The X-ray spectrum of the atoll source 4U 1608−52

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ABSTRACT
The transient atoll source 4U 1608−52 was extensively observed by the Rossi X-ray Timing Explorer (RXTE) during its 1998 outburst. We analyse its X-ray spectra as a function of inferred accretion rate from both the 1998 outburst and the 1996 and 1998 non-outburst data. We can fit all the spectra by a model in which seed photons from the neutron star surface are Comptonized in a boundary layer. The Comptonized emission illuminates the accretion disc surface, producing an ionized, relativistically broadened reflection signature, while the direct emission from the accretion disc can also be seen. The evolution of the source can be explained if the main parameter driving the spectral evolution is the average mass accretion rate, which determines the truncation radius of the inner accretion disc. At low mass accretion rates, in the island state, the disc truncates before reaching the neutron star surface and the inner accretion flow/boundary layer is mostly optically thin. The disc emission is at too low a temperature to be observed in the RXTE spectra, but some of the seed photons from the neutron star can be seen directly through the mostly optically thin boundary layer. At higher mass accretion rates, in the banana state, the disc moves in and the boundary layer becomes much more optically thick so its temperature drops. The disc can then be seen directly, but the seed photons from the neutron star surface cannot, as they are buried beneath the increasingly optically thick boundary layer.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: 4U 1608−52.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) with a neutron star primary can be observationally divided into two main categories, namely atolls and Z sources (Hasinger & van der Klis 1989). This classification is based on changes in both spectral and timing properties as the source varies, and probably reflects differences in both mass accretion rate, $M$, and magnetic field, $B$. The Z sources have high luminosity (typically more than 50 per cent of the Eddington limit) and magnetic field ($B > 10^9$ G), while the atolls have lower luminosity (generally less than 10 per cent of Eddington) and low magnetic field ($B \sim 10^8$ G) (Hasinger & van der Klis 1989).

Both atolls and Z sources show spectral changes that form a well-defined track in a colour–colour diagram. The atolls show hard, power-law spectra at low luminosities (island state), which are startlingly like the low/hard spectra of galactic black hole binaries (e.g. Barret & Vedrenne 1994; van Paradijs & van der Klis 1994; Barret et al. 2000). At higher luminosities the spectra are typically much softer (banana state, e.g. Di Salvo et al. 2000; Piraino, Santangelo & Kaaret 2000). The Z sources always show soft spectra, but there are subtle spectral changes which show up as a Z-shaped track on a colour–colour diagram. Both types of sources move along their tracks on the colour–colour diagram on a time-scale of hours to days, except for the island state of atolls, where motion can take days or weeks. They do not jump between the track branches. Most of the X-ray spectral and timing parameters depend only on the position of a source in this diagram. This is usually parametrized by the curve length, $S$, along the track.

Until recently the atolls were thought to show a characteristic C-shaped (or atoll-shaped) track on the colour–colour diagram. However, mapping the full range of colour–colour changes for these LMXBs is difficult because the data available from most of the sources show little variability. There are only a few transient LMXBs with enough observations covering a wide range of luminosities to follow the whole track traced out in the colour–colour diagram. In these transient systems the C-shaped path is only a subset of a larger track. At low luminosities, evolution within the island state forms an upper branch, turning the C into a Z (Gierliński & Done 2002; Muno, Remillard & Chakrabarty 2002).

While the colour–colour diagram is clearly useful as a way of parametrizing the spectral changes, true spectral fitting gives much more information on the underlying physical changes in the source emission. Here we look at the detailed spectral shape of the transient atoll 4U 1608−52 as a function of its position on the colour–colour

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We have analysed 3 DATA ANALYSIS 1999). are only found in a limited range of the colour diagram, near – 4 keV count rates, and a hard colour as a 9.7–16 keV over 6.4–9.7 keV ratio. These count rates are corrected for the slow variations in the PCA response (van Straaten et al. 2000; see Gierliński & Done 2002, for technical details applied here). The diagram is shown in Fig. 1.

