchoux P., Rodriguez J., 2000, IAU Circ. 7427
Zurita C., Casares J., Shahbaz T., Wagner R. M., Foltz C. B., Rodriguez-Gil P., Hynes R. I., et al., 2002, MNRAS, 333, 791