Measurements of accretion disc corona size in LMXB: consequences for Comptonization and LMXB models

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ABSTRACT
We present results of measurements of the radial extent of the accretion disc corona in low mass X-ray binaries, i.e. of the radial extent of the thin, hot ADC above the accretion disc. These results prove conclusively the extended nature of the ADC, with radial extent varying from 20,000 km in the faintest sources to 700,000 km in the brightest, a substantial fraction of the accretion disc radius, typically 15 per cent. This result rules out the Eastern model for LMXB which is extensively used, in which the Comptonizing region is a small central region. The ADC size depends strongly on the 1 – 30 keV source luminosity via a simple relationship $r_{ADC} = L^{0.88 \pm 0.16}$ at 99 per cent confidence, which is close to a simple dependence $r_{ADC} \propto L$. We also present limited evidence that the ADC size agrees with the Compton radius $r_C$, or maximum radius for hydrostatic equilibrium. Thus, the results are consistent with models in which an extended ADC is formed by illumination of the disc by the central source. However, the dependence on luminosity may reflect the known decrease of coronal temperature as the source luminosity increases leading to an increase of $r_C$. The extended nature of the ADC means that the seed photons for Comptonization must consist of emission from the disc to the same radial extent as the corona, providing copious supplies of soft seed photons. We thus demonstrate the importance of the size of the ADC to the correct description of Comptonization, and we derive the Comptonized spectrum of a LMXB based on the thermal Comptonization of these seed photons and show that this differs fundamentally from that of the Eastern model, which assumes a cut-off in the spectrum below 1 keV. Finally, we argue that our results are inconsistent with the assumption often made that the X-ray emission of accreting Black Holes and Neutron Stars has a common mechanism depending on the properties of the accretion flow only.

Key words: accretion: accretion discs – binaries: close – stars: neutron – X-rays: binaries

1 INTRODUCTION
A major problem that has impeded understanding of Low Mass X-ray Binaries containing neutron stars over many years has been the controversy over the location and nature of the X-ray emission regions. Two radically different descriptions were developed in the mid-1980s, the Western model and the Eastern model. In the Western model, the dominance of Comptonization in the spectra of LMXB was acknowledged by modelling the spectra with the Generalised Thermal model having the form of a power law, cut off at high energies corresponding to the energy limit of Comptonizing electrons (White, Stella & Parmar 1988). The Eastern model assumes multi-temperature blackbody emission from the inner disc, plus emission from the neutron star providing the seed photons for the observed Comptonized emission (Mitsuda et al. 1989). Comptonization is assumed to take place either in the atmosphere of the neutron star or in a small, central region containing hot electrons. Both Western and Eastern model were generally capable of providing good fits to the spectra of LMXB, and so could not be discriminated between on this basis, although the values of model parameters obtained are sometimes not physically acceptable (see below). In the 1990s, there was increasing evidence that two emission components were present in all sources, whereas the Western model only needed a second component in bright sources. A new model (the Birmingham model) closely related to the Western model was proposed in which two continuum components exist in all LMXB, simple blackbody emission from the neutron star plus Comptonized emission from an extended accretion disc corona (ADC) above the accretion disc (Church & Baluci\-ni\-ska-Church 1995). The addition of the blackbody re-
sults in markedly different spectral fitting results compared with the Western model for parameters such as the cut-off energy (e.g. Church et al. 1998b). Clearly, the physical descriptions contained in the Birmingham model and the Eastern model are radically different and the failure to resolve which model is correct has been a major impediment to understanding. This includes understanding of the phenomena in LMXB, for example, the physical changes taking place during track movement in the Z-track and Atoll sources.

