Modelling the high mass accretion rate spectra of GX 339–4: Black hole spin from reflection?

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ABSTRACT

We extract all the XMM-Newton EPIC pn burst mode spectra of GX 339–4, together with simultaneous/contemporaneous RXTE data. These include three disc dominated and two soft intermediate spectra, and the combination of broad band-pass/moderate spectral resolution gives some of the best data on these bright soft states in black hole binaries. The disc dominated spectra span a factor three in luminosity, and all show that the disc emission is broader than the simplest multicolour disc model. This is consistent with the expected relativistic smearing and changing colour temperature correction produced by atomic features in the newest disc models. However, these models do not match the data at the 5 per cent level as the predicted atomic features are not present in the data, perhaps indicating that irradiation is important even when the high energy tail is weak. Whatever the reason, this means that the data have smaller errors than the best physical disc models, forcing use of more phenomenological models for the disc emission. We use these for the soft intermediate state data, where previous analysis using a simple disc continuum found an extremely broad residual, identified as the red wing of the iron line from reflection around a highly spinning black hole. However, the iron line energy is close to where the disc and tail have equal fluxes, so using a broader disc continuum changes the residual ‘iron line’ profile dramatically. With a broader disc continuum model, the inferred line is formed outside of 30 R_g, so cannot constrain black hole spin. We caution that a robust determination of black hole spin from the iron line profile is very difficult where the disc makes a significant contribution at the iron line energy i.e. in most bright black hole states.

Key words: accretion, accretion discs, black hole physics, relativity, X-rays: binaries

1 INTRODUCTION

Black hole spin is currently a subject of intense debate as it is very difficult to measure. Unlike mass, spin only leaves an imprint on the spacetime very close to the event horizon. Nonetheless, there are now two ways to study this. The first uses the temperature and luminosity of the accretion disc formed by material falling into the black hole. These parameters are determined by the combination of the rate at which material is swept through the disc, and how far down the disc can extend close to the black hole. A spinning black hole drags spacetime around with it, so that the accretion disc can extend closer in. This gives higher temperature and luminosity for a given accretion rate, or equivalently in terms of observables, a higher disc temperature for a given luminosity (e.g. Done, Gierliński & Kubota, 2007).

The second method uses the profile of an iron line produced by fluorescence where the X-rays illuminate the accretion disc. The closer the disc extends down to the black hole, the faster it orbits around, and the stronger the effects of special and general relativity. The large velocity and strong gravity sculpt the line profile, broadening it from a narrow atomic transition in a way which can now be observed (e.g the review by Fabian et al. 2000).

It is obviously important to compare results from these two methods. However, the current level of agreement is not very encouraging. One of the most clearcut cases is GX 339–4, where there are claims of extremely high spin from a very broad iron line in 3 datasets, but where the disc continuum fits strongly prefer lower spin. However, two of
the three broad iron line detections have been challenged as being due to instrumental pile-up (Miller et al. 2006 vs. Done & Diaz Trigo 2010 and Miller et al. 2008 vs Yamada et al. 2009). Pile-up occurs where the source is so bright that there is a high probability of two photons hitting either a single pixel within the readout time of that pixel, so that the sum of the energies is assigned to a single photon (energy pile-up) or of two photons hitting adjacent pixels, and being treated as a single photon split between two pixels (double event) with summed energy (pattern pile-up). Both processes distort the spectrum in a way which is not well understood, making detailed spectral fitting (as required for the iron line profile) difficult.

