Mon. Not. R. Astron. Soc. **000**, 1–11 (2002) Printed 2 February 2008 (MN LATEX style file v2.2)

Black hole accretion discs: reality confronts theory

Marek Gierliński[1,2] and Chris Done[1]
[1]*Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[2]*Obserwatorium Astronomiczne Uniwersytetu Jagiellońskiego, 30-244 Kraków, Orla 171, Poland*

Submitted to MNRAS

ABSTRACT

Disc spectra from highly luminous black hole binaries are observed to be rather simple, despite theoretical predictions to the contrary. We collate the disc-dominated spectra from multiple observations of 10 separate sources, and show that these overwhelmingly follow a multi-temperature disc blackbody spectrum with luminosity $\propto T^4$, and that such discs are stable. These results are in conflict with standard Shakura-Sunyaev α-discs predictions, including proposed modifications such as additional energy loss in a jet, wind or corona. Accretion disc spectra can be useful, reliable guides to the disc structure, and should be used to test the next generation of accretion disc models, in which the disc viscosity is calculated self-consistently from the magnetically generated turbulent dynamo.

Key words: accretion, accretion discs – X-rays: binaries

1 INTRODUCTION

Accretion onto a compact object is believed to be the source of power in X-ray binaries (see e.g. Tanaka & Lewin 1995). At accretion rates in excess of a few percent of Eddington rate most of the black hole binaries dwell in the so-called soft, or high, X-ray spectral state. Their X-ray spectra are then dominated by a soft thermal component, of typical temperature $\lesssim 1$ keV. The standard model of accretion (Shakura & Sunyaev 1973, hereafter SS73) explains these spectra as emission from an optically thick and geometrically thin disc. This can form a stable emitting structure down to the minimum stable orbit (which depends on the black hole spin), so its spectrum contains the imprint of strong special and general relativistic effects (e.g. Cunningham 1975; Ebisawa, Mitsuda & Hanawa 1991).

This all makes disc spectra an exciting potential probe of the dramatically curved space-time in the vicinity of the black hole. However, there are many problems in interpreting them. Firstly, the quasi-thermal component which is identified as the disc emission is generally accompanied by a power-law tail out to much higher energies (e.g. Tanaka & Lewin 1995). This tail is well fit by Comptonization of seed photons from the disc, requiring that some of the energy is *not* thermalized in the disc but is instead dissipated in an optically thin environment, e.g. a corona above the disc. The disc structure here *must* be different to that assumed by disc equations where all the energy is dissipated in the optically thick material. Secondly, these coronal hard X-rays can illuminate the disc, again changing its structure (e.g. Nayakshin, Kazanas & Kallman 2000a). Thirdly, even without the coronal emission, the disc spectrum at a given radius is not a simple blackbody as the absorption opacity is small at the high temperatures expected for X-ray binary discs (SS73). The amount of deviation from blackbody (termed a colour temperature correction) depends on details of the disc vertical structure, but the net result is to increase the observed peak 'temperature' of the disc (SS73)

A pessimistic response to this complexity is simply to abandon any information the disc spectra might contain as being too difficult to disentangle. However, some black holes can show spectra which are dominated by the disc component, with very little hard X-ray emission. These offer a way of circumventing the first two problems described above, so these spectra can equally be viewed as giving *observational* constraints on the disc structure, black hole mass and spin (see e.g. Ebisawa et al. 1991; 1994; Kubota, Makishima & Ebisawa 2001; Kubota & Makishima 2003)

Further motivation for this more optimistic approach is that the disc stability is also a sensitive indicator of how the gravitational energy is dissipated within the disc. Standard discs (α-discs) in which the heating is proportional to the total (gas plus radiation) pressure, are viscously (Lightman & Eardley 1974) and thermally (Shakura & Sunyaev 1976) unstable when radiation pressure dominates. In this regime the disc undergoes limit-cycle variability on time-scales of a few hundred seconds between a low accretion rate, gas pressure dominated state and a high accretion rate, advectively cooled slim disc (Honma, Matsumoto & Kato 1991; Szuszkiewicz & Miller 1997, 1998; Zampieri, Turolla & Szuszkiewicz 2001).

Here we compile all the available *Rossi X-ray Timing Explorer RXTE* observations of several black hole binaries which show disc-dominated spectra to see what information can be reliably extracted from the data. The observed disc spectra are surprisingly simple. They can be well modelled by a multi-colour disc blackbody, and individual objects which span a large range in disc luminosity, $L_{\rm disc}$, generally have an observed disc temperature $\propto L_{\rm disc}^{1/4}$. We use the sample as a whole to set constraints on the colour temperature correction and limits on how this changes as a function of luminosity, and show that such spectra *can* be used to derive black hole spin if the binary system parameters are well known. We use the data on the colour temperature correction, together with the observed stability of the light curves, to constrain the disc structure. We show it must be somewhat different to that predicted by the standard α-disc viscous heating prescription, irrespective of phenomenological modifications such as winds/jets/coronae. The data are also probably inconsistent with an alternative viscosity prescription in which the heating is proportional to gas pressure alone (Stella & Rosner 1984).

While no current models can fully explain the observations, we stress that disc spectra *can be* a simple, useful and reliable probe of the accretion mechanisms. These tests will be especially important for the next generation of models which will calculate the heating *ab initio* from the MHD dynamo (Balbus & Hawley 1991) rather than using the *ad hoc* viscosity prescriptions described above.

2 DISC TEMPERATURE AND LUMINOSITY

An optically thick, geometrically thin accretion disc around a non-rotating black hole has a very robust predicted spectrum. It does not depend on the details of the viscous heating if the gravitational energy released at a given radius R is emitted locally as a blackbody of temperature $T_{\rm eff}(R)$. The total spectrum of the disc is the sum of these blackbodies (generally termed a multicolour disc blackbody), with maximum temperature $T_{\rm eff,max}$ occurring close to the minimum stable orbit. The luminosity of the disc is $L_{\rm disc} \propto T^4_{\rm eff,max}$, and this completely determines the disc spectrum.

However, a given radius in the disc need not emit as a true blackbody. The absorption opacity at the high temperatures characteristic of X-ray binary discs is small, so scattering is important. In this case the disc spectrum is either a modified blackbody (with detailed shape depending on the vertical density and temperature structure of the disc) or Comptonized into a Wien peak (SS73). When these are taken into account, the emergent disc spectrum can still be approximated by a multicolour disc blackbody but of maximum *colour* temperature, $T_{\rm max} \equiv f_{\rm col} T_{\rm eff,max}$ (Shimura & Takahara 1995; Merloni et al. 2000), where $f_{\rm col}$ is called the colour temperature correction, or spectral hardening factor, since it is always greater then unity.

To find the numerical coefficient linking luminosity and temperature, we assume the disc extends down to the minimum stable orbit at $6R_g$ in a pseudo-Newtonian potential (Paczyński & Wiita 1980),

$$\Phi(R) = -\frac{GM}{R - 2R_g}, \tag{1}$$

where G is the gravitational constant, M is the black hole mass and $R_g \equiv GM/c^2$ is the gravitational radius. This is a simple and accurate approximation of the gravitational potential around a non-rotating black hole. The maximum disc temperature is produced at $\approx 9.5R_g$ with the stress-free inner boundary condition (e.g. Novikov & Thorne 1973). Appendix A of Gierliński et al. (1999) shows that the integrated disc luminosity is related to the maximum observed colour temperature, $T_{\rm max}$, as

$$L_{\rm disc} = \frac{\pi \sigma G^2 M^2 T^4_{\rm max}}{6 c_0^4 f^4_{\rm col} c^4}. \tag{2}$$

Here σ is the Stefan-Boltzmann constant and $c_0 \approx 0.1067$. The above formula can be expressed in terms of Eddington luminosity, $L_{\rm Edd} = 1.48 \times 10^{38} (M/{\rm M}_\odot)$ erg s^{-1}, as

$$\frac{L_{\rm disc}}{L_{\rm Edd}} \approx 0.583 \left(\frac{1.8}{f_{\rm col}}\right)^4 \left(\frac{M}{10 M_\odot}\right) \left(\frac{kT_{\rm max}}{1\ {\rm keV}}\right)^4, \tag{3}$$

where k is the Boltzmann constant.