The Eastern model is extensively used. For example, the model has been applied in analysis of BeppoSAX data of XB1658-298 (Oosterbroek et al. 2001a), for GX3+1 and Ser X-1 (Oosterbroek et al. 2001b), and in studies of globular cluster sources (Sidoli et al. 2001). Done, Życki & Smith (2002) argued for the model on theoretical grounds and then applied the Eastern model to analysis of data on Cyg X-2, as was the case for 4U 1608-52 (Gierlinski & Done 2002). Barret, Olive & Oosterbroek (2003) used the Eastern model for BeppoSAX and RXTE observations of 4U 1812-12, but concluded that the blackbody emission was from the neutron star. Narita, Grindlay & Barret (2001) carried out spectral fitting of ASCA observations of GX 354-0 and KS 1731-260 and give a detailed discussion in terms of the models above. The physical description of the emitting regions can be made very specific by proponents of the Eastern model. For example, Done et al. (2002) assume that there is an intrinsic low energy cut-off in the spectrum at ~1 keV due to lack of low energy seed photons, and that the emission of the neutron star is probably buried beneath an optically thick boundary layer, leaving the disc and the boundary layer as the emitters. Seed photons can be from the inner disc or neutron star surface. It is assumed that the disc dominates the spectrum at low energies and the Comptonized boundary layer dominates at high energies. These assumptions have a major effect on the description of the X-ray emission, and will be reviewed in the context of the results of the present work in Sect. 4.

Theoreticians have in general considered it natural that the Comptonization region will be located close to the neutron star and so have supported the Eastern model (e.g. Kluzniak & Wilson 1991; Popham & Sunyaev 2001). Moreover, based on the similarity of the spectra of black hole binaries (BHB) and neutron star binaries that is sometimes claimed, and on similarities in their timing properties, there has been a tendency to assume a common mechanism for X-ray formation (e.g. Poutanen 2001). To be independent of the type of compact object, the mechanism must be a property of the accretion flow only. However, this makes the assumption that the X-ray emission of the neutron star does not modify substantially the geometry, properties and X-ray emission of the ADC. In the present work, we show that the evidence is against this assumption. Moreover, in neutron star systems there is strong evidence for neutron star blackbody emission, while in BHB there is disc blackbody emission.

In fact, the key to resolving the controversy of the correct emission model has lain with the dipping LMXB which provide more diagnostics of the emission regions that non-dipping sources and more strongly constrain spectral models. These sources having inclination angle between 65° and 85° exhibit orbital-related X-ray dips due to absorption in the bulge in the outer disc (White & Swank 1982; Walter et al. 1982). An acceptable description of spectral evolution in dipping in these sources requires fitting not only the non-dip spectrum but also the spectra of several levels of dipping, selected typically in intensity bands. Moreover, only absorption parameters can be allowed to vary in the fitting, and emission parameters must be held constant, so that fitting strongly constrains emission models in these sources. On the basis of such work, the Birmingham model was proposed by Church & Balucina-Church (1993, 1995). It was apparent from the start that one emission component was very extended, since this non-thermal component of the spectra was removed very slowly in dipping as the extended absorber overlapped an extended emission region (e.g. Church et al. 1997). It also became apparent that the ADC was thin (i.e. $H/r << 1$) since it would be very unlikely that 100 per cent deep dipping would be observed if the extended ADC was spherical, this requiring an absorber on the outer disc extending out of the orbital plane to very large distances. Application of the new model provided substantial evidence that the blackbody component was present in all sources in varying degrees. Over a period of years it has been shown that the model provides very good fits to all of the ~10 dipping sources (e.g. Church et al. (1997, 1998a, 1998b); Balucinska-Church et al. (1999, 2000); Smale, Church & Balucinska-Church (2001, 2002); Barnard, Church & Balucinska-Church (2001). It also fits well the Atoll and Z-track sources included in an ASCA survey of LMXB (Church & Balucinska-Church 2001) showing that the model describes well all classes of LMXB. Thus both the Eastern and the Birmingham models are two-component models, each having a thermal and a Comptonized component. However, it is difficult to decide from spectral fitting (a single spectrum) between the models. The crucial factor is, in fact, the origin of the Comptonized emission, which in the Eastern model is a small central region, i.e. of the order of 100 km radius or less, and in the model of Church and Balucinska-Church is very extended of radial extent typically 50000 km (Church 2001), i.e. 500 times larger. In the dipping sources, measurement of emission region sizes by the technique of dip ingress timing is possible, and this clearly holds the key to discriminating between these two models. Under conditions where the angular size of the absorber is larger than that of the extended emitter, the ingress time is determined by the size of the source. This condition will hold if dipping is 100 per cent deep at any energy, and we have applied the technique to several of the dipping LMXB (Church et al. 1998a, 1998b; Balucinska-Church, et al. 1999, 2000; Smale et al. 2001, 2002). In the present work, we have assembled our previous measurements of ADC size and have analysed further observations providing good quality dip data, and present the results in Sect. 2. These results do not allow the Eastern model to be possible. In the second part of the paper, we deal with the consequences of this. Specifically, the correct Comptonization model for LMXB or BHB depends strongly on the size of the Comptonizing ADC. We compare the Comptonized emission for the Eastern model with a small central Comptonizing region, with that taking place in the actual extended ADC revealed by our measurements. We thus show that the description of Comptonization in the Eastern model is not correct, and that use of this model in analysis will not produce correct results.
2 OBSERVATIONS AND ANALYSIS