Next, we extracted the PCA and High Energy X-ray Timing Experiment (HEXTE) spectra corresponding to different positions in low-luminosity observations in 1996 December (P10094) and 1998 June, August and September (P30419). All these data belong to the Proportional Counter Array (PCA) gain Epoch 3. A conservative prescription to characterize uncertainties in the instrument response is to add 2 per cent systematics to the data for bright sources (e.g. Cui et al. 1997), irrespective of which detector/layer combination and gain epoch are used. However, inspection of data from the Crab shows that in Epoch 3, when using only top layer data from detectors 0 and 1, smaller systematics of 0.5 per cent are more appropriate (Wilson & Done 2001). We have repeated this Crab analysis, and found that even using a single absorbed (fixed at N_H = 3.2 × 10^21 cm^{-2}; Massaro et al. 2000) power law gives a reduced \chi^2 = 1.1 with 0.5 per cent systematic errors. This clearly shows that there are no residuals in the response (e.g. features from the xenon edge at 4.7 keV, or from the rapid decrease in effective area at low energies) of the top layer of detectors 0 and 1 at this level at this time. This is not the case for all layers and all detectors, where the reduced \chi^2 = 2.2 with 0.5 per cent systematic errors and there is a clear feature in the residuals at low energies. Thus we use only data from Epoch 3, and from the top layer of detectors 0 and 1, and apply 0.5 per cent systematic errors. However, we have checked that our conclusions are robust even to using 1 per cent systematics, although this gives unrealistically low \chi^2 values.

First, we created PCA light curves for each energy channel in 128 s time bins. We excluded all the data affected by the type I bursts. This gave us 240 ks of PCA data. The light curves were used to build a colour–colour diagram, defining a soft colour as a ratio of 4–6.4 keV to 3–4 keV count rates, and a hard colour as a 9.7–16 keV over 6.4–9.7 keV ratio. These count rates are corrected for the slow variations in the PCA response (van Straaten et al. 2000; see Gierliński & Done 2002, for technical details applied here). The diagram is shown in Fig. 1.
the colour–colour diagram. We have assumed that 4U 1608–52 shows a Z-shaped track on the diagram, with inferred accretion rate increasing along the Z: from left to right on the upper branch, through the diagonal to the lower branch (Gierliński & Done 2002; Muno et al. 2002). The diagonal branch is sparsely covered in this data selection. We divided the diagram into eight regions (boxes), as shown in Fig. 1, and averaged the spectra over each box. Neutron star LMXBs are known to vary in luminosity at given colours, creating the so-called parallel lines in colour–intensity diagrams (e.g. van der Klis 2001). Therefore, within one box we average spectra of different intensities. Though not necessary identical, these spectra should be very similar, considering nearness of colours. In the classic terminology of the atoll sources, boxes 1–3 belong to the island state, boxes 5–8 to the banana, while the status of box 4 cannot be established without joint spectral and timing analysis. To avoid accumulating spectral data from periods distant in time, we have created spectra 1 and 2 from 1996 data only (crosses in Fig. 1), and spectra 3–8 from 1998 data only (filled squares in Fig. 1). The PCA spectra are accompanied by the simultaneous HEXTE spectra extracted from cluster 0. We will refer to these joint spectra as S1–S8.

For spectral fitting we use the X-ray spectral fitting package XSPEC version 11 (Arnaud 1996). The error of each model parameter is given for a 90 per cent confidence interval. We use the 3–20 keV PCA data and 20–150 keV HEXTE data. The relative normalization of the PCA and HEXTE instruments is still uncertain, so we allow this to be an additional free parameter in all spectral fits.