There is considerable speculation as to whether the inner stress-free boundary condition is accurate. The viscosity is now known to be derived from an MHD dynamo, and magnetic reconnection can give continuous stress across the last stable orbit (Agol & Krolik 2000). Ironically, in this case the simple DISKBB model (Mitsuda et al. 1984; in the XSPEC spectral fitting package) is more appropriate as it does not incorporate the stress-free boundary condition (though it also has a Newtonian potential rather than pseudo-Newtonian). In any case, the shape of the DISKBB spectrum is extremely close to that derived from the pseudo-Newtonian, stress-free disc model (DISKPN in XSPEC) described above, requiring only a 4 per cent temperature shift to match the spectrum at all energies above $\sim 0.5kT_{max}$ (Gierliński et al. 1999). Thus we use the DISKBB model with an additional temperature correction factor of $\xi \approx 1.04$.

The emerging disc emission is then affected by the relativistic effects in strong gravitational potential of the black hole. Following Cunningham (1975) and Zhang, Cui & Chen (1997) we apply corrections g and $f_{\rm GR}$ for the observed flux and temperature, respectively:

$$F' = g(i, a_*) \frac{L_{\rm disc}}{2\pi D^2} \tag{4}$$

and

$$T'_{\rm max} = f_{\rm GR}(i, a_*) \xi T_{\rm max}. \tag{5}$$

where i is the inclination angle, and D is the distance to the source. The dimensionless spin is defined as $a_* \equiv Jc/GM^2$, where J is the angular momentum of the black hole. The primed quantities denote values in the observer's frame. We use the values of g and $f_{\rm GR}$ from table 1 in Zhang et al. (1997).

3 SAMPLE SELECTION

We want to select disc-dominated spectra, where contribution from the Comptonized tail is as small as possible. We use the black hole sample of Done & Gierliński (2003, hereafter DG03) as our basis. This consists of all the well observed *RXTE* black holes with low absorption which showed state transitions, i.e. these include soft state spectra. We extend the sample to include XTE J1650–500 and two black hole systems which were always in the soft state when observed with *RXTE* (LMC X-1 and GRS 1739–278). We also include data from the *Ginga* black hole transient GS 1124–68 (a.k.a. Nova Muscae), as this showed a soft (disc dominated) spectrum over much of its outburst (Ebisawa et al. 1994).

To select the disc-dominated spectra from the whole sample we fit the data by the model consisting of the disc emission and its thermal Comptonization. We describe the model and fitting procedure in the next section. Ideally we would require that there was *no* Comptonized tail present. However, this sort of ultrasoft spectrum is not very common, so in order to have a larger sample we allow up to 15 per cent of the total bolometric luminosity to be present in the tail. This is somewhat model dependent, but the precise value of the coronal fraction is not important as long as it is small enough to have a negligible effect on the disc structure.

Fig. 1 shows the complete intrinsic colour-colour and colour-luminosity diagram as in DG03 for our observed sources. The lower curving line in the background shows the colours expected for a

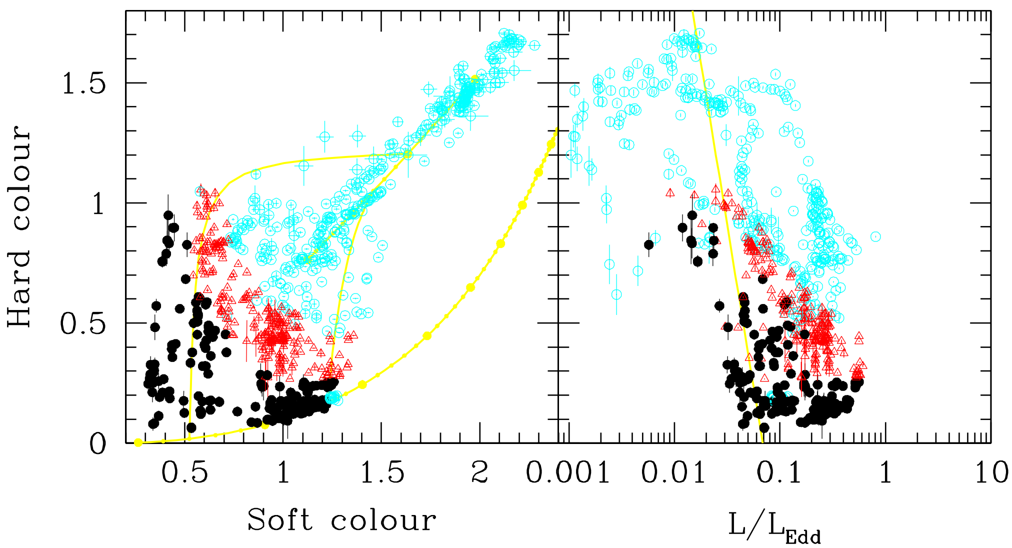

Figure 1. The colour-colour (left) and colour-luminosity (right) diagram of the sources listed in Table 1. See DG03 for detailed description of these diagrams. Different symbols correspond to different fraction of the total luminosity released in the Comptonized tail above the disc spectrum: $\leqslant 5$ per cent (black filled circles), 5–15 per cent (red open triangles) and > 15 per cent (cyan open circles). Only the data with disc-dominated spectra ($\leqslant 15$ per cent of Comptonized emission) are analysed in this paper. See electronic edition of the journal for the colour version of this figure.

pure DISKBB spectrum with temperature increasing along the line from 0.5 keV (lower left) to 4.5 keV (top right); see also fig. 1 in DG03. This line forms a lower bound on the disc-dominated spectra. The Comptonized fraction increases with increasing both colours, roughly along the diagonal. The disc-dominated data selected for further analysis are marked by black filled circles and red open triangles, to denote spectra where the Compton tail fractional luminosity is between 0–5 and 5–15 per cent, respectively. Typical X-ray spectra for the selected data are shown in panels a, g, h, i and j of fig. 3 in DG03.

The limit of 15 per cent of flux in the Compton tail excludes all data from XTE J1118+480, a source well observed by *RXTE* (e.g. McClintock et al. 2001), as it has been seen only in the hard state. More surprisingly perhaps it also excludes Cyg X-1 as although this makes a transition to the soft state, its X-ray spectra always include a substantial fraction of Comptonized emission (see e.g. Gierliński et al. 1999; Frontera et al. 2001; DG03). The interesting source GRS 1915+105 is also excluded as again the spectra generally show substantial Comptonized emission as well as having high (and probably variable) absorption which complicates the spectral fitting. This gives a sample of 10 black hole systems, as listed in Table 1. In this table we also list the mass, distance, inclination and absorption column used in the analysis, together with their uncertainties. There are two sets of distance estimates quoted for GRO J1655–40, as the recently updated value (Mirabel et al. 2002) is significantly different to the previous determination.

The intrinsic colour-colour diagram (Fig. 1) shows an almost one-to-one match between colour and the fraction of Comptonization inferred from the spectrum. There is, however, one exception – a cluster of points from GRO J1655–40 around colours (1.25, 0.20). They lie almost on the disc blackbody line and their spectra *can* be fitted by the disc blackbody model with temperature of $\sim$ 1.4 keV. However, as shown by Kubota et al. (2001), these spectra can be also interpreted as emission from the disc of lower temperature plus additional Comptonization in an optically thick plasma. The details of spectral modelling differ slightly between Kubota et al. (2001) and this work, in particular we use a Comptonization model rather than a power law to characterize the tail. However, the general result is the same: these particular spectra can be fitted either by a dominating disc, or by a much weaker disc plus strong Comptonization. In Fig. 2 we show the unabsorbed model components of both fits. They both give a similar χ^2 but the disc-dominated model (left panel in Fig. 2) yields an unphysically small inner disc radius (see also Kubota et al. 2001). Therefore, we select the strongly Comptonized model (right panel in Fig. 2) as the more physically realistic. Since these spectra are then dominated by the Comptonized emission rather than by the disc they are excluded from further analysis.

4 SPECTRAL MODELLING

For the *RXTE* sources we use the same data selection as DG03, i.e. extract one Proportional Counter Array (PCA) spectrum per one pointing (designated by a unique observation ID), typically giving exposures of a few kiloseconds. We use data from detectors 0, 2 and 3, top layer only, except for GRO J1655–40 and XTE J1739–278, where detector 3 was off most of the time, so we used detectors 0 and 2 only. We fit these spectra in 3–20 keV band, after adding 1 per cent systematic error in each energy channel. For the *Ginga* observations of GS 1124–68 we use the spectra extracted by Życki et al. (1998) and fit these over the 2–20 keV bandpass with 0.5 per cent systematic error.