The observations selected consist primarily of data obtained using the satellites ASCA, Rosat, BeppoSAX and Rossi-XTE previously analysed by us in detail as shown in Table 1. Apart from our proprietary observations, data are included resulting from our collaborations with ISAS, Japan, ESTEC in The Netherlands and LHEA in the USA. High quality data were used as discussed below, and we note that data from Chandra or XMM will not necessarily provide better values of ingress times, which vary between 100 and 16000 seconds, i.e. are not difficult to measure. Figure 1 shows a schematic of a LMXB (not to scale) including the accretion disc and the bulge on the outside of the disc responsible for X-ray dipping. The technique of dip ingress timing determines the overall radial extent $r_{ADC}$ of the corona, i.e. of the continuum emitting region. It cannot determine whether the ADC has any “inner” radius. The only way in which ingress times might not provide true values for the radial extent of the corona would be if the absorbing bulge on the outer accretion disc had a complex structure resulting in the gradual removal of intensity from a point-like corona. Attempts to model dipping in XB 1916-053 on this basis failed to reproduce the observed light curves (Zycki, private communication, 2001) and it appears that this possibility can be discounted. Also shown is a schematic of dip ingress and egress with ingress time $\Delta t$ for the case that the angular size of the absorber is larger than that of the extended emitter, the ADC, so that dipping is 100 per cent deep. This was the main criterion for inclusion of data, that dipping had to be $\sim$100 per cent deep in any energy band covered by the instrument used. Weak dipping at the 10 per cent level cannot be used as we cannot be certain that the absorber angular size is greater than the ADC angular size. Thus, data on the sources X 1755-338 and XB 1746-371 was not used, although data were available from Exosat and ASCA. Similarly, Rossi-XTE data or XB 1323-619 had only 50 per cent deep dipping.

We also rejected data in which dip ingress was poorly defined, not allowing sensible measurement of ingress times, such as the Rosat observation of XBT 0748-676. In the observations included in Table 1, typically containing 4 or more dips per observation, ingress times were only included in analysis for which the ingress was well-defined. Frequently this was not the case if Earth occultation or SAA passage caused data gaps during dipping. In observations containing several well-defined dips, such as the BeppoSAX observation of XB 1916-0563, an error estimate was obtained from the scatter of $\Delta t$ about the mean. In XBT 0748-676, we have revised upwards our previous value for $\Delta t$ (Church et al. 1998a).

The radius of the ADC, $r_{ADC}$ is related to the accretion disc radius $r_{AD}$ via the equation:

$$\frac{2\pi r_{AD}}{P} = \frac{2r_{ADC}}{\Delta t}$$

(1)

where $P$ is the orbital period. In each source we used the latest values of orbital period, including a period of 3000.6508 s for XB 1916-053 (Chou, Grindlay & Bloser 2001), and 20.8778 ± 0.0003 hr for X 1624-490 from our recent work on this source (Smale et al. 2001). The radius of the sphere having the same volume as the Roche lobe of the neutron star $r_{L1}$ was calculated from the expression of Eggleton (1983) accurate to 1 per cent:

$$r_{L1} = \frac{0.49 a (M_1/M_2)^{2/3}}{0.6 (M_1/M_2)^{2/3} + \ln(1 + (M_1/M_2)^{1/3})}$$

(2)

where $a$ is the separation of the stars in the binary system,
the parameters of the binary systems used. The fraction \( f \) in the ADC radial extent obtained is the error in the ingress depending on composition. The main source of uncertainty & Swank (1982), the change would be only 10 – 25 per cent a low mass white dwarf as suggested by White of the companion so that if it were assumed that the com-

\( M_1 \) is the mass of the neutron star, and \( M_2 \) is the mass of the companion star.