4 SPECTRAL MODEL

Unlike black holes, the accreting neutron stars have both a surface and a magnetic field. Therefore, their X-ray spectra are expected to be more complex than those of the black holes. As well as emission from the accretion flow [direct emission from an optically thick, X-ray illuminated disc and/or an optically thin inner flow, corona or active regions (e.g. Czerny, Czerny & Grindlay 1986; Esin, McClintock & Narayan 1997; Beloborodov 1999)], there can be emission from the neutron star surface and the boundary layer (e.g. Popham & Sunyaev 2001).

Observationally, the X-ray spectra of LMXBs in the soft state are well known to require at least two different spectral components, but the interpretation of these is not unique. The so-called Eastern model (Mitsuda et al. 1984, 1989) assumes that the soft component is from the disc, while the hard component is due to Comptonization in the boundary layer or the inner disc. In the Western model (White, Stella & Parmar 1988), the soft component is a single-temperature blackbody from the surface, while the hard component is a Comptonized emission from the disc. While it is likely that both disc and boundary layer are Comptonized at some level, it seems more probable that the boundary layer should have a higher temperature than the accretion disc (Popham & Sunyaev 2001).

The hard-state X-ray spectra of LMXBs are similar to those of the black hole candidates in their low/hard spectral state. They are dominated by a power law, with some contribution from an additional soft thermal component. The power law is usually interpreted as Comptonization of seed photons in hot, optically thin plasma (see e.g. Barret et al. 2000).

Thus, a physically motivated model that can potentially fit the hard component in all spectral states is thermal Comptonization. An optically thin, hot plasma would produce a power-law spectrum (island state), while a plasma with intermediate or high optical depth and lower temperature can create a softer spectrum in which the high-energy rollover due to the electron temperature can be seen (banana state). We model the Comptonized spectrum using an approximate solution of the Kompaneets (1956) equation (Zdziarski, Johnson & Magdziarz 1996). The model (hereafter THCOMP, not included in the standard distribution of XSPEC) is parametrized by the plasma electron temperature, \( T_e \), and optical depth, \( \tau \), or equivalently the asymptotic spectral index, and blackbody seed photon temperature, \( T_{seeder} \).

The seed photon energy is very important in the Comptonization model, since it gives a low-energy cut-off in the spectrum. For typical mass accretion rates onto a neutron star, the seed photons from either the inner accretion disc or neutron star surface should have \( kT_{seeder} \sim 1 \) keV. This is plainly not far from the observed X-ray bandpass, so simple analytic approximations (e.g. the COMPST model or a cut-off power law) for the Compton scattered spectrum are not valid, since they extend towards lower energies as an uncut power law (see e.g. Done, Zyci & Smith 2002). The model THCOMP we use in this paper treats the seed photon low-energy cut-off properly.

The boundary layer should illuminate the inner disc, producing a relativistically broadened iron line and associated reflected continuum. While a broad iron line is often identified in atoll spectra, the reflected continuum which must accompany any line emission has only been fitted to island state spectra. We calculate the Compton reflection of the THCOMP continuum spectrum using a model where both the continuum reflection and the line are calculated self-consistently for a given ionization state (Zyci, Done & Smith 1998). The reflected spectrum (continuum and line) is also relativistically smeared for a given inner disc radius, \( R_{in} \). We approximate relativistic smearing by convolving the reflected spectrum with a relativistic line profile (Fabian et al. 1989).

First we demonstrate explicitly the need for a two-component continuum in all the data sets. The THCOMP continuum model and its reflection alone cannot give satisfactory fits for the spectra S1–S5, where \( \chi^2 > 120 \) at 80 or 79 degrees of freedom (d.o.f.). There is a strong soft excess in the residuals below \(~5\) keV, which is particularly marked in S1 and S5 where \( \chi^2 > 200 \). We use a multi-colour disc blackbody (DISKBB in XSPEC; Mitsuda et al. 1984) to describe the soft component. This model is parametrized by the disc temperature, \( T_{disk} \), at the inner disc radius (\( R_{in} \)) and normalization \( N_{soft} \propto R_{in}^{-\alpha} \). However, its shape is poorly constrained by the RXTE data, so it can equally well be a single-temperature blackbody. The spectra S6–S8 give good fits without the soft component (\( \chi^2 = 80, 88, 75 \) at 78 d.o.f., for S6, S7 and S8, respectively), though even here inclusion of DISKBB improves the fits significantly.