We follow DG03 and fit the data with a model consisting of multicolour disc blackbody (DISKBB in XSPEC) and its thermal Comptonization (Zdziarski, Johnson & Magdziarz 1996). We add a Gaussian line and smeared edge in the iron Kα complex to approximately account for the effects of Compton reflection. This adequately fits *all* the data from all black hole (and neutron star) spectral states (DG03). We stress that though the model is highly simplified, it is appropriate for our purpose. We are not interested here in detailed spectral modelling of Comptonized emission (which is probably non-thermal rather than thermal in the soft

Source Name	M ($M_\odot$)	D (kpc)	i (deg)	N_H (10^{22} cm^{-2})
LMC X-3	7 (5–11)^a	52 (51.4–52.6)^b	60 (50–70)^c	0.07^d
LMC X-1	10 (4–12.5)^e	52 (51.4–52.6)^b	45 (24–64)^e	0.5^f
GS 1124–68	7 (6.4–7.6)^g	2.8 (2.8–4)^h	54 (52.5–55.5)^g	0.16^i
XTE J1550–564	10 (9.7–11.6)^j	5.3 (2.8–7.6)^j	72 (70.8–75.4)^j	0.65^k
XTE J1650–500	[10]	4 (2–6)^l	30 (<40)^m	0.78^n
GRO J1655–40	7 (6.8–7.2)^o	3.2±0.2^p or 0.9±0.1^q	70 (64–71)^r	0.8^f
GX 339–4	6 (2.5–10)^s	4 (2.6–5)^t	40 (20–60)^s	0.6^t
GRS 1739–278	[10]	8.5 (6–11)^u	[60]	2^u
XTE J1859+226	[10]	7.6 (4.6–8)^v	[60]	0.8^w
XTE J2012+381	[10]	[8.5]	[60]	1.3^x

Table 1. The list of the sources used in this paper, together with assumed mass (M), distance (D), disc inclination (i) and absorption column (N_H) and their uncertainties. The numbers in square brackets correspond to assumed values where the constraints are not known. The numbered references are as follows: [a] Soria et al. 2001 [b] di Benedetto 1997 [c] Cowley et al. 1983 [d] Haardt et al. 2001 [e] Hutchings et al. 1987 [f] Gierliński, Maciołek-Niedźwiecki & Ebisawa 2001 [g] Gelino, Harrison & McNamara 2001 [h] Shahbaz, Naylor & Charles 1997 [i] Życki, Done & Smith 1998 [j] Orosz et al. 2002 [k] Gierliński & Done 2003 [l] Tomsick et al. 2003 [m] Sánchez-Fernández et al. 2002 [n] Miller et al. 2002 [o] Shahbaz et al. 1999 [p] Hjellming & Rupen 1995 [q] Mirabel et al. 2002 [r] van der Hooft et al. 1998 [s] Cowley et al. 2002 [t] Zdziarski et al. 1998 [u] Greiner, Dennerl & Predehl 1996 [v] Hynes et al. 2002 [w] dal Fiume et al. 1999 [x] Campana et al. 2002

state: Gierliński et al. 1999) nor in its reflection. Since we select the only disc-dominated spectra, the details of the Comptonization/reflection modelling affect the disc results only very weakly. On the other hand, our Comptonization model includes a proper low-energy cutoff around seed photon energy, which *is* important. An extrapolation of a power law to low energies predicts much more flux in the tail at the seed photon energy than that given by a Comptonization model. This decreases the inferred disc flux, especially for the steep tails associated with the soft states (see e.g. Done, Życki & Smith 2002).

The highest disc temperature in the sample is $\approx$ 1.3 keV. The maximum power of the DISKBB model is emitted at around $2.4kT_{\rm max}$. The useful observing bandpass of the PCA extends down to about 3 keV, below which the detector's sensitivity rapidly drops and systematic uncertainties become important. This means that the PCA can only seldom observe the peak of the disc emission, though it can still see a large fraction of its Wien tail. For example, a multicolour disc with $kT_{\rm max} = 0.5$ keV has an amplitude of $\sim$ 30 per cent of maximum at 3 keV in a $\nu F(\nu)$ spectrum. Therefore it is feasible for the PCA to effectively measure the observed disc temperatures down to $\sim$ 0.5 keV. While fitting the spectra we limit $kT_{\rm max} \geqslant 0.4$ keV (or 0.3 keV for the *Ginga* data as these have bandpass down to 2 keV) and reject observations for which the measured $kT_{\rm max}$ are consistent with this lower limit (within statistical errors) as potentially unconstrained.

The temperature of the Comptonized component is difficult to constrain from the PCA data alone, particularly in the soft state, where the high-energy tail is weak. Leaving this parameter free makes deriving uncertainties of the disc parameters difficult for most of the soft-state spectra. Therefore, we fix it at 50 keV, which is well above the high energy limit of the PCA data of 20 keV. This makes no difference to the derived disc parameters from the disc-dominated spectra.

This model fits the data very well indeed. We fit all the observations in XSPEC, obtaining reduced $\chi^2/\nu < 1.5$ (except for one GRO J1655–40 observation with strong absorption lines, see Ueda et al. 1998). As a result we get the disc temperature, $T'_{\rm max}$, and the unabsorbed, bolometric disc flux F'. From this we calculate the luminosity in Eddington units, $L_{\rm disc}/L_{\rm Edd}$, and temperature corrected for relativistic effects, $T_{\rm max}$, using formulas (4) and (5), assuming a non-rotating black hole, $a_* = 0$ and mass and distance for each source from Table 1.

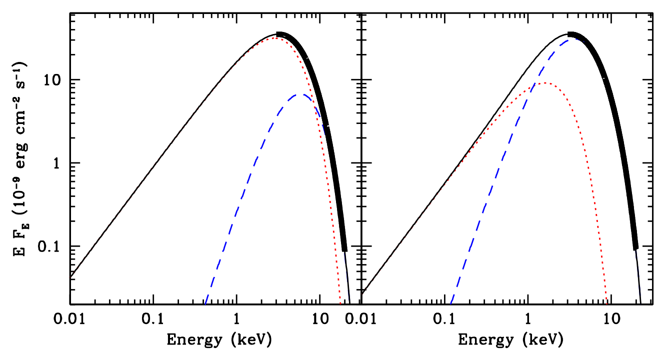

Figure 2. Unabsorbed model components fitted to the spectrum of GRO J1655–40 corresponding to a point in the colour-colour diagram (Fig. 1, left panel) of colours (1.25, 0.20). The softer component (dotted line) represents the disc emission, the harder one (dashed line) – its Comptonization. The heavy line depicts the observed data. The two different models presented here give a similar fit to the data. However, the disc-dominated model (on the left) requires an unphysically small inner disc radius.

5 RESULTS

The observed disc temperature-luminosity (hereafter T-L) relations are presented in Figs. 3 and 4. They are roughly consistent with $L_{\rm disc} \propto T^4_{\rm max}$ for all the sources over a broad range of luminosity. This means there can be only little change in $f_{\rm col}$ with accretion rate.

In each of the figures we also plot the expected T-L relation from Eq. (3) for a colour-correction factor of $f_{\rm col} = 1.8$. Obviously, the calculated $T_{\rm max}$ and $L_{\rm disc}/L_{\rm Edd}$ depend on rather uncertain values of the distance, mass and inclination angle (and unknown black hole spin). The major uncertainties from distance and mass are included in the figures; the cyan (or light grey in B&W) shadows above/below the data points correspond to the upper distance and lower mass/lower distance and upper mass estimates, respectively. For three sources: XTE J1650–500, GRS 1739–278 and