Masses of the companion stars were found using appropriate mass-period relationships, using the form for Main Sequence stars in the case of XB 1323-619, XB 1254-690, X 1624-490 and XBT 0748-676. It was assumed that the un-

Spectral fitting results previously obtained by us were used to provide the source fluxes in the band 1 – 30 keV, chosen to include as much of the spectrum as possible without requiring large extrapolations for data limited to 10 keV. Total source luminosities \( L_{1-30}^{\text{Tot}} \) in this band are shown in Table 1. In the case of the Exosat observation of X 1624-490, we obtained a background-subtracted spectrum from the HEASARC archive, and fitted this with the Birmingham two-component model, as the original fitting had used a one-

| source     | satellite | date            | \( L_{1-30}^{\text{Tot}} \) | \( d \) | \( \Delta t \) | \( P \) | \( r_{\text{AD}} \) | \( f \) | ref. |
|------------|-----------|-----------------|-----------------|-----|-----------|------|-------------|-----|-----|
| XB 1916-053 | Asca      | 1993, May 2     | \( 4.11 \times 10^{-36} \) | 9.0 | 160±48   | 0.834 | 2.02 | 3.39 | 16.8 | 1   |
| XB 1916-053 | Rosat     | 1992, Oct 17    | \( 3.28 \times 10^{-36} \) | 9.0 | 112±34   | 0.834 | 2.02 | 2.37 | 11.7 | 2   |
| XB 1916-053 | SAX       | 1995, Oct 13    | \( 3.91 \times 10^{-36} \) | 9.0 | 146±15   | 0.834 | 2.02 | 3.09 | 15.3 | 3   |
| XBT 0748-676 | Asca | 1993, May 7     | \( 3.98 \times 10^{-36} \) | 10.0 | 280±84   | 3.820 | 4.07 | 2.60 | 6.4  | 4   |
| XB 1323-619 | SAX       | 1997, Aug 22    | \( 3.21 \times 10^{-36} \) | 10.0 | 254±57   | 2.938 | 3.51 | 2.65 | 7.5  | 5   |
| XB 1254-690 | RXTE      | 2001, May 9     | \( 2.18 \times 10^{-37} \) | 12.0 | 950±190  | 3.933 | 4.14 | 8.72 | 21.1 | 6   |
| XB 1254-690 | Exosat    | 1984, Aug 6     | \( 1.25 \times 10^{-37} \) | 12.0 | 840±250  | 3.933 | 4.14 | 7.71 | 18.6 | 7   |
| X 1624-490  | RXTE      | 1999, Sep 27    | \( 1.44 \times 10^{-38} \) | 15.0 | 12500±2500 | 20.98 | 11.15 | 58.0 | 52.2 | 8.9 |
| X 1624-490  | Exosat    | 1985, Mar 25    | \( 1.10 \times 10^{-38} \) | 15.0 | 15500±2500 | 20.98 | 11.15 | 71.9 | 64.8 | 10  |

References: 1 Church et al. 1997; 2 Morley et al. 1999; 3 Church et al. 1998a; 4 Church et al. 1998b; 5 Balucińska-Church et al. 1999; 6 Smale et al. 2002; 7 present work; 8 Balucińska-Church et al. 2000; 9 Smale et al. 2001; 10 Church & Balucińska-Church 1995.
3 RESULTS

Fig. 2 displays two significant results: it confirms that the ADC is very extended as is also apparent from spectral fitting of dip spectra (Sect. 1), and secondly, there is a strong correlation between \( r_{ADC} \) and source luminosity, although this may be a direct dependence due to X-ray irradiation, or an indirect dependence on \( M \). The extended ADC varies between a minimum of \( \sim 7 \) per cent of the accretion disc radius to a maximum of 65 per cent (in X 1624-490). In the case of XB 1916-053, our measured ingress times fall within the range of values obtained by Narita et al. (2003), who also found some evidence for a dependence of ADC size on mass accretion rate in data on this one source having limited variation in luminosity. Least squares fitting provides the power law dependence \( r_{ADC} = (r_{Tot}^{0.85})^{1.16} \) at 99 per cent confidence, suggesting a simple proportionality.