However, the remaining observation of GX 339–4 in which the very broad line is seen was taken in the burst mode of XMM-Newton, which is especially designed to handle the highest count rates without pile-up. It does this by reducing the readout time, but at the cost of a dramatic reduction in the detector live time. Only 3% of the available photons are collected, but the spectrum is free from the uncertainties associated with pile-up. However, while this fast timing burst data mode has been available for the XMM-Newton EPIC pn detector since the launch, it has only recently been calibrated well enough to give reliable spectra (see e.g. Guainazzi et al. 2010: XMM-SOC-CAL-TN-0083). Here we re-examine all the XMM-Newton burst mode spectra of GX 339–4 to assess the level of agreement between the spin derived from disc continuum and iron line profile. We find that the black hole spin derived from disc fitting with CCD data is similar to that derived from disc fitting of the higher energy RXTE data. However, the data also show that the best current disc continuum models give 5–10% residuals, as they predict (smeared) atomic absorption features in the disc photosphere which are not present in the data. This is unlikely to be due to any remaining calibration issues in this mode of XMM-Newton, or to interstellar absorption, as similar residuals are seen in Suzaku data from LMC X-3, which has a very low galactic column (Kubota et al. 2010). Instead it seems more likely that illumination (either self illumination of the inner disc by its own emission or by the hard tail) drives the photosphere towards isothermality. Whatever the underlying cause, the disc dominated spectra are clearly broader than expected from an emissivity weighted sum of blackbody spectra, such as the diskbb model (Mitsuda et al. 1984).

The shape of the disc spectrum is especially important when it comes to disentangling the iron line profile from the continuum. Fitting a narrow diskbb shape to the accretion disc emission forces a broad residual into the data. Similarly, the high energy continuum is not a simple power law (Kubota et al. 2001; Zyczyk, Done & Smith 2001, Gierliński et al. 1999), so fitting such models again forces a broad residual into the spectrum. The iron line shape derived from our fits including a broader disc spectrum and a Comptonised continuum is not extremely broad. It is easily consistent with the lower spin derived from the disc spectral fitting. We caution that the continuum is complex in the soft states, especially the brighter soft states where the disc extends to 6–7 keV, and that how the continuum components are modelled makes a difference to the derived profile of the iron line.

2 OBSERVATIONS AND DATA REDUCTION

GX 339–4 reaches a flux of $\sim 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, i.e. $\sim$0.5 Crab (e.g. Dunn et al. 2008). This corresponds to count rates in XMM-Newton of $\sim 5000$ c/s, well above the nominal pile-up limit of the timing mode of 800 c/s. Thus the only option for robust spectral fitting is the burst mode. Table 1 gives details of all burst mode observations of GX 339–4, along with details of the RXTE dataset closest in time to each observation. Figure 1 shows where these spectra fall on the long term RXTE PCA lightcurve of this source, with 2 datasets in the 2002/2003 and 3 in the 2007 outbursts.

The pn burst mode data were reduced using the latest version of the XMM-Newton Science Analysis System (SAS) v10.0. While the count rates of 1000–5000 c/s ($\sim 0.1$ – 0.5 Crab) are well below the nominal pile-up limit of 60,000 c/s of this mode, an analysis of the Crab nebula showed that sources of this intensity are somewhat affected by pile-up at $\leq$180 due to the special readout (Kirsch et al. 2006). We follow their recommendation for robust spectral determination, i.e. extract events in RAWY [1:160]. Slightly different positioning on the chip for the different observations means that we use either RAWX [31:41] or RAWX [31:42]. We only use integer column numbers as the SAS tasks for generating response and ancillary files (RMFGEN and ARFGEN) silently truncate any fractional column number. We use only single and double events (PATTERN $\leq$ 4) and ignore band pixels with #XMMEA_EP and FLAG==0. We correct for rate-dependent charge transfer inefficiency

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1 http://xmm.vilspa.esa.es/external/xmm_sw_cal/calib/documentation.shtml
will otherwise lead to the spectral fits to be weighted more towards these low energies than the high, and hence artificially low $\chi^2$ values. Each bin was also set to have minimum of 25 counts. Background was not extracted as all regions on the chip are contaminated by the source (Done & Diaz Trigo 2010, see Appendix A).

For each XMM-Newton observation we also extract the RXTE data nearest in time. These all have significantly shorter exposure than the XMM-Newton datasets. Observations 1, 2 and 4 are all within the corresponding XMM-Newton dataset, but 3 and 5 have no overlap in time. However, disc dominated states are known to have rather slow variability, so variability is probably only a potential issue for the observation with the most dominant hard tail (Obs 4). Hence we time filter this XMM-Newton dataset to the RXTE observation to get truly simultaneous data. We allow there to be a free normalisation between the PCA and XMM-Newton data, but tie all the spectral parameters across the two datasets.