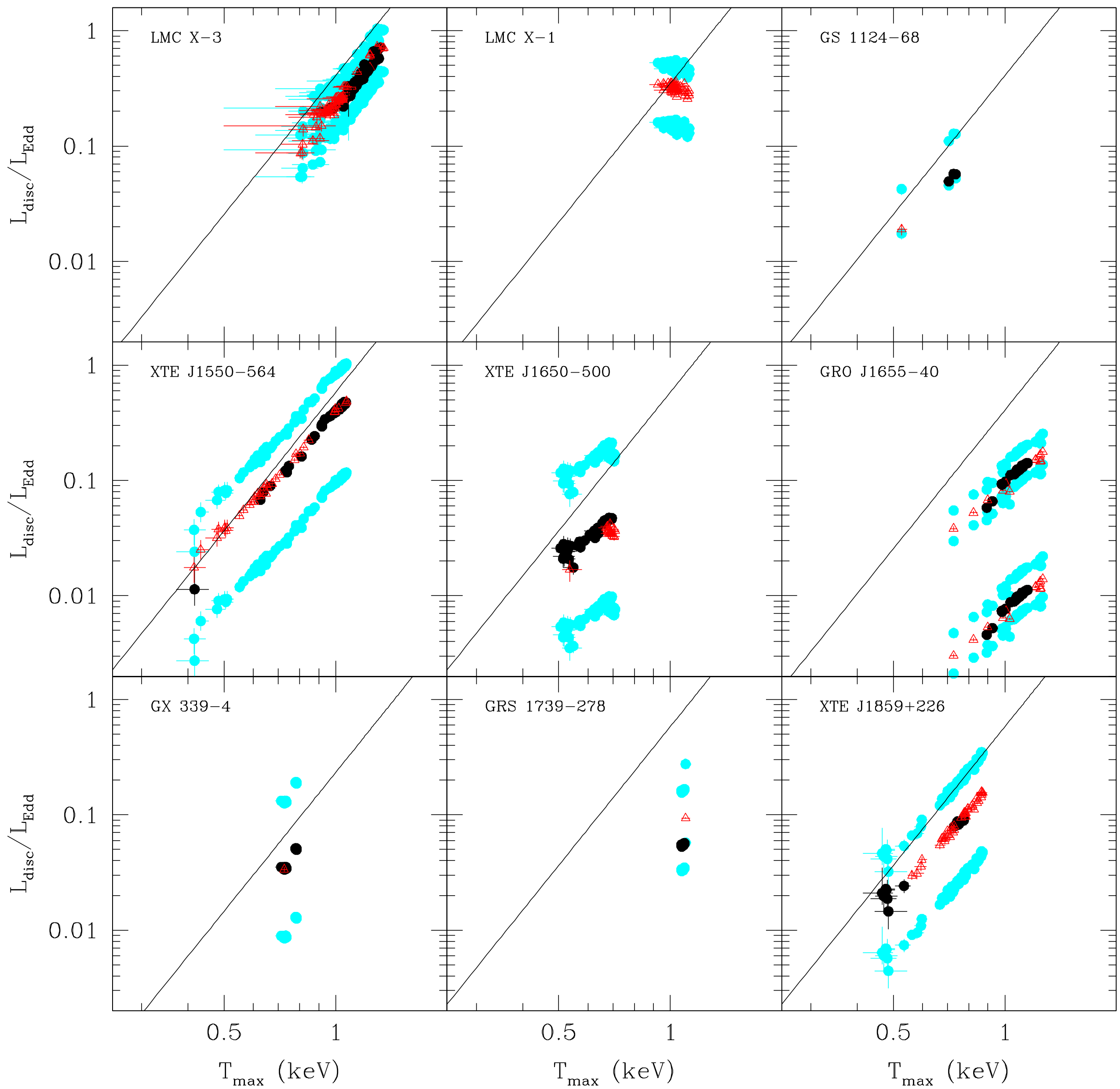

Figure 3. Disc luminosity versus its maximum temperature in nine sources from Table 1 (XTE J2012+361 is shown separately in Fig. 4). The black filled circles and red open triangles have the same meaning as in Fig. 1. The cyan (or light grey in B&W) points represent lower and upper limits on the data resulting from uncertainties in the distance and black hole mass (see Table 1). The lower and upper data points of GRO J1655–40 correspond to distances of 0.9 ± 0.1 (Mirabel et al. 2002) and 3.2 ± 0.2 kpc (Hjellming & Rupen 1995), respectively. The diagonal line plotted in each panel represents a relation $L_{\rm disc} \propto T_{\rm max}^4$ for a non-rotating black hole (Eq. 3), calculated for the best-estimated mass (Table 1) and $f_{\rm col} = 1.8$. See electronic edition of the journal for a colour version of this figure.

XTE J1859+226, where the mass is unknown, we have assumed a ‘canonical’ black hole mass of 10 $M_\odot$ with error range of 5–12 $M_\odot$ following the mass distribution of known sources (Bailyn et al. 1998). In case of XTE J2012+381 there are no mass or distance estimates whatsoever, so we plot its results in a separate figure (Fig. 4) for representative values of M = 10 $M_\odot$ and D = 10 kpc.

We stress that though both $T_{\rm max}$ and $L_{\rm disc}/L_{\rm Edd}$ depend on uncertain parameters, for a given source its distance, mass, spin and inclination are *constant*. Therefore, the *shape* of the pattern it traces in the T-L diagram is robust. In particular, most of the observed sources follow a straight line in the T-L diagram (which is a log-log plot) corresponding to a $L_{\rm disc} \propto T_{\rm max}^4$ relation. This can be particularly clearly seen for LMC X-3 (see also Kubota et al. 2001), XTE J1859+226 and XTE J2012+381.

XTE J1550–564 is particularly interesting, since it spans almost two orders of magnitude in luminosity. It generally follows $L_{\rm disc} \propto T_{\rm max}^4$ relation, though there is a small departure from this: with increasing temperature it seems to be slightly underluminous. This is particularly pronounced above $kT_{\rm max} \approx 0.9$ keV where a break in the T-L relation can be seen. This has been also reported by Kubota & Makishima (2003), who noticed that the data above the break is consistent with $L_{\rm disc} \propto T_{\rm max}^2$. They refer to this as the *apparently standard regime*, and suggest that it is associated with a transition to a slim disc (Abramowicz et al. 1988). However, this should only occur at/above $L_{\rm Edd}$ (Abramowicz et al. 1988; Shimura & Manmoto 2003), so it seems more likely to represent a subtle change in colour temperature correction.

Other subtle deviations from a constant colour temperature correction can also be seen. LMC X-1 does not show much variability, but over the observed small range it has an apparent anticorrelation of temperature and luminosity. XTE J1650–500 shows similar behaviour at the high-temperature end of the T-L diagram, where data points depart from the $T_{\rm max}^4$ line. In both cases the observations in question show larger fraction of Comptonized luminosity. They might belong to the *anomalous regime* (Kubota et al. 2001; Kubota & Makishima 2003), where Comptonization of the disc becomes important. We note that the points on the low-temperature end of XTE J1650–500 have significant error bars and are consistent with $L_{\rm disc} \propto T_{\rm max}^4$ relation.

The overall consistency of the disc-dominated data with $L_{\rm disc} \propto T_{\rm max}^4$ relation means there is little change in $f_{\rm col}$ with luminosity (see Eq. 3). The slight departures from this relation, seen in GRO J1655–40 and XTE J1550–564 correspond to $f_{\rm col}$ increasing with luminosity. This is an important observational constraint on disc models. Shimura & Takahara (1995) and Merloni et al. (2000) both calculate the colour temperature correction expected from a standard SS73 disc around a black hole, including radiative transfer through the vertical structure of the disc. Their predictions are shown in Fig. 5, together with the XTE J1550–564 data. The observations are clearly inconsistent with the Merloni et al. (2000) results, which predict a significant decrease of $f_{\rm col}$ with luminosity. This shows that the vertical structure is *not* as assumed in these calculations. On the other hand, these data *are* consistent with predictions of Shimura & Takahara (1995), which are marked by stars in Fig. 5.

The absolute value of $f_{\rm col}$ (as opposed to its rate of change with $L_{\rm disc}/L_{\rm Edd}$) is somewhat more complex to constrain. At a given $L_{\rm disc}/L_{\rm Edd}$ the temperature can be higher if the black hole is spinning, or if there is continuous stress at the last stable orbit as opposed to the stress-free boundary condition. However, none of these effects will push the temperature *down*. For the best constrained source, GS 1124–68, the data show that the maximum value of the colour temperature correction is $\sim$ 2.3. For other sources it can be much higher. There is no stringent lower limit on $f_{\rm col}$ from the data, as the same T-L relation can be characterized be a black hole with higher spin and smaller $f_{\rm col}$. Therefore, a conservative minimum value of $f_{\rm col}$ is unity, i.e. we see a true blackbody spectrum. However, this seems entirely unlikely given the high temperature and associated low absorption opacity. The lowest $f_{\rm col}$ suggested in this case is ~ 1.6 (Shimura & Takahara 1995). Considering GS 1124–68 to be a representative source, we can roughly limit $f_{\rm col}$ to be between 1.6 and 2.3.