We wish, of course, to understand the formation of the ADC, which previously has been very unclear, or controversial, and this will be discussed in Sect. 5. However, one issue will be whether the increase is size with luminosity is due to increasing illumination of the disc, or whether the ADC size is limited by the fact that hydrostatic equilibrium is not possible outside a limiting radius. For a small number of sources, we have broadband spectra obtained from BeppoSAX extending to 100 keV which allowed the mean Comptonization cut-off energy to be obtained, and from this the mean electron temperature \( T_e \) of the Comptonizing ADC. Information on the ADC from observation is, of course, quite limited, and we can do no more than obtain mean quantities. However, theoretically, a strong radial variation of \( T_e \) is not expected. In a corona with \( kT \sim 10 \) keV, it is expected that at radius \( r_C \), the Compton radius, hydrostatic equilibrium will fail, since

\[
KT > GMMp/r \quad \text{and} \quad r_C \sim GMm_p/ KT
\]

where \( m_p \) is the proton mass, and outside this radius, the ADC will dissipate as a wind. In reality, hydrostatic equilibrium may begin to fail at somewhat smaller radial distances (e.g. Woods et al. 1996). In Table 2, we show values of \( r_C \) calculated for the two cases: a high optical depth (\( \tau \)) corona, in which the Comptonization cut-off energy \( E_{CO} = 3KTe \), and a low optical depth corona, for which \( E_{CO} = KTe \). It can be seen that the values are substantially less than the radii of the accretion disc in these sources, the high-\( \tau \) values being about 30 per cent of the disc radius and the low-\( \tau \) values being about 10 per cent.

It can be seen that for the bright source X 1624-490, there is good agreement between the measured size of the ADC (Table 1) and the high-\( \tau \) value of the limiting radius. For the other two, relatively faint, sources XB 1916-053 and XB 1323-619, the agreement is better with the low-\( \tau \) value. It is not appropriate to give a detailed discussion based on 3 sources; however, there is clearly some evidence that the ADC size is limited to the maximum hydrostatic size. In the case of X 1624-490, the large value of \( r_C \) is a consequence of the low value of coronal electron temperature. Formation of ADC (Table 1) and the high-

\[
E_{CO} \quad kT \quad r_C \quad r_C \quad r_{ADC}
\]

| Source     | E_{CO} | kT_e | \( r_C \) High | \( r_C \) Low | \( r_{ADC} \) |
|------------|--------|------|---------------|---------------|-------------|
| XB 1916-053| 80     | 26.7 | 7.2           | 2.4           | 3.0         |
| XB 1323-619| 44     | 14.7 | 13.1          | 4.4           | 2.7         |
| X 1624-490 | 12     | 4.0  | 48.2          | 16.1          | 60          |

References: Church et al. 1997; Bahcinsula-Church et al. 1999, 2000.

4 THE DEPENDENCE OF COMPTONIZATION ON ADC SIZE

4.1 Seed photons and Comptonized spectra

In the following, we compare the Eastern model with the Birmingham model, i.e. a model having an extended ADC as revealed by the present work. In Figs. 3 and 4, we show the seed photon spectra (left panels) and the corresponding Comptonized spectra (right panels). The Comptonized spectra are shown for 1 – 30 keV luminosities of \( 10^{36} \), \( 10^{37} \) and \( 10^{38} \) erg s\(^{-1}\), for a source at 10 kpc. To allow direct comparison, we keep the ADC size constant at 50000 km; however, allowing this to increase would only affect the spectrum below 0.01 keV.

In the Eastern model, it is assumed that seed photons originate on the neutron star or inner disc and so are modelled by a simple blackbody with \( kT \sim 1 \) keV (e.g. Done et al. 2002). Typical values of \( kT \) of 0.53, 0.94 and 1.67 keV were chosen which would produce luminosities of \( 10^{36} \), \( 10^{37} \) and \( 10^{38} \) erg s\(^{-1}\) assuming emission from the whole neutron star. For convenience we obtain the approximate form of the Comptonized spectrum for this seed photon input using the TCOMPPE thermal Comptonization model (Zdziarski, Johnson & Magdziarz 1996) which is a non-standard model in Xspec which assumes a simple blackbody for the seed photons. An electron temperature \( kTe \) of 20 keV was used.
representative of values derived from broadband spectra between 5 and 100 keV, and a typical power law photon index of 1.7. The Comptonized spectrum of the Eastern model is shown in Fig. 3 (right panel) with normalizations in the model adjusted to provide the three standard luminosities above. The normalization of each seed photon spectrum was chosen such that the bolometric blackbody luminosity was one fifth of that of the Comptonized emission, and from the equivalent mass accretion rate, the temperature distribution in the disc was calculated. A non-standard Xspec model was produced allowing the disc blackbody emission with this temperature profile to be integrated between 10 km, the surface of the neutron star, and 50000 km.