The soft component in the case of the weakest improvement (for S6 where \( \Delta \chi^2 = 11.6 \)) is statistically significant at 99.7 per cent level.

The Compton reflection (including the self-consistent iron line emission) is always significantly detected also. Using the two-component continuum model (DISKBB + THCOMP) without a reflected component gives an increase in \( \chi^2 \) by more than 50 in all spectra (corresponding to an extremely high significance level).

These results motivate us to choose a model consisting of thermal Comptonization, its Compton reflection and the disc blackbody as the model with which to fit all the spectra.

5 RESULTS

For spectral fitting we use the model described in the previous section. We apply absorption corresponding to a fixed galactic hydrogen column of \( N_H = 1.5 \times 10^{21} \) cm\(^{-2}\) (Penin in 1989). In the island state spectra, S1–S3, the HEXTE statistics at higher
energies are not good enough to constrain the electron temperature of the Comptonized component, $T_e$. The high-energy cut-off begins to be seen in S4 and S5, although again the uncertainties on $T_e$ are large. All of these spectra provide only lower temperature limits. Therefore, we fit the spectra S1–S5 with $kT_e$ fixed at 50 keV, a value consistent with all these data sets, and then calculate the lower limits on the electron temperature. On the other hand, the spectra S6–S8 are able to constrain the electron temperature well.

The data cannot constrain the inner disc radius from relativistic smearing of the reflected component. Spectral fitting gives only lower limits on $R_{\text{in}}$, which are typically 10–20 $R_g$ (where $R_g = GM/c^2$) except for spectra S4 and S5, which are consistent with $R_{\text{in}} = 6R_g$. We fix $R_{\text{in}} = 20R_g$ in all the fits.

We fit all the spectra with the above constraints, and show the spectra unfolded with the best-fitting models in Fig. 2. The best-fitting model parameters are shown in Table 1 and Fig. 3.

We calculate the unabsorbed bolometric flux, $F_{\text{bol}}$, from the model. We cannot precisely estimate its uncertainties, as these depend on the model used as well as on the statistics. However, fits with different soft component model (disc or blackbody) show consistently similar results, with the same trend: an increase from S1 to S3, a drop at S4, and a further increase from S5 to S8. This supports the inferred direction of the increasing accretion rate on the colour–colour diagram, tracing out a Z-shaped track (see also Gierliński & Done 2002).

With increasing inferred accretion rate, the spectra become brighter, softer and have a decreasing electron temperature, as seen from the high-energy cut-off. The change in the spectral shape between the island and banana states is clearly visible. Spectrum S4 bears more similarities to the banana state spectra than to island state, so it probably belongs to the banana state. The curvature expected from the low-energy cut-off in the Comptonized spectrum close to the seed photon energy is clearly seen in spectra S4–S8, where $kT_{\text{seed}} > 1$ keV. The lower seed photon temperature derived for the island state means the low-energy cut-off is less pronounced (not significantly detected) in spectra S1–S3.

The electron temperature of the hard Comptonized component is consistent with a monotonic decline along the colour–colour track, while the optical depth is consistent with a corresponding monotonic increase. These two parameters are difficult to disentangle in data in which the high-energy rollover (at a few $kT_e$) is not observed, as in the island state spectra. However, while the optical depth derived for a given temperature also depends on the assumed geometry, it is clear that the island state spectra have $\tau_e$ of order
The X-ray spectrum of 4U 1608–52