Thus the use of $f_{\rm col} = 1.8$ seems to be well justified. Many of the sources in Fig. 3 lie close to the T-L line for a Schwarzchild black hole with stress-free inner boundary condition. Again, the well constrained objects give the most information. A colour temperature correction of 1.8 implies that LMC X-3 and GS 1124–68 are neither spinning *nor* have large amounts of energy released via continuous stress across the last stable orbit. Zero spin is clearly not a problem, but the lack of stress at the inner boundary is in conflict with the numerical simulations of (non-radiative) disc structure (Agol & Krolik 2000).

Several of the sources lie below the expected T-L line, most noticeably GRO J1655–40 (especially when D = 0.9 kpc is assumed) and GRS 1739–278. Since we have already constrained the colour temperature correction and stress at the inner boundary then the only parameter left to change is spin. A spinning black hole might also have a different colour temperature correction or boundary stress condition, but we assume these stay constant to demonstrate the effect of the black hole spin. Since the position of the T-L line predicted by Eq. (3) depends on the mass of the source, this creates another source of uncertainty. Therefore, we look at two sources with relatively precise mass estimates, namely XTE J1550–564 and GRO J1655–40. In Fig. 6 we plot their T-L diagrams once again, but this time assuming a maximally rotating black hole ($a_* = 0.998$, with the T-L relation taken from Page & Thorne 1974). Clearly, XTE J1550–564 is not consistent with a maximal spin, while GRO J1655–40 can be maximally rotating if its distance is given by the most recent determination of 0.9 kpc (Mirabel et al. 2002).

All the accretion discs observed here are apparently stable and show no sign of the limit-cycle variability expected at high accretion rates. To confirm this, we examine the light curves (16-s resolution) corresponding to analysed spectra. They are typically very smooth, with rms variability not exceeding 4 per cent. Only in the highest coronal fraction observations of LMC X-1 and GRO J1655–40 can the rms can reach 8–10 per cent.

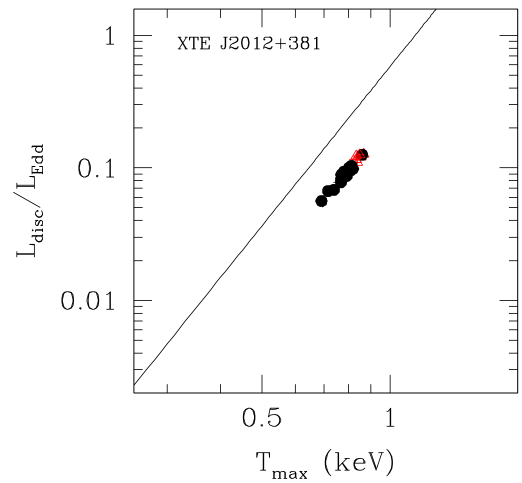

Figure 4. Disc luminosity versus its maximum temperature for XTE J2012+361. See Fig. 3 for description of symbols and the diagonal line. There are no constraints for mass or distance for this source and we assume M = 10M$_\odot$, D = 10 kpc and $i = 60°$.

6 THEORETICAL COLOUR TEMPERATURE CORRECTIONS

Fig. 3 shows that in general the disc-dominated spectra have $L_{\rm disc} \propto T_{\rm col}^{1/4}$. This implies a *constant* colour temperature correction over a wide range of luminosity. This is somewhat unexpected from theoretical models of disc structure, as these predict that the emitted spectrum is formed under rather different conditions for different accretion rates, $\dot{m}_{\rm disc}$ ($\equiv \eta \dot{M}_{\rm disc} c^2/L_{\rm Edd}$, where accrestion efficiency $\eta = 1/16$). The first regime is at low $\dot{m}_{\rm disc}$ where the opacity is dominated by absorption processes and scattering is unimportant. The spectrum from a single radius is then very close to a simple blackbody of temperature $T_{\rm eff}$, so $f_{\rm col} = 1$. What we see should be close to the disc blackbody predictions.

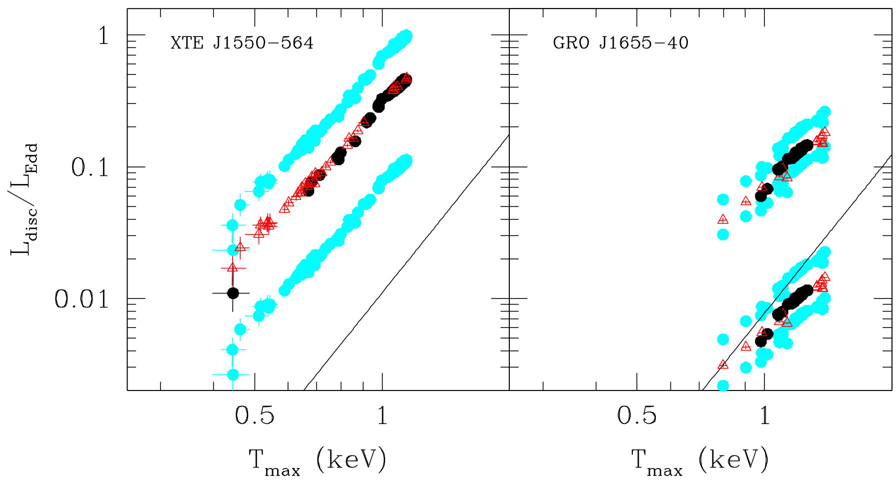

Figure 6. Temperature-luminosity diagram for two sources selected from Fig. 3, but for a maximally rotating black hole ($a_* = 0.998$). In this figure the diagonal line was calculated using formulae from Page & Thorne (1974).

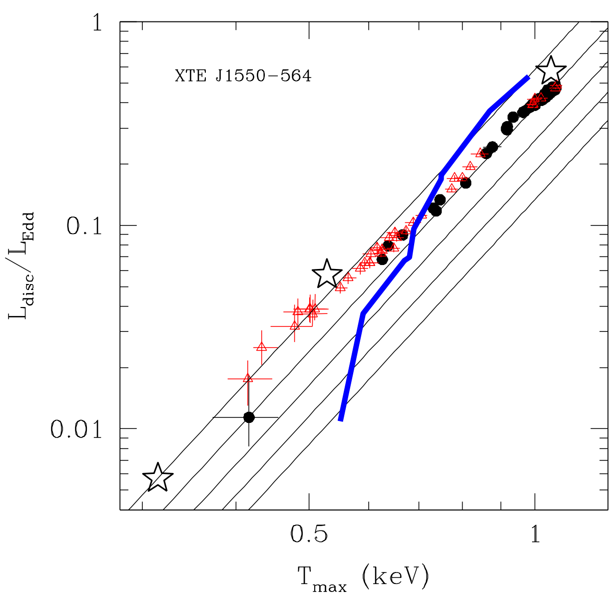

Figure 5. Disc luminosity versus its maximum temperature for XTE J1550–564 taken from Fig. 3. For clarity, we don't show distance/mass uncertainties, i.e. the data points here correspond to D = 5.3 kpc and M = 10 $M_\odot$. The diagonal lines are calculated for different values of the colour-correction factor, f_{col} = 1.8, 2.0, 2.2, 2.4 and 2.6 (from top to bottom). The overplotted thick line is the expected T-L relation from Merloni et al. (2000), which predicts significant decrease in f_{col}, with increasing accretion rate. Contrary to this prediction, the data are consistent with f_{col} remaining constant (or perhaps slightly increasing) over a very wide range of disc luminosity. The three stars represent calculations of Shimura & Takahara (1995), which are in agreement with the data.

At higher $\dot{m}_{\rm disc}$ the temperature rises and the absorption opacity drops, so scattering can become important. The spectrum is distorted from a true blackbody to a modified blackbody (e.g. Rybicki & Lightman 1979). This has a lower emissivity than a blackbody, but must still dissipate the same amount of gravitational energy, so its 'temperature' needs to be higher. Since the modified disc blackbody spectrum depends on the absorption opacity, it is also dependent on the density structure of the plasma. The resultant spectrum differs depending on whether the density structure is constant with height (radiation pressure dominated) or Gaussian (gas pressure dominated: see equations 3.6 and 3.7 and fig. 2 of SS73). However, there is also a further effect which is that radiation can escape from much deeper into the disc, where the material is hotter. Both these effects give an observed temperature which is higher than $T_{\rm eff}$, so $f_{\rm col} > 1$.

At even higher $\dot{m}_{\rm disc}$, the absorption opacity is so small that scattering dominates. Emission from deep in the disc (very hot material) can escape to the surface without being absorbed, but it is downscattered by its many interactions with electrons in the cooler outer layers of the disc. The spectrum is dominated by a Wien peak, again giving $f_{\rm col} > 1$ (see fig. 2 of SS73).