For the extended ADC, we calculated the multi-temperature disc blackbody emission of the seed photons by integrating to \( r = 50000 \) km. This was done assuming the temperature profile of a Shakura-Sunyaev thin disc (Shakura & Sunyaev 1976), making the zero torque assumption that has the effect of causing \( T(r) \) to decrease at the inner disc (Abramowicz & Kato 1989). We again assume a value for the amplification factor, but this is not critical as we only wish to show the relation between the forms of the seed and output spectra. We assumed that the total emitted X-ray luminosity of the Comptonized emission \( L_{\text{tot}} = L_s + L_h \), where \( L_s \) is the luminosity of the seed photons and \( L_h \) is the heating supplied by the electrons, giving an amplification factor \( A = L_{\text{tot}}/L_s \), and we assumed \( A = 5 \). Thus the bolometric seed photon luminosity was made one fifth of that of the Comptonized emission, and from the equivalent mass accretion rate, the temperature distribution in the disc was calculated. A non-standard Xspec model was produced allowing the disc blackbody emission with this temperature profile to be integrated between 10 km, the surface of the neutron star, and 50000 km.

To obtain the Comptonized spectrum of these seed photons, we made a dedicated Xspec model based on the thermal Comptonization model TCOMPS (derived from THCOMPFE and provided by P. Życki) which calculates the Comptonized spectrum for seed photons produced by the complete accretion disc, assuming the DISKBB form for the seed photons (Mitsuda et al. 1989) in which the zero torque assumption is not embodied. Our modification involved changing the input seed photon spectrum to correspond to the inner 15 per cent of the disc, and we produced two versions: with and without the zero torque assumption. Basing our model on TCOMPS was done for convenience to show the approxi-
mate form of the Comptonized spectrum, but assumes low optical depth, whereas our evidence is for high optical depth in the ADC (Church 2001). However, this will not affect the major conclusions of the present work. An electron temperature $kT_e$ of 20 keV was assumed, as before. In Fig. 4 we show the spectra of the seed photons and the Comptonized spectrum assuming zero torque for the extended ADC.

Comparison of Figs. 3 and 4 reveals the strong differences between Comptonization in the Eastern model and in the Birmingham model with an extended ADC; for clarity we do not include the second thermal component also present in each model. The difference between the seed photon spectra are extreme, in the Eastern model consisting of a blackbody of $kT_\text{b} \sim 1$ keV, but for the actual extended ADC consisting of a disc blackbody peaking at 0.003 keV for the lowest luminosity and at 0.01 keV for the highest luminosity. These differences have a major effect on the Comptonized spectra such that in the Eastern model, the spectrum decreases below a peak at 1 – 3 keV depending on luminosity, reflecting a widely-held view that a Comptonized X-ray spectrum cannot continue to follow a power law at low energies because of an expected shortage of seed photons. However, the consequence of an extended ADC is that the Comptonized spectrum below 1 keV does continue to rise causing the Comptonized spectrum also to rise. Eventually there is a turn-over in the spectra at 0.01 keV, however, this is considerably below the minimum energy in X-ray telescopes. A much less pronounced change in slope takes place in the Comptonized spectrum at energies of $\sim$1 keV due to the corresponding break in the seed photon spectrum. This change of slope would be difficult to detect even with data extending to 0.1 keV because of low energy absorption. Finally, the high energy cut-off in Fig. 4 can be seen at $\sim$80 keV corresponding to the maximum energy of Comptonizing electrons.

The zero torque assumption is appropriate to a black hole binary where the accretion flow cannot interact with the stellar surface; however, it is not clear whether it is appropriate in a neutron star system. We have tested the effect of this assumption, and find it does not affect our main results. Not making the zero torque assumption is to modify the seed photon spectrum by moving the energy of the slight break in slope from 1 keV to 1.5 keV (for the central curve).