Table 1. Fitting results of the thermal Comptonization (with Compton reflection) plus disc blackbody model to the spectra S1–S8. The bolometric, unabsorbed flux, \( F_{\text{bol}} \), was estimated from the model. Units are as follows: 
\( kT_{\text{seed}} \) and \( kT_{\text{disk}} \) are in keV; \( N_{\text{H}}^{1/2} \) is in km; \( \xi \) is in erg cm s\(^{-1}\); and \( F_{\text{bol}} \) in \( 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\). Brackets in the \( kT_{\text{e}} \) column denote the fits in which \( T_{\text{e}} \) was fixed, and its lower limits were calculated additionally (no upper limits were found). Results from this table are visualized in Fig. 3. A detailed description of the model used is given in Section 4. The individual spectra are selected from the data as shown in Fig. 1. The spectra and the best-fitting models are shown in Fig. 2.

| Obs. | \( kT_{\text{seed}} \) | \( \tau_{\text{e}} \) | \( kT_{\text{e}} \) | \( \Omega/2\pi \) | \( \log(\xi) \) | \( kT_{\text{soft}} \) | \( N_{\text{H}}^{1/2} \) | \( F_{\text{bol}} \) | \( \chi^2/\text{d.o.f.} \) |
|------|------------------|-----|-----------------|---------|--------------|--------------|--------------|-------------|----------------|----------------|
| 1    | 0.54±0.07        | 1.7±0.9 | (50)±22         | 0.16±0.07 | 0.06         | 2.7±0.5 | 0.68±0.08 | 0.06 | 7.6±2.7 | 1.0 | 81.7/78 |
| 2    | 0.26±0.06        | 1.7±0.9 | (50)±38         | 0.17±0.09 | 0.06         | 2.5±1.3 | 0.84±0.09 | 0.06 | 3.5±1.1 | 1.0 | 70.0/78 |
| 3    | 0.26±0.06        | 1.9±1.3 | (50)±26         | 0.07±0.04 | 0.03         | 2.8±0.8 | 1.16±0.11 | 0.16 | 2.7±1.3 | 3.1 | 17.5/77 |
| 4    | 1.01±0.23        | 1.0±1.5 | (50)±33         | 0.68±1.32 | 0.48         | 4.9±0.4 | 0.63±0.13 | 0.14 | 22±12  | 2.4 | 101.9/77|
| 5    | 1.40±0.07        | 0.4±2.3 | (50)±45         | 0.23±1.2 | 0.09         | 4.6±0.2 | 0.71±0.05 | 0.05 | 28±8   | 6.5 | 106.1/77|
| 6    | 1.2±0.11         | 3.6±1.8 | 4.9±1.5         | 0.08±0.07 | 0.02         | 3.6±0.9 | 0.74±0.10 | 0.10 | 28±8  | 2.4 | 68.2/76 |
| 7    | 1.13±0.25        | 6.0±0.8 | 3.3±0.7         | 0.09±0.01 | 0.02         | 3.4±0.6 | 0.80±0.02 | 0.22 | 42±7   | 36  | 52.8/76 |
| 8    | 1.08±0.21        | 7.2±0.7 | 3.1±0.3         | 0.09±0.03 | 0.02         | 3.5±0.6 | 0.74±0.23 | 0.20 | 49±6   | 14 | 55.3/76 |

Unity, while the banana branch has \( \tau_{\text{e}} \gg 1 \). We derive similar optical depths and temperatures when we replace the approximate "TThcomp" thermal Comptonization model with COMPS Comptonization code (Poutanen & Svensson 1996), which finds a numerical solution of the Comptonization problem explicitly considering successive scattering orders.

Reflection (mostly driven by the detection of the self-consistently produced iron line) is always significantly detected, although the inferred solid angle subtended by the reflecting material is generally rather low, with \( \Omega/2\pi \approx 0.1 \). The spectrum S4 has somewhat more reflection, but this is not strongly statistically significant. Reflection is always strongly ionized, with ionization increasing in the higher-luminosity banana spectra. The presence of reflection in all spectra (in both island and banana states) demonstrates that the broad, ionized iron line seen from these sources can indeed be produced by illumination of the accretion disc.