### Table 1. Details of the observations. The quoted exposure times are the exposures used in this analysis.

| Obsid          | Date              | Exp(s) | State       |
|----------------|-------------------|--------|-------------|
| 1              | 0093562701        | 60640  | Disc dom.   |
| 2              | 0156760101        | 75601  | SIMS        |
| 3              | 0410581201        | 15048  | Disc dom.   |
| 4              | 0410581301        | 3200   | SIMS        |
| 5              | 0410581701        | 8658   | Disc dom.   |

### Figure 2. The high mass accretion rate spectra of GX 339−4. Colour convention same as in Figure 1: Obs 1. in cyan, Obs 2. in magenta, Obs 3. in red, Obs 4. in green and Obs 5. in blue.

(CTI), using EPFAST, which is included in the latest version of SAS. CTI occurs where electrons are caught in charge traps rather than being read out. This causes small shifts to the energy gain, so is most noticeable where the effective area of the instrument changes i.e. at the Si and Au features. The level of residuals at these energies is a measure of success of the CTI correction. Our residuals around the Au edge are at the 2-5% level expected for the current calibration, but this is larger than the 1% systematic error applied to the rest of the spectrum, so we exclude this region from the fit.

Finally the spectra were rebinned using the SAS task SPECGROUP. The number of bins per instrumental energy resolution was set to 3, as recommended for the EPIC pn, to make sure that all the channels are indeed independent for the $\chi^2$ calculations. The high signal-to-noise at low energies and the high oversampling of the XMM-Newton response

### 3 SPECTRAL ANALYSIS OVERVIEW

We previously analysed all the disc dominated RXTE PCA data from GX 339−4 using a multicolour disc and its thermal Comptonisation, together with a Gaussian line and smeared edge to approximately model the expected reflection features \((\text{TBABS} \times \text{SMEDGE} \times \text{DISKBB+THCOMP+GAUSS})\); Kolehmainen & Done 2010, Model 1a in Table 2). We now test this same model on our composite \(\text{RXTE/XMM-Newton}\) datasets which extends the low energy bandpass to 0.7 keV. We could include the simultaneous RXTE HEXTE data in the fit, but the much lower signal to noise at these high energies mean that these points are given very little weight in the spectral fitting. Instead, we include these data after the fit, and ratio the observed flux to the model prediction in the 25–100 keV bandpass to assess how well the model extrapolates to higher energies.

Figure 2 shows the derived spectra for the joint pn-PCA datasets. Clearly all of these have a large disc component, but formally only observations 1, 3 and 5 (cyan, red and blue) are disc dominated, while observations 2 and 4 (magenta and green) are soft intermediate states. Observations 1 and 3 have the most dominant disc, while observation 4 has the strongest tail.

Figure 3 shows the disc luminosity-temperature plot from Kolehmainen & Done (2010) (black points) assuming a distance, mass and inclination of 8 kpc, 10 $M_\odot$ and 60$^\circ$, respectively. The crosses show the parameters for the PCA data alone, derived from Model 1a with the absorption fixed at $6 \times 10^{21}$ cm$^{-2}$ (as in Kolehmainen & Done 2010). All these observations lie on the same $L \propto T^4$ relation as the disc dominated data from Kolehmainen & Done (2010). The solid symbols show how this changes when the pn data are included. Including the lower energy data shifts the best-fit disc parameters to lower temperature/lower luminosity, as predicted from simulations of changing bandpass with more sophisticated disc models (Done & Davis 2008), but the effect is rather small. The disc dominated spectra lie closer to the previous luminosity-temperature relation, while the soft intermediate states are increasingly shifted, so that they have lower temperature than expected for their luminosity.
Table 2. THE MODELS

| Model    | Expression                                                                 |
|----------|-----------------------------------------------------------------------------|
| Model 1a | `tbabs*smedge*(diskbb+thcomp+gaussian)`                                    |
| Model 1b | `tbabs*smedge*(bhspec+thcomp+gaussian)`                                    |
| Model 2  | `tbabs*(bhspec+thcomp+kdblur*refxion*(thcomp))`                            |
| Model 3  | `tbabs*(simpl(bhspec)+kdblur*refxion*simpl(bhspec))`                       |
| Model 4  | `tbabs*(simpl(diskbb+comptt)+kdblur*refxion*simpl(diskbb+comptt))`         |