### 4.2 Fitting with the Eastern model

In the above, we compare the Comptonized spectrum expected for an extended ADC with that of the Eastern model. We now address the question of what effect this will have in spectral fitting with the Eastern model. To answer this, we have simulated 20 ks of XMM EPIC data using the Comptonized spectrum of an extended ADC (as in Fig. 4, right panel) with parameter values: $kT_e = 20$ keV, power law index $\Gamma = 1.7$, peak disc temperature 0.4 keV, column density $0.2 \times 10^{22}$ atom cm$^{-2}$, an appropriate instrument response function, and fitted this using the thermal Comptonization model corresponding to the Eastern model: THCOMPFE. We make this comparison of Comptonized spectra without adding further emission components that exist in real data to the simulation. It was arranged that $L^{\text{thcompfe}} = 10^{37}$ erg s$^{-1}$.

In Fig. 5, we show the result of fitting this simulated data with the THCOMPFE model. Initially, we fixed the blackbody temperature at 1 keV as is typical for results from using the Eastern model, and implies that seed photons can originate on the neutron star, and so can have higher $kT$ than the inner disc temperature used above. The model fits very badly, particularly below 2 keV with $\chi^2$/d.o.f. = 628/100 as shown in Fig. 5. With $kT$ free, an acceptable fit was obtained, but with a value of $kT = 0.14$ keV, which is inconsistent with the seed photons assumed in the Eastern model. Thus, it was not possible to fit the data sensibly with the THCOMPFE model, as might be expected, since the data were simulated assuming an extended disc blackbody source of seed photons, and fitted by a localized source. The only way to obtain an acceptable fit with $kT \sim 1$ keV was found to be by adding a second, unreal, model component (in fact, an extra blackbody component) which was not present in simulating the data. We conclude that fitting the Eastern model is likely to produce incorrect results. Fitting real data will be complicated by the presence of a second emission component, which we associate with the neutron star.

### 5 DISCUSSION

The present work provides strong evidence for the Birmingham model of LMXB, and against the Eastern model. In particular, we have shown that the Comptonizing region cannot be a small, central region, as in the Eastern model, but is, in fact, an extended, flat, hot region above the inner 15 per cent typically of the accretion disc, i.e. constituting a thin ADC above a thin disc. We have also shown that the size of the Comptonizing region has strong implications for the correct form of the Comptonization model to be used. The relevance to ADC formation is discussed below; however, we first address briefly two issues. The identification of blackbody emission in LMXB has been a problem; the Eastern model identifies this with disc emission whereas we, and others, identify this with emission from the neutron star. Given the large ADC, we expect all of the X-ray emitting...
inner disc to be covered by ADC. Moreover, there is evidence for the high optical depth of the ADC plasma (e.g. Church 2001; Narita et al. 2001), and it is likely that essentially all of the disc emission will be reprocessed in the ADC and so not observed, and that the observed thermal emission originates on the neutron star. Secondly, several authors have proposed that X-ray emission in accreting black holes and neutron stars has a common origin depending on the properties of the accretion flow only, effectively a unifying model. For example, spectral similarities between low state black holes and neutron star binaries, and similarities in timing properties suggest a common mechanism for X-ray production (Poutanen 2001). In BHB, the thermal emission component is clearly from the disc, whereas in LMXB, disc emission will be reprocessed in the ADC and so not seen. Thus the present work does not support a common emission mechanism, since this relies on the assumption that disc blackbody emission is observed from each type.

5.1 Formation of the ADC

The dependence of ADC size on X-ray luminosity shown in Fig. 2 has implications for understanding ADC formation. Various mechanisms for ADC production have been proposed. Liang & Price (1977) suggested that internal processes within the disc would transfer energy to a corona with low density which would not radiate and cool efficiently. Paczyński (1978) invoked gravitational instability in the disc. Various mechanisms for ADC production have been presented. For example, spectral similarities between low state black holes and neutron star binaries, and similarities in timing properties suggest a common mechanism for X-ray production (Poutanen 2001). In BHB, the thermal emission component is clearly from the disc, whereas in LMXB, disc emission will be reprocessed in the ADC and so not seen. Thus the present work does not support a common emission mechanism, since this relies on the assumption that disc blackbody emission is observed from each type.