Merloni et al. (2000) and Shimura & Takahara (1995) show detailed calculations of the spectra from standard α-viscosity accretion discs. Both find that Compton down-scattering and the vertical temperature structure give rise to $f_{\rm col} \sim 1.8$ at high $\dot{m}_{\rm disc} \gg 0.1$, where the disc is dominated by radiation pressure. However, their calculations differ at low $\dot{m}_{\rm disc} \ll 0.1$ where the disc becomes gas pressure dominated (see Fig. 5). Both Merloni et al. (2000) and Shimura & Takahara (1995) agree that Compton down-scattering is not important in these spectra, but disagree on the resulting colour temperature correction, giving $f_{\rm col}$ = 2.7 and 1.8, respectively.

There are potential problems with both sets of calculations. Shimura & Takahara (1995) do not include heavy element opacity, so underestimate the true absorption in the disc, especially at low $\dot{m}_{\rm disc}$. Merloni et al. (2000) do include these elements, but they assume that the vertical density profile is always given by that of a radiation pressure dominated disc i.e. is constant with height (SS73; Ross & Fabian 1996). However, their lowest $\dot{m}_{\rm disc}$ calculations, where the colour temperature correction becomes very large, give a gas pressure dominated disc. Given that these calculations are in the modified disc blackbody regime, this would overpredict the temperature as the constant density discs give a larger colour temperature correction than the gas pressure dominated ones (fig. 2 of SS73). The extent of this overestimate can be estimated for an isothermal atmosphere from equations 3.6 and 3.7 of SS73 as $\sim 1.66/1.2 = 1.38$, which reduces the Merloni et al. (2000) prediction to $f_{col} \sim 1.9$.

Thus with self-consistent vertical density structure, it appears that *both* Merloni et al. (2000) and Shimura & Takahara (1995) predict that the spectral hardening factor for Shakura-Sunyaev discs is more or less constant over the range of $\dot{m}_{\rm disc}$ explored here, as observed.

7 DISC STABILITY

Standard α-discs are viscously and thermally unstable when radiation pressure, $P_{\rm rad}$, dominates over gas pressure, $P_{\rm gas}$. This is because the α-viscosity prescription assumes that the viscous heating rate is proportional to the total pressure $P_{\rm tot} = P_{\rm rad} + P_{\rm gas}$. A small increase in mass accretion rate produces a small rise in temperature, which leads to a much larger increase in heating in the radiation pressure dominated regime (as $P_{\rm rad} \propto T^4$) than in the gas pressure dominated case (where $P_{\rm gas} \propto T$). Radiative cooling cannot keep pace with the intense heating in the radiation pressure dominated disc, so these α-discs are unstable at this point. The runaway heating can be halted when the α-disc equations are extended to include radial energy transport (optically thick advection). The advective cooling can balance even the intense $P_{\rm rad}$ heating, so these *slim* discs are stable (Abramowicz et al. 1988).

However, while the $\dot{m}_{\rm disc}$ at which the disc becomes radiation pressure dominated is well defined, this merely marks the point at which the disc becomes *locally* unstable at a given radius. To translate this into *global* limit cycle of the inner disc requires that the instability can propagate to neighbouring radii, and this depends on details of the disc structure equations. Global numerical simulations with simple vertical disc structure show that this leads to limit cycle behaviour at $\dot{m}_{\rm disc} = 0.06$ (Honma et al. 1991; Szuszkiewicz & Miller 1997; 1998; Zampieri et al. 2001), while a more sophisticated vertical structure treatment shows that the disc is *globally* (but not locally) stable up to $\dot{m}_{\rm disc} = 0.28$ (Janiuk, Czerny & Siemiginowska 2002).

The objects observed here span the range $0.01 \lesssim L/L_{\rm Edd} \lesssim 0.5$ and *all* of them are stable. The unusual microquasar GRS 1915+105 (not included in our sample) is the *only* source which shows variability which can be interpreted as this limit-cycle (Belloni et al. 1997). One possible explanation for this unique behaviour might be that GRS 1915+105 goes to higher $L/L_{\rm Edd}$ than the sources considered here, i.e. that the Shakura-Sunyaev disc models are indeed correct in predicting that there should be a radiation pressure instability, but that they underestimate the accretion rate required for the onset of the limit-cycle.

Plainly, the disc structure is different to that predicted by the standard α-prescription. Either there are additional cooling mechanisms which act to stabilize the intense viscous heating predicted by these models, and/or the α-prescription for viscous heating is incorrect.

7.1 Additional Cooling Mechanisms

The disc is cooler if some fraction, f, of the gravitational potential energy released by viscous heating is dissipated outside of the optically thick disc. This could also be associated with a mass accretion rate, $\dot{m}_{\rm loss}$, so that the total mass accretion rate is $\dot{m} = \dot{m}_{\rm disc} + \dot{m}_{\rm loss}$.

In the limit of $\dot{m}_{\rm loss} = 0$ the disc structure can be derived under the standard α-viscosity prescription (Svensson & Zdziarski 1994). The disc is less luminous and cooler for a given $\dot{m}_{\rm disc}$, or alternatively, for a given disc luminosity and temperature the disc is denser, delaying the onset of the radiation pressure instability (Svensson & Zdziarski 1994). The obvious candidate for this energy loss channel is in powering a corona above the disc, since hard X-ray emission is generally seen from these systems. However, we have chosen to use only spectra which have $f \lesssim 0.15$, where Svensson & Zdziarski (1994) show that the stability of the disc is very little changed from that of the straightforward SS73 disc. These models do not include irradiation of the disc by this corona, but again the limit of 15 per cent of the power dissipated in the hard X-ray emission means that it has very small effect on the disc structure (e.g. Nayakshin et al. 2000a).

Another candidate energy loss mechanism is to power an outflowing wind or jet. Jets are commonly seen from black hole binaries *except* when their spectra are disc dominated (e.g. Fender & Kullkers 2001), ruling this out as a major energy loss route. Winds could be present, but line driving mechanisms which can power most of the mass loss inferred from the UV emitting discs around supermassive black holes and white dwarfs are *not* efficient in the much higher temperature X-ray binary discs (Proga & Kallman 2002). A magnetically driven wind is the only remaining possibility, in which case the results depend on the form of the wind (e.g. Nayakshin, Rappaport & Melia 2000b). However, such a wind would have to be unfeasibly powerful in order to stabilise the disc. Svensson & Zdzairski show that more than 95 per cent of the energy must be dissipated in an invisible energy loss channel in order to produce a stable disc at radiating at $L_{\rm disc}/L_{\rm Edd} = 0.5$.

Models in which the energy dissipation is also associated with some fraction of the mass accretion are no better. In the limit where the $f = \dot{m}_{\rm loss}/\dot{m}_{\rm disc}$, i.e. the energy released in the disc and alternative loss channel are proportional to their mass accretion rates, the disc is identical to a standard Shakura-Sunyaev disc with accretion rate $\dot{m}_{\rm disc}$ i.e. is unstable over the observed $0.01 \lesssim L/L_{Edd} \lesssim 0.5$, and there is no obvious identification of this proposed energy/mass loss channel. A hard X-ray corona is still ruled out from lack of hard X-ray emission, jets are still ruled out from lack of radio emission, and (unobserved) winds would still need to be very powerful in order to stabilise the disc. However, these models also include the energy exchange (via conduction and radiation) between the two accreting phases in the case of a corona. These 'accreting corona' models calculate the vertical structure associated with an standard α-disc, and show that a hot skin can develop over the main body of the disc. However, this corona is always optically thin, and becomes negligible at the high $L/L_{\rm Edd}$ considered here (Witt, Czerny & Życki 1997; Różańska & Czerny 2000), so has no effect on the disc stability.

7.2 Alternative viscosity prescriptions

The difficulties of avoiding the radiation pressure instability with standard α-discs make alternative prescriptions attractive. One old idea is to replace the α-viscosity (in which the heating is proportional to the total pressure, $P_{\rm tot} = P_{\rm gas} + P_{\rm rad}$) with one which simply depends only on $P_{\rm gas}$. Such discs (hereafter termed β-discs) are stable even when dominated by radiation pressure (Lightman & Eardley 1974; Sakimoto & Coroniti 1981; Stella & Rosner 1984), since the heating is always $\propto T$.