**Figure 3.** The L–T^4 diagram of all previous disc dominated data from the RXTE PCA sample of Kolehmainen & Done 2010 (black points) fitted with the simple Model 1a (see Table 2). The L–T^4 points fitted with the same model from the PCA data corresponding to each burst mode observation are shown as the coloured solid symbols (same colouring convention as in Fig 1), while the L–T^4 points from joint pn-PCA fits are shown as circles. These show a lower colour-temperature correction, as expected, but lie progressively further from the line as the strength of the hard tail increases.

4 THE DISC DOMINATED SPECTRA

4.1 The brightest disc dominated state: Obs. 3

As the uncertainties in reconstructing the intrinsic disc properties increase when the tail gets stronger, the disc dominated spectra provide the clearest view of the underlying disc physics. We start our analysis with the bright disc dominated state at the peak of the 2007 outburst (Obs 3).

The simplified model used in the previous section (Model 1a in Table 2) gives acceptable results for the limited resolution of the PCA detectors over the 3–25 keV bandpass. However, it gives a very poor fit to the joint pn-PCA data ($\chi^2 = 745/185$). This is to be expected as the true disc is not as simple as a multicolour blackbody. However, replacing diskbb with a better disc model bhspec (Davis et al. 2005, Model 1b; assuming $M=10 M_\odot$, $D=8$ kpc and an inclination of 60$^\circ$) makes the fit only moderately better ($\chi^2 = 530/185$). Thus it seems more likely that the issue is with the very approximate description of the reflected continuum. We have combined the refxion tabulated reflection models of Ross & Fabian (2005) with the older pexriv models to make a convolution model which can be used with any input continuum (rather than the hardwired power law with exponential cutoff of the refxion models), and with normalisation given in terms of inclination and solid angle (as for pexriv), but with the much more accurate treatment of the ionised reflection of refxion (see also an older version of this using the Ballantyne et al. 2001 tabulated reflection models in Done & Gierliński 2006). We convolve this reflected emission with the relativistic smearing Greens functions of Laor (1991), so the total model is $\text{tbabs}^*(\text{bhspec}+\text{thcomp}+\text{kdblur}_2\text{refxion}^*(\text{thcomp}))$ (Model 2). This results in another slight improvement, with $\chi^2 = 505/186$, but the model clearly underpredicts the higher energy HEXTE data, with model 25–100 keV count rate of 2.5, compared to the 4.8±0.3 observed.

One issue with the model above is that the Compton scattering of seed photons from the disc by a corona should also remove disc photons from our line of sight (see the discussion of different geometries in Kubota & Done 2004). The Comptonisation model used here, trhcomp, does not couple the disc and tail together, so instead we replace it with the convolution model simpl (Steiner et al. 2009), which removes as many photons from the disc as are scattered up into the tail. This model has the additional advantages that it takes the seed photon shape from the model, rather than assuming blackbody or diskbb shape as for the trhcomp model. It also assumes a power law tail, better suited to modelling the probably non-thermal emission seen in the high/soft states than thermal Compton scattering (Gierliński et al. 1999).

However, the simpl model, as released, does not allow the model to be used to calculate the tail separately. This is required for the reflection modelling, as only the coronal emission should be reflected. Hence we re-coded the simpl model to allow it to do this. However, this model (Model 3 in Table 2, with parameters tabulated in Table 3) gives only a slightly better $\chi^2 = 426/186$ than Model 2, with very similar parameters, including the mismatch between the extrapolated model and the observed HEXTE flux. Thus the issue is not with the description of the Comptonised tail.

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Figure 4. The bright disc dominated spectrum (Obs. 3) modelled with Model 3. The top panel shows the data+model, along with the model components (disc+reflection). The model residuals are plotted in the bottom panel.