Kallman (2002) also addressed the effects of X-ray irradiation of the disk, with the aim of explaining the UV emission of LMXB, not presently understood. They concentrated on the reprocessing of X-rays in the disc so as to boost the UV emission of the disc and the possible driving of a disc wind by UV lines. Then the UV-driven wind could be a source of the observed UV radiation. Ionization by X-rays was found to prevent this mechanism, although winds could be produced by thermal expansion and other effects. The part of the disc considered was that between $1 \times 10^9$ and $1 \times 10^{10}$ cm, the region typically between 0.03 and 0.3 of the accretion disc radius. Proga & Kallman considered that the Compton radius where a static corona becomes an unbound wind would be $\sim 10^{13}$ cm, greater than the disc size, equivalent to assuming a coronal temperature of $1 \times 10^7$ K. However, our work has shown that the electron temperature $kT_e$ is $\sim 5 - 30$ keV, or more, giving a Compton radius typically $\sim 2 - 10 \times 10^n$ cm, and a reasonable explanation of our measured ADC radial extents is that they are determined by the Compton radius. Thus, we expect that a wind will exist anyway over much of that part of the disc considered by Proga & Kallman, but for a different reason: because the corona is unbound.

The present work clearly supports the modelling in which a very extended ADC is formed by illumination of the disc by the central source. The observational results indicate a strong dependence on $L_{\text{Tot}}$, and there is some evidence (Table 2) that the size is limited to the maximum radius for hydrostatic equilibrium, suggesting that the modelling should also include this effect. If this effect is dominant, the size varies inversely with coronal temperature, and it is because brighter sources have lower Comptonization cut-off energies (e.g. Church et al. 1997; Balucinska-Church et al. 2000) and so lower temperatures that the ADC becomes much larger.

In terms of earlier proposals for ADC formation, such as an internal mechanism in the disc, the process would have to form an ADC of size varying substantially with mass accretion rate (and thus $L_{\text{Tot}}$), and also predict an extended ADC. In general, the processes proposed do not predict an extended ADC. For example, the magnetic loop process (Galeev et al. 1979) is concentrated in the inner disc. One difficulty in making this comparison is that the theoretical treatments are often ‘local’, i.e. do not consider the radial dependence. However, it appears that internal processes would not produce an ADC of the radial extent found in the present work. Thus we conclude that ADC formation by direct X-ray irradiation is more likely, in which case both the inner disc and the neutron star probably contribute to ADC formation.

5.2 The correct form of the Comptonization term in spectral fitting

We have shown that the present results imply a particular form for the Comptonized emission in LMXB. In our previous work on LMXB, the Birmingham model with spectral form $BB + CPL$ consisting of a simple blackbody identified with emission from the neutron star, plus a cut-off power law to represent Comptonization provided good fits to all spectra. It may not appear that a cut-off power law is a sufficiently complex form to describe Comptonization. The forms
of Xspec models such as THCOMPDS, THCOMPFE and COMPTT differ from a cut-off power law in the shape of the knee. We have carried out simulations that show that unless data of the highest quality are available, i.e. with very small Poisson errors, which are broadband, i.e. extending well above the knee, there is little error in using a cut-off power law. The knee occurs between 10 – 100 keV in all but the brightest sources, so broadband data normally means in the energy range 1 – 100 keV. For such high quality broadband data, use of the CPL model would give somewhat inaccurate values of the power law index, and the thermal Comptonization model suggested by the present work should be used. In our previous work, we have not had available data of sufficient quality that using a cut-off power law has caused significant errors.

In Sect. 4, we addressed the correct form for Comptonization models, and showed that we expect the spectrum to continue to rise below 1 keV. It was recently claimed that the Birmingham model was not a correct description of Comptonization (Done et al. 2002), since we do not include the marked turnover at low energies inherent in the Eastern model (Fig. 3, right panel). If we neglect the turn-over, we overestimate the Comptonized emission and so underestimate blackbody emission. This might explain the unphysically small values of inner disc radius, in many cases less than 0.5 km, we obtained in applying the Eastern model (in the form disc blackbody plus cut-off power law) in a survey of LMXB with ASCA. The present work demonstrates that with an extended ADC, there will not be a low energy cut-off in the spectrum and so the above argument that the blackbody term is underestimated does not appear valid.

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