The rather small reflected fraction in the island state is in conflict with \( \Omega/2\pi \approx 0.5–1 \) found in 2–20 keV Ginga X-ray spectra of 4U 1608–52 by Yoshida et al. (1993) and Zdziarski, Lubinski & Smith (1999). This is mostly due to the continuum model used. A power law and its reflected component does indeed give a larger \( \Omega/2\pi \), but these fits are statistically unacceptable, as well as physically inconsistent. Comptonization does not give rise to a power law at energies close to the seed photon energies, and the data also require a soft component as well as the Comptonized emission. Our results are consistent (although with large uncertainties) with a reflection–spectral shape correlation for spectra S1–S4, as claimed by Zdziarski et al. (1999), although there is plainly no overall correlation that extends from the island state all the way through the banana branch.

The observed soft component shows rather complex behaviour. Fig. 4 shows the soft component flux derived from the model given in Table 1, versus its temperature, \( T_{\text{disk}} \). There is a striking difference between the behaviour of the soft component in the island and banana states. The figure also shows the curve \( F_{\text{soft}} \propto T_{\text{soft}}^4 \), as expected if the disc geometry remained constant. The uncertainties are large, but, while the banana state spectra could be consistent with this relation, the island state is clearly not. This can also be seen from the fitting results (Fig. 3), where the normalization \( N_{\text{H}} \propto R_{\text{in}}^2 \) is fairly constant along the banana track.

The difference in the soft component between the island and banana states can be further seen in Fig. 5. The seed photon temperature is systematically higher than the soft component temperature in the banana state. Though the 90 per cent confidence errors for \( T_{\text{disk}} \) and \( T_{\text{seed}} \) overlap (see Table 1), these two parameters are correlated and a fit with forced \( T_{\text{disk}} = T_{\text{seed}} \) is significantly worse. In the island state the uncertainties on these temperatures are substantial but \( T_{\text{seed}} \) is consistent with being equal to \( T_{\text{disk}} \), and the soft component can be the source of seed photons. This result does not change when we use a single-temperature blackbody instead of the multicolour disc. Conversely, in the banana state, the observed soft component is not the source of seed photons for the Comptonized component.

In the island state, the observed seed photons (which are consistent with being the seed photons) have rather low normalization. If these were emitted from a disc, then the inner disc radius can be estimated from the DISKBB model as

\[
R_{\text{in}} \approx 0.61 N_{\text{H}}^{1/2} \frac{2.7}{\eta} \frac{D}{3.6 \text{ kpc}} \left( \frac{f_{\text{col}}}{1.8} \right)^2 \left( \frac{0.5}{\cos i} \right)^{1/2} \text{ km},
\]

where \( D \) is the distance to the source, \( i \) is the inclination angle of the disc, \( f_{\text{col}} \) is the ratio of the colour to effective temperature (Shimura & Takahara 1995) and \( \eta \) is the correction factor for the inner torque-free boundary condition (Gierliński et al. 1999; \( \eta = 2.7 \) for \( R_{\text{in}} = 6R_{\odot} \) and less for higher \( R_{\text{in}} \)). With \( \eta = 2.7, D = 3.6 \text{ kpc}, f_{\text{col}} = 1.8 \text{ and } \cos i = 0.5 \), we find \( R_{\text{in}} < 5 \text{ km} \) for S1–S3. This is less than the expected neutron star radius of \( \sim 10 \text{ km} \), and suggests that, though we fitted the soft component by a disc model, it might not be a disc at all. Even if the colour–temperature correction is as high as \( f_{\text{col}} = 2.7 \) (Merloni, Fabian & Ross 2000), then S3 still yields \( R_{\text{in}} < 5.5 \text{ km} \). There are of course more unknowns in equation (1), in particular the inclination angle, but \( R_{\text{in}} > 10 \text{ km} \) requires \( i > 81^\circ \), which is excluded by the lack of X-ray eclipses.