Figure 5. Same as Fig 4, this time modelled with Model 4.

(thermal vs. non-thermal) or with the disc normalisation needing correcting for Compton scattering.

Figure 4 shows the deconvolved $\nu F_\nu$ spectrum. Plainly the fit does actually describe the data quite well below 20 keV, but the Compton tail has a much steeper index than expected, at $\Gamma = 3.19^{+0.09}_{-0.05}$ compared to the typical $\Gamma \sim 2.2$ seen in the high/soft state. To get through the 10–20 keV PCA data then requires a very large reflection fraction $\Omega/2\pi = 6.9^{+0.4}_{-0.6}$ to flatten the spectrum, but reflection rolls over above 30–50 keV so the extrapolation falls well below the level of the HEXTE flux.

Thus the key issue is the derived steep Comptonisation index. One possible reason for this is that the extremely high signal-to-noise in the pn spectra are driving the fit, so that small residuals from the disc model are compensated for by a steep Comptonisation tail. This could indicate that the disc is broader than the BHSPEC model, so we replace this by a phenomenological disc spectrum made from diskbb+comptt (Model 4 in Table 2). This gives a much better fit to the data $\chi^2 = 210/186$, as seen by the lower level of residuals below 1.5 keV (Figure 5). There are still two features below 1 keV, possibly Ne III and Ne II lines from the interstellar medium (Miller et al. 2004b), but no big residuals at iron.

At first sight it seems likely that the better fit with the phenomenological disc spectrum could simply be compensating for remaining calibration uncertainties in the instrument response of this mode. Figure 6 shows a comparison of the phenomenological diskbb+comptt continuum with the BHSPEC continuum. Clearly the biggest difference is that BHSPEC predicts absorption features from ionised oxygen and iron L in the disc photosphere from 0.7–1.5 keV. These should be smeared by relativistic effects, resulting in the broad dip predicted by BHSPEC rather than sharp edges. The phenomenological model does not have these features, but is as broad as the BHSPEC continuum. This pattern of residuals is very similar to that obtained from a recent Suzaku spectrum of LMC X-3 in a disc dominated state (Kubota et al. 2010). These are seen even more unambiguously in LMC X-3 due to its much smaller galactic column density along the line of sight ($0.038 \times 10^{22}$ cm$^{-2}$ compared to $\sim 0.52 \times 10^{22}$ cm$^{-2}$ for GX 339–4). The different instrument (Suzaku) also means that the issue is not likely to be simply the XMM-Newton burst mode calibration.

However, the shape of the derived disc continuum is difficult to explain. It is as broad as the total continuum predicted by the BHSPEC models, but these models produce the broad continuum partly by the changing colour-temperature correction associated with the atomic features yet the atomic features are not observed. Relativistic smearing of a single colour-temperature corrected disc spectrum (as in the KERRBB disc model; Li et al. 2005) is not broad enough to explain the data (green line in Fig 6). For comparison, we also show the best fit diskbb model, which is plainly far too narrow (Fig 6).

Thus it seems most likely that even the best current disc models do not describe the observed disc spectra at the 5-10% level, so we also use the best fit phenomenological description (Model 4) in all the following analysis.

4.2 The other disc dominated states: Obs. 1 & 5

We fit the two other disc dominated states with Models 3 and 4 described above, with best-fit parameters given in Tables 3 and 4, respectively. We see the same pattern as before, namely that the best current disc models are not quite the right shape to match with the high signal-to-noise EPIC pn data, so they drag the Comptonisation index to higher values to compensate, which in turn requires more reflection to flatten the spectrum in the 10–20 keV bandpass so that it can match the observed PCA data. This then fails to fit the HEXTE points. By contrast, the phenomenological
Figure 6. Comparison of different disc continuum models with Obs 3. \textsc{diskbb}+\textsc{comptt} is plotted in red, \textsc{bhspec} in blue, \textsc{kerbb} in green and \textsc{diskbb} in magenta. The bottom panel shows the ratio of \textsc{bhspec} to \textsc{diskbb}+\textsc{comptt}. The phenomenological \textsc{diskbb}+\textsc{comptt} continuum is clearly most agreeable with the data, and hence is chosen as the disc model in the followin analysis.