While such models trivially solve the disc stability, they give a very different disc structure and hence predict different behaviour for colour temperature correction as a function of accretion rate. For low $\dot{m}_{\rm disc}$, where gas pressure dominates, then the β- and α-

disc structures are identical, hence should have $f_{\rm col} \sim 1.8$ (see Section 6). However, at high $\dot{m}_{\rm disc}$, where radiation pressure dominates, the density of the β-disc is much larger than that of the standard α-disc (Stella & Rosner 1984), though the disc thickness is unchanged (Stella & Rosner 1984). Compton down-scattering is not important in these spectra at any $\dot{m}_{\rm disc}$ (Nannurelli & Stella 1989), so the disc spectrum is in the modified blackbody regime. Its shape at any radius depends on how the density and temperature change as a function of height in the disc (SS73). While full calculations have yet to be done, we can use the α-disc calculations in a comparable regime (radiation pressure dominated, but where the emission is not strongly Comptonized) to estimate the resulting colour temperature corrections. This corresponds to the lowest $\dot{m}_{\rm disc}$ of the Merloni et al. (2000) calculations, i.e. to $f_{\rm col} \sim 2.7$. Thus it seems that the β-disc viscosity predicts $f_{\rm col}$ increasing from ~ 1.8 at low $\dot{m}_{\rm disc}$ to ~ 2.7 at high $\dot{m}_{\rm disc}$. This is strongly at odds with what is observed, leading us to conclude that the $\alpha P_{\rm gas}$ heating law is ruled out observationally (see also Janiuk et al. 2001).

Thus *none* of the *ad hoc* viscosity prescriptions appears able to give a disc structure which matches both the observed colour temperature corrections and stability. The answer probably lies in the next generation of accretion disc models which will superseded these *ad hoc* viscosity prescriptions. The physical mechanism for angular momentum transport is now known to be the magneto-rotational instability (MRI: Balbus & Hawley 1991). Numerical MHD simulations of the global disc structure of gas pressure dominated discs show that the α-prescription applies approximately in the disc body (with vertically integrated $\langle\alpha\rangle = 0.1$). However, these also show strong gradients in the ratio of viscous heating to pressure in both radial and vertical directions, and large fluctuations in the heating as a function of time at any point (e.g. Hawley & Balbus 2002). For the bright discs considered here, radiation pressure strongly affects the dynamics, and the mechanics of the MRI induced turbulence changes (Agol & Krolik 1998; Blaes & Socrates 2001). The coupled radiation and magneto-hydrodynamics is a difficult and very computationally intensive problem, but preliminary results indicate that the average heating is unlikely to be proportional to total pressure, as in the standard α-disc (Turner, Stone & Sano 2002; Turner et al. 2003). Even if it were, the MRI induced turbulence and associated convection may lead to enhanced cooling rates (Turner et al. 2002; 2003)

Self-consistent disc models open up the possibility of being able to *calculate* the viscous heating and convective turbulent cooling associated with the MRI. When these models are sufficiently robust to predict the vertical disc structure and associated radiation spectra, then the data presented here offer a crucial test.

8 BLACK HOLE SPIN

'Black holes have no hair': they should be purely characterised by their mass and spin (any charge would always quickly be neutralized by accretion). The stellar remnant black holes all have very similar masses, so the only free parameter to give observable differences at the same (steady state) accretion rate is spin. Prograde spin drags the last stable orbit closer to the black hole, resulting in higher luminosity and temperature for a given accretion rate onto a spinning black hole compared to a Schwarzschild one. This shifts the expected T-L relation to the right (Fig. 3), giving an observable determination of the black hole spin (e.g. Zhang et al. 1997; Gierliński et al. 2001). Retrograde spin has the opposite effect, but is highly unlikely since the binary stars formed together from a single cloud, so spin and orbital angular momentum should be coupled.

Plainly, most of the black holes in this sample are consistent with Schwarzchild, lying on or close to the zero-spin T-L relation. LMC X-1, LMC X-3 and GS 1124–68, where the system parameters are tightly constrained, have very little room for even moderate spin. Conversely GRO J1655–40 and GRS 1739–278 have significant spin.

All these (apart from GRS 1739–278) were known previously: GS 1124–68 (Cui et al. 1997), GRO J1655–40 (Cui et al. 1997; Gierliński et al. 2001; Kubota et al. 2001), LMC X-3 (Cui et al. 1997; Kubota et al. 2001), LMC X-1 (Gierliński et al. 2001). What is new here is the size of the sample, which shows clearly that a constant colour temperature correction is a fairly good approximation. The rest of the objects have rather large uncertainties, and are compatible with moderate (but not extreme) spin. However, the fact that the best estimates for the system parameters put XTE J1550–564, GX 339–4, XTE J1650–500 and XTE J1859+228 so close to the Schwarzchild line is certainly suggestive, if not compelling.

Better system parameters from optical/infrared studies of the systems will reduce the uncertainties, and provide a clear determination of the black hole spin. This is especially important (but for different reasons) for two of the systems here. XTE J1550–564 has a superluminal radio jet (Hannikainen et al. 2001; Corbel et al. 2002), so confirmation of its Schwarzchild nature would provide a conclusive counterexample to the paradigm in which relativistic jets are triggered by black hole spin (e.g. Moderski, Sikora & Lasota 1998). XTE J1650–500 is claimed to have maximal spin from detailed fitting of the iron line profile in the X-ray spectrum (Miller et al. 2002). Currently, with no good mass estimate our data cannot constrain its spin, though in future it might give an independent measurement. Here the issues are even more emotive, as the line profile in XTE J1650–500 is similar to that of the AGN MCG–6–30-15 (Wilms et al. 2001), the defining example of a spinning black hole. We stress that the ultrasoft X-ray binary spectra offer an independent constraint on the spin, and hence give a check on iron line modelling.

9 CONCLUSIONS

We observe discs emitting in the luminosity range $0.01 \lesssim L_{\rm disc}/L_{\rm Edd} \lesssim 0.5$. Individual objects which span a large range in $L_{\rm disc}/L_{\rm Edd}$ are generally consistent with $L_{\rm disc} \propto T^4$, implying a constant colour temperature correction. In LMC X-3 and GS 1124–68, the distance, mass and inclination of the black hole are well constrained, giving $f_{\rm col} \sim 1.8$, and, by implication, require a Schwarzchild black hole. Conversely, for GRO J1655–40 and GRS 1739–278 the disc temperature requires moderate-to-high spin, i.e. a Kerr geometry. For black hole binaries which show disc-dominated spectra this gives an alternative way to check the inner disc geometry derived from modelling the relativistic smearing of the iron line and reflected spectra.

The observed range of $0.01 \lesssim L_{\rm disc}/L_{\rm Edd} \lesssim 0.5$ is where standard Shakura-Sunyaev models predict that the inner disc should be unstable due to the dominance of radiation pressure. The models predict limit-cycle behaviour in this range, yet observations show that the light curves are characterized by very little variability. These observations strongly require that the disc is stable in this range of $L_{\rm disc}/L_{\rm Edd}$.

Stability could be retrieved in the Shakura-Sunyaev disc models if the disc remains gas pressure dominated. This can be arranged if there are other cooling mechanisms (corona, jet, winds) which give a much denser disc for a given $\dot{m}_{\rm disc}$. However, since we choose only disc-dominated spectra, the coronal emission is negligible. These spectra are also always observed to have strongly quenched radio emission, so limiting the jet emission, while winds would have to be unfeasibly powerful. Hence there is only very limited potential for avoiding the conclusion that radiation pressure does dominate in our high $L_{\rm disc}/L_{\rm Edd}$ discs.

The only other known way to circumvent the radiation pressure instability is to change the viscosity prescription so that the disc heating is proportional to $P_{\rm gas}$ rather than the standard α-disc prescription where it is proportional to $P_{\rm tot} = P_{\rm gas} + P_{\rm rad}$. This avoids the tremendous increase in heating rate so the disc can remain stable even when dominated by radiation pressure. While proper calculations have yet to be made, it appears that such discs should have a colour temperature correction which changes $\sim$1.8 to $\sim$2.7 as $\dot{m}_{\rm disc}$ increases. Conversely, the standard α-discs predict that the colour temperature correction should remain stable at $\sim$1.8 for the range of $\dot{m}_{\rm disc}$ considered here. The observation that the colour temperature correction remains stable over a wide range in $L_{\rm disc}/L_{\rm Edd}$ appears to rule out the alternative viscosity prescription, and strongly supports the vertical structure as predicted by a standard α-disc.