It is therefore unlikely that the soft component is the accretion disc in the island state. Instead, we suggest that it comes from the neutron star surface. A fit of a model including a single-temperature blackbody instead of a disc to the island state data yields an apparent radius of the blackbody of \( 4 \pm 2 \text{ km} \).

Conversely, in the banana state, the soft component is consistent with emission from the accretion disc, although these photons do not provide the seed photons for Compton scattering. The inner disc radius is consistent with remaining constant throughout the banana state. From the fit to the typical banana spectrum S6, we estimate...
Results from Table 1. Units are as follows: $kT_{\text{soft}}$ and $kT_{\text{seed}}$ are in keV; $N^{1/2}_{\text{soft}}$ is in km; $\xi$ is in erg cm s$^{-1}$; and $F_{\text{bol}}$ is in $10^{-9}$ erg cm$^{-2}$ s$^{-1}$. While fitting spectra S1–S5, $T_\text{e}$ was fixed at 50 keV, and its lower limits were calculated additionally (no upper limits were found). The symbols used here correspond to the symbols in Figs 4 and 5. We note that the box number on the horizontal axis does not exactly correspond to the curve length in the colour–colour diagram, and, in particular, there is a gap between boxes 3 and 4. This figure can be seen in colour on *Synergy*, in the online version of the journal.

Figure 4. Soft component flux versus its temperature. The curve represents the best fit of a function $F_{\text{soft}} = AT_{\text{soft}}^4$ to the spectra S4–S8. The island state spectra S1–S3 are not consistent with this relation. This figure can be seen in colour on *Synergy*, in the online version of the journal.

Figure 5. Seed photon temperature versus soft component temperature. The line shows where $T_{\text{seed}} = T_{\text{soft}}$. In the banana state (S4–S8) $T_{\text{seed}}$ is systematically higher than $T_{\text{soft}}$, and therefore the soft component cannot be the source of seed photons. In the island state (S1–S3) the uncertainties are large, but it is possible that the soft component is the source of seed photons. This figure can be seen in colour on *Synergy*, in the online version of the journal.

of trend in $T_{\text{seed}}$ and $N_{\text{seed}}$ between S3 and S4 (see Fig. 3) is naturally explained, and does not contradict our assumption about the direction of increase in the accretion rate in the upper branch in the colour–colour diagram. We discuss a physical picture for the evolution of the soft and seed photons in Section 7.

6 COMPARISON TO OTHER SOURCES

The X-ray spectra of 4U 1608–52 analysed here are entirely typical of atoll sources. Having a good coverage of a large luminosity variation, we can compare our results to previous observations of other atolls in various luminosity states.

The island state is characterized by a hard, power-law spectrum, similar to the hard state of black hole binaries, though a bit softer.
The presence of a soft component has been reported before in SAX J1808.4–3658 (Gierliński, Done & Barret 2002), 4U 1724–308 (Guainazzi et al. 1998), 1E 1724–3045 and SLX 1735–269 (Barret et al. 2000). In these sources, the radius of the soft component is not consistent with the accretion disc [except perhaps SLX 1735–269, though there is a Galactic bulge emission component in the spectrum, which makes spectral modelling difficult (see Barret et al. 2000)], This is consistent with what we find in 4U 1608–52 and suggestive that the soft component arises from the neutron star surface rather than from the accretion disc.

The banana state X-ray spectra are soft, and here again 4U 1608–52 is entirely similar to other atolls. A two-component model has been successfully applied to, for example, KS 1731–260 (Narita, Grindlay & Barret 2001), GX 3+1, Ser X-1 (Oosterbroek et al. 2001) and MXB 1728–34 (Di Salvo et al. 2000), the soft component being consistent with the disc. On the other hand, one must be very cautious here, since the soft component properties strongly depend on the Comptonization model applied, and inappropriate approximations have often been used (see Done et al. 2002, for details).