\textsc{diskbb}+\textsc{comptt} disc continuum fits the data much better, gives more reasonable values for the Comptonisation index and amount of reflection, and extrapolate to the HEXTE band.

Figures 4 – 8 show the deconvolved spectra for both model fits to observations 1 and 5. Unlike the more luminous spectrum discussed in the previous section, there is now a clear mismatch above 4 keV between the pn and PCA spectra. This is most likely due to the lack of background subtraction in the burst mode data, which is now beginning to become an issue at high energies for this lower luminosity spectrum. We discuss this in more detail in Appendix A.

The remaining disc dominated spectrum, Obs. 1, is very similar to the Obs. 3 so we do not show the deconvolved spectra, but give details of the fits in Tables 3 and 4. Again, the main difference between Model 3 and 5 is that the \textsc{bhspec} models predict smeared absorption features which are not seen in the best fit \textsc{diskbb}+\textsc{comptt} models.

5 THE SOFT INTERMEDIATE STATE SPECTRA (SIMS)

A significant advantage to using the \textsc{simpl} model is that it also allows us to fit spectra with strong tails in addition to the thermal dominated ones. We now use the same models (3 and 4) to go through the SIMS spectra in order of the strength of the tail.

5.1 The 2002/2003 outburst: Obs. 2

The tail carries roughly 25% of the total luminosity, and Figure 3 shows that it is slightly steeper than the tail seen in the disc dominated spectra. Our best-fit for Model 3 gives a very poor $\chi^2$ of 798/199 d.o.f., while Model 4 gives a better fit with $\chi^2=451/196$. These are shown in Figures 10 and 11. Both have clear residuals above 6 keV in the pn but not the PCA. The residuals in Model 3 look like there may be...
Figure 9. Same as Fig 6 for Obs. 5, now showing the phenomenological model diskbb+comptt in red and the best theoretical model bhspec in blue. The bottom panel shows the ratio of bhspec to diskbb+comptt.

Figure 10. The 2002/2003 SIMS spectrum (Obs. 2) modelled with Model 3. The top panel shows the data+model, along with the model components. The model residuals are plotted in the bottom panel.

Figure 11. Same as Fig 10, modelled with Model 4.

be that the disc ionisation parameter hits its upper limit \((\log \xi = 4.00\pm0.04)\), i.e. the model does not extend to high enough ionisation to fit the data.

These data were previously analysed (though with older versions of the SAS which did not include CTI corrections) by e.g. Miller et al. (2004;2006;2008;2009) and Reis et al. (2008). These studies observed a very skewed iron line at \(\sim6.4\) keV, indicating an almost maximally spinning black hole. This is in sharp contrast to the results from either Model 3 or 4 in our spectral fits, where the derived inner radius is quite large at \(R_{in} = 34^{+10}_{-17}R_g\). We return to this point in Section 6.

5.2 The 2007 outburst: Obs. 4

Figure 2 shows that the strongest tail is in the 2007 outburst, in observation 4 (green). Results from fits with Models 3 and 4 are again shown in Tables 3 and 4, and the spectra shown in Figures 12 and 13.

Model 3 gives an unacceptable \(\chi^2=968/186\) d.o.f. The predicted continuum falls substantially below the HEXTE points and the derived column is lower than for the other datasets, at \(N_H = 5.0^{+0.04}_{-0.02} \times 10^{21}\) cm\(^{-2}\). Model 4, on the other hand, gives a best-fit \(\chi^2=297/183\) d.o.f (though there is still a mismatch in residuals between the pn and the PCA above 7 keV), with hydrogen column of \(N_H = 5.45 \times 10^{21}\) cm\(^{-2}\), more consistent with the other datasets. The reflected continuum has moderate solid angle of \(\Omega/2\pi = 0.63^{+0.016}_{-0.10}\) and again, the smearing is not at all extreme, with \(R_{in} = 42^{+18}_{-30}R_g\). This reflection is highly ionised, but is within the range of tabulated models at \(\log \xi = 3.9 \pm 0.1\).