This leads to an impasse. Observations show that the disc is most likely radiation pressure dominated, with standard α-viscosity. Such discs should undergo limit cycle behaviour, yet are observed to be stable. There are strong indications that the solution to this lies in the self-consistent heating and cooling generated by the MRI turbulence which is the physical source of the viscosity. While coupled radiative magneto-hydrodynamic calculations cannot yet predict the disc vertical structure in a robust way, this will probably become possible in the next few years.

Irrespective of the outcome of detailed calculations, it is clear that accretion disc spectra *can* constrain disc models. While spectra which contain a substantial Compton component at higher energies are indeed ambiguous, we challenge the Merloni et al. (2000) assertion that fitting the accretion disc spectrum gives results which are *not* in general directly related to the actual disc parameters. As also shown by Ebisawa et al. (1994), Kubota et al. (2001) and Kubota & Makishima (2003), the disc dominated spectra *can be* a reliable guide to the accretion disc structure.

ACKNOWLEDGEMENTS

We thank Omar Blaes, Bożena Czerny, Julian Krolik and Aya Kubota for useful discussions. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA's Goddard Space Flight Center.

REFERENCES

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Agol E., Krolik J., 1998, ApJ, 507, 304
Agol E., Krolik J. H., 2000, ApJ, 528, 161
Bailyn C. D., Jain R. K., Coppi P., Orosz J. A., 1998, ApJ, 499, 367
Balbus S. A., Hawley J. F., 1991, ApJ, 376, 214
Belloni T., Mendez M., King A. R., van der Klis M., van Paradijs J., 1997, ApJ, 488, L109
Blaes O., Socrates A., 2001, ApJ, 553, 987
Campana S., Stella L., Belloni T., Israel G. L., Santangelo A., Frontera F., Orlandini M., Dal Fiume D., 2002, A&A, 384, 163
Corbel S., Fender R. P., Tzioumis A. K., Tomsick J. A., Orosz J. A., Miller J. M., Wijnands R., Kaaret P., 2002, Sci, 298, 196
Cowley A. P., Crampton D., Hutchings J. B., Remillard R., Penfold J. E., 1983, ApJ, 272, 118
Cowley A. P., Schmidtke P. C., Hutchings J. B., Crampton D., 2002, AJ, 123, 1741
Cunningham C. T., 1975, ApJ, 202, 788
dal Fiume D., et al., 1999, IAUC, 7291, 2
di Benedetto G. P., 1997, ApJ, 486, 60
Done C., Gierliński M., 2003, MNRAS, 342, 1041
Done C., Życki P. T., Smith D. A., 2002, MNRAS, 331, 453
Ebisawa K., Mitsuda K., Hanawa T., 1991, ApJ, 367, 213
Ebisawa K., et al., 1994, PASJ, 46, 375
Eddington A. S., 1926, The Internal Constitution of the Stars. Cambridge University Press, Cambridge
Fender R. P., Kuulkers E., 2001, MNRAS, 324, 923
Frontera F., et al., 2001, ApJ, 546, 1027
Gelino D. M., Harrison T. E., McNamara B. J., 2001, AJ, 122, 971
Gierliński M., Done C., 2003, MNRAS, 342, 1083
Gierliński M., Zdziarski A. A., Poutanen J., Coppi P. S., Ebisawa K., Johnson W. N., 1999, MNRAS, 309, 496
Gierliński M., Maciołek-Niedźwiecki A., Ebisawa K., 2001, MNRAS, 325, 1253
Greiner J., Dennerl K., Predehl P., 1996, A&A, 314, L21
Haardt F., et al., 2001, ApJS, 133, 187
Hannikainen D., Campbell-Wilson D., Hunstead R., McIntyre V., Lovell J., Reynolds J., Tzioumis T., Wu K., 2001, ApSSS, 276, 45
Hjellming R. M., Rupen M. P., 1995, Nature, 375, 464
Honma F., Matsumoto R., Kato S., 1991, PASJ, 43, 147
Hutchings J. B., Crampton D., Cowley A. P., Bianchi L., Thompson I. B., 1987, AJ, 94, 340
Hynes R. I., Haswell C. A., Chaty S., Shrader C. R., Cui W., 2002, MNRAS, 331, 169
Janiuk A., Czerny B., Madejski G. M., 2001, ApJ, 557, 408
Janiuk A., Czerny B., Siemiginowska A., 2002, ApJ, 576, 908
Kubota A., Makishima K., 2003, ApJ, submitted
Kubota A., Makishima K., Ebisawa K., 2001, ApJ, 560, L147
Lightman . P., Eardley D. M., 1974, ApJ, 187, L1
McClintock J. E., et al., 2001, ApJ, 555, 477
Merloni A., Fabian A. C., Ross R. R., 2000, MNRAS, 313, 193
Miller J. M., et al., 2002, ApJ, 570, L69
Mirabel I. F., Mignani R., Rodrigues I., Combi J. A., Rodríguez L. F., Guglielmetti F., 2002, A&A, 395, 595
Mitsuda K., et al., 1984, PASJ, 36, 741
Moderski R., Sikora M., Lasota J.-P., 1998, MNRAS, 301, 142
Nannurelli M., Stella L., 1989, A&A, 226, 343
Nayakshin S., Kazanas D., Kallman T. R., 2000a, ApJ, 537, 833
Nayakshin S., Rappaport S., Melia F., 2000b, ApJ, 535, 798
Novikow I. D., Thorne K. S., 1973, in Black Holes, ed. C. De Witt & B. De Witt (New York: Gordon & Breach), 343
Orosz J. A., et al., 2002, ApJ, 568, 845
Paczyński B., Wiita P. J., 1980, A&A, 88, 23
Page D. N., Thorne K. S., 1974, ApJ, 191, 499
Proga D., Kallman T. R., 2002, ApJ, 565, 455
Ross R. R., Fabian A. C., 1996, MNRAS, 281, 637
Różańska A., Czerny B., 2000, A&A, 360, 1170
Rybicki G. B., Lighman A. P., 1979, Radiation Processes in Astrophysics, Wiley-Interscience, Nyew York
Sakimoto P. J., Coroniti F. V., 1981, ApJ, 247, 19
Sánchez-Fernández C., Zurita C., Casares J., Castro-Tirado A. J., Bond I., Brandt S., Lund N., 2002, IAUC, 7989, 1
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shakura N. I., Sunyaev R. A., 1976, MNRAS, 175, 613
Shimura T., Manmoto T., 2003, MNRAS, 338, 1013
Shimura T., Takahara F., 1995, ApJ, 445, 780

Shahbaz T., Naylor T., Charles P. A., 1997, MNRAS, 285, 607
Shahbaz T., van der Hooft F., Casares J., Charles P. A., van Paradijs J., 1999, MNRAS, 306, 89
Soria R., Wu K., Page M. J., Sakelliou I., 2001, A&A, 365, L273
Stella L., Rosner R., 1984, ApJ, 277, 312
Svensson R., Zdziarski A. A., 1994, ApJ, 436, 599
Szuszkiewicz E., Miller J. C., 1997, MNRAS, 287, 165
Szuszkiewicz E., Miller J. C., 1998, MNRAS, 298, 888
Tanaka Y., Lewin W. H. G. 1995, in X–Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs & E. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
Tomsick J. A., Kalemci E., Corbel S., Kaaret P., 2003, ApJ, in press
Turner N. J., Stone J. M., Sano T., 2002, ApJ, 566, 148
Turner N. J., Stone J. M., Krolik J. H., Sano T., 2003, preprint (astro-ph/0304511)
van der Hooft F., Heemskerk M. H. M., Alberts F., van Paradijs J., 1998, A&A, 329, 538
Wilms J., Reynolds C. S., Begelman M. C., Reeves J., Molendi S., Staubert R., Kendziorra E., 2001, MNRAS, 328, L27
Witt H. J., Czerny B., Życki P. T., 1997, MNRAS, 286, 848
Zampieri L., Turolla R., Szuszkiewicz E., 2001, MNRAS, 325, 1266
Zdziarski A. A., Johnson W. N., Magdziarz P., 1996, MNRAS, 283, 193
Zdziarski A. A., Poutanen J., Mikołajewska J., Gierliński M., Ebisawa K., Johnson W. N., 1998, MNRAS, 301, 435
Zhang S. N., Cui W., Chen W., 1997, ApJ, 482, L155
Życki P. T., Done C., Smith D. A., 1998, ApJ, 496, L25