The ambiguity in the spectral shape of the soft component has been reported before (e.g. Guainazzi et al. 1998; Barret et al. 2000). Interestingly, in MXB 1728–34, even BeppoSAX spectra, which extend down to much lower energies than the PCA, cannot distinguish between a disc and blackbody spectrum for the soft component (see Di Salvo et al. 2000).

Compton reflection has been reported before in the island state, for example in SAX 1808.4–3658 (Gierliński et al. 2002), 4U 1728–34 (Narita et al. 2001), 4U 0614+091 (Piraino et al. 1999), GS 1826–238 and SLX 1735–269 (Barret et al. 2000). However, this paper shows the first detection of reflection in the banana state. Previous work has generally fit an ad hoc broad Fe Kα line, rather than including the self-consistently produced reflected continuum, for example in GX 3+1, Ser X-1 (Oosterbroek et al. 2001) and 4U 1728–34 (Piraino et al. 2000; Di Salvo et al. 2000).

7 DISCUSSION AND CONCLUSIONS

We fit the spectra of the atoll 4U 1608–52 at all points along its track on the colour–colour diagram by a physically motivated model, consisting of thermal Comptonization and its Compton reflection, together with a soft component. Both reflection (with the self-consistently calculated iron line emission) and the soft component are always statistically significantly detected in the spectra.

There is a dramatic change in spectral shape between the island and banana states, probably caused by an equally dramatic change in the accretion flow geometry. In the island state the observed soft component luminosity and temperature imply an emission region that is smaller than an accretion disc around a neutron star. We suggest that it arises from optically thick, thermal emission from the surface of the neutron star. The hard component is consistent with Comptonization of these observed soft photons from the neutron star surface by hot electrons in an inner optically thin accretion flow (or outer boundary layer). The optically thin Comptonization medium has a temperature of $\gtrsim 20$ keV. We do not see direct emission from the accretion disc in the PCA energy range, but we do see weak reflected emission implying that the disc subtends a solid angle $\sim 0.1 \times 2\pi$ from the point of view of the hard X-ray source.

In the banana branch spectra the Comptonized component is much softer, with a temperature of $\sim 5$ keV and optical depth of $\gtrsim 1$. Here the observed soft component is consistent with being from the disc, but the seed photons are not consistent with being the observed soft component, and again it is more likely that the seed photons are produced predominantly by the neutron star surface. This interpretation favours the Eastern model of LMXBs on the banana branch.

A scenario consistent with all of the above results is one in which the main parameter driving the spectral evolution is the average mass accretion rate, which determines the truncation radius of the inner accretion disc. At low mass accretion rates the optically thick disc does not extend down to the neutron star surface, and the inner accretion flow/boundary layer is mostly optically thin. The large radius of the optically thick disc means that its temperature and luminosity are low, so it cannot be seen directly in the PCA spectra, and it subtends a rather small solid angle for reflection. Since the accretion flow is not very optically thick, then some fraction $\sim e^{-\tau} \sim 0.3$ of the emission from the neutron star surface can be seen directly, while the rest is Comptonized into the hard component.

As the mass accretion rate increases, so the disc extends further in and the optical depth of the inner flow/boundary layer increases. Eventually the neutron star surface is shrouded by the increasingly optically thick flow, so that these seed photons cannot be seen. The high optical depth also means that the boundary layer emission is then close to thermalizing, so its temperature drops, while the decreasing inner radius of the disc means that its emission starts to become more important in the PCA bandpass.

In this scenario the island state/banana branch transition is marked by the point at which the inner accretion flow collapses into a disc. The disc extends further in so that it is observed more easily as a soft component, softening the soft colour. Also this means that the boundary layer becomes much more optically thick, so its temperature drops, softening the hard colour.

It is plain that this can explain qualitatively the atoll source evolution. We will investigate the quantitative implications of this in a later paper.

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