Since these data are brighter, it seems unlikely that the ionisation parameter is truly higher in the previous soft intermediate state above (Obs. 2). Instead, this probably indicates that the previous data are more complex than the model fit.
6 BLACK HOLE SPIN

6.1 Disc continuum fits: bhspec

The bhspec model fits directly for black hole spin from the dominant disc component for a given mass, distance and inclination. These system parameters are quite poorly known for GX 339–4 (see e.g. Kolehmainen & Done 2010), but fixing these at reasonable values of 10\(M_\odot\), 8 kpc and 60°, respectively, gives derived spin values which are low to moderate (\(a_* = 0.1 - 0.5\)). This is as expected from the previous fits to the RXTE PCA data (Kolehmainen & Done 2010). However, the derived spin is not constant, even when restricted to the disc dominated spectra (Table 3) due to the mismatch between the broad absorption features from oxygen and iron L predicted by bhspec and the data (Figs 6 and 10). The excellent statistics of the XMM-Newton data means that these 5–10% residuals drive the Comptonised continuum to a much steeper index to compensate for this lack of flux at low energies. This level of mismatch between the data and model is enough to distort the entire fit.

These fits (Table 3) also give an estimate for black hole spin from the iron line profiles. However, since the fits are so distorted, these are clearly not reliable.

6.2 Iron line

The disc continuum is much better modelled using the phenomenological diskbb+comptt description. With this, the amount of smearing of the reflected emission should be indicative of the inner radius of the disc. However, none of our spectral fits give a line which is so broad as to require that the disc extends down to the last stable orbit around even a Schwarzschild black hole. This is in sharp contrast to the claim of Miller et al. 2004; Reis et al. 2008 for the less extreme soft intermediate state spectrum (Obs. 2), that the iron line is so broad as to require that the black hole in GX 339–4 has high spin, of \(a_* = 0.935\). This value is also in conflict with the upper limit for the spin of \(a_* \leq 0.9\) in GX 339–4 (Kolehmainen & Done, 2010). We repeat their analysis on this specific dataset (Obs. 2, combined with RXTE PCA data), and fit the spectrum, excluding the 4–7 keV (i.e. Fe line) region, with a simple diskbb+power law. We then plot residuals including the Fe line bandpass. Our residuals indeed show a very similar line profile to their results, with an extremely broad red wing to the iron line (Figure 14a). Furthermore, we also add a relativistic emission line model (laor; Laor 1991) to describe the Fe line more physically. Again we see similar results in terms of a very small disc inner radius, low inclination and a very centrally peaked emissivity.

However, modelling complex spectral curvature such as this is a delicate task. Fig 2 shows that the iron line is in an area where the curvature changes from being dominated by the disc to being dominated by the tail. The ‘iron line’ residual will then be strongly affected by a small change in the continuum model. We show this explicitly by fitting our best continuum model (diskbb+comptt for the disc, convolved with simpl for the tail) to the data, again excluding the Fe line region. Figure 14b then shows the same as Fig 14a but with the continuum modelled using Model 4. We overplot the previous residuals for direct comparison and change in shape of the derived line profile is immediately apparent.

The line profile derived by this method is clearly very sensitive to a change in underlying continuum shape. The analysis of the disc dominated spectra in Section 4 shows that the disc continuum is substantially broader than a diskbb due mainly to relativistic smearing of the disc continuum and radiative transfer through the disc photosphere. Fitting a diskbb continuum then forces a broad residual into the data from the poor match to the disc continuum. However, this broad residual on the tail of the disc spectrum is in...
the same energy band as the expected red wing of the iron line. We caution that the derived iron line shape depends on the assumed continuum, and that this is especially important where the continuum curvature changes rapidly under the iron line. This is the case for all the bright disc dominated and soft intermediate spectra considered here.

Table 4 shows that with our best fit model the line is not extremely smeared in these data (consistent with Fig 14b), with $R_{in} = 34^{+10}_{-17} R_g$. This does not mean that we infer the disc to be truncated. Quite the contrary, the unfolded spectrum has a clear disc shape below $\sim6$ keV and the disc contributes to $\sim75\%$ of the total luminosity. Our fit also requires that the reflecting material is highly ionised, as expected from the high effective temperature of the disc. It seems more likely that the inner disc is so highly ionised that iron is completely stripped, so no longer contributes to the atomic features which are the best tracer of the reflecting material. We also caution that while this model is our best fit, our iron line parameters will also depend on our assumed continuum form. While our reflection is derived from the best currently available models (Ross & Fabian 2005), these are calculated for the lower density and temperatures of AGN discs. Newer reflection models including the effect of collisional ionisation should instead be used (Ross & Fabian 2007), but we caution that these alone will not solve the sensitivity of the iron line profile to the underlying continuum shape.

7 DISCUSSION AND CONCLUSIONS

The new calibration of the XMM-Newton EPIC pn burst mode allows detailed spectral fitting of bright black hole binaries. We use these data together with (mostly) simultaneous RXTE data to explore the shape of the disc dominated and soft intermediate state 0.7–200 keV spectra from GX 339–4. This is an important object to understand as there are conflicting measures of the black hole spin in this object, with disc continuum fitting of disc dominated states from RXTE showing an upper limit of $a_* < 0.9$ (Kolehmainen & Done 2010) while the iron line profile in an XMM-Newton dataset from a soft intermediate state gives $a_* = 0.935$ (Miller et al. 2004; Reis et al. 2008).

We find that while the disc dominated states are well fit with the simple diskbb model (together with a tail to high energies and its reflection) in the PCA, the lower energy extent of the CCD bandpass shows that this is not a good representation of the disc emission. This is as expected, as the disc continuum should also be smeared by relativistic effects, making it substantially broader. We fit the best current disc models to the data instead. These include full radiative transfer through the disc photosphere as well as relativistic smearing (bhspec: Davis et al. 2005). However, these are not a good match to the data either, as although they are broader, they predict smeared atomic absorption features at oxygen/iron L which are not present in the data. This mismatch is also seen in Suzaku data from LMC X-3 (Kubota et al. 2010), making it unlikely to be a residual calibration feature of XMM-Newton. Instead, it could be due to irradiation of the photosphere by the weak high energy tail.

Whatever its origin, the disc dominated spectra clearly show that the observed disc spectrum can only be currently well matched by phenomenological models. We use the same phenomenological description to fit the disc component in the soft intermediate state. This broader disc spectrum has a profound effect on the derived iron line profile, as the line energy is close to where disc and tail components have equal flux. A small change in the disc spectrum then makes a large change in the residual flux at the iron line energy.
We find that we cannot constrain black hole spin in these
data with our continuum model as the line profile (which is
already smeared by Compton scattering in the highly ionised
reflector) is not strongly relativistically smeared, so arises
predominantly from radii which are rather larger than even
the last stable orbit around a Schwarzschild black hole. This
probably indicates that the inner disc is so highly ionised
that iron is completely stripped and hence does not produce
any characteristic atomic features.

We caution that using simple continuum models for
complex spectra will result in broad residuals in the data
simply from deficiencies in the continuum modelling rather
than giving a robust, model independent way to see the iron
line profile. All bright black hole binary spectra are com-
pared to the tail by the very dimmest disc dominated spectra, where the
line region is on the cross-over between the disc and tail.

Only the very dimmest disc dominated spectra, where the
line region is on the cross-over between the disc and tail.

The best-fit parameter values of Model 3. The errors quoted are shown for illustrative purposes only, in summary of the freedom
of fit.

Table 4. The best-fit parameter values of Model 4. The errors quoted are shown for illustrative purposes only, in summary of the freedom
of fit.
APPENDIX A: BURST MODE BACKGROUND

Background subtraction of bright sources in burst (and timing) modes is very challenging. The bright source contaminates the whole CCD chip, and hence background was not subtracted in the reduction phase of this analysis. To illustrate this effect, we extract a ‘background’ spectrum for all of our observations. The extraction region was selected as a strip of RAWX [3:10] and RAWY [1:160], near the edge of the chip, away from the source itself.

Figure A1 (top panel) shows the source spectrum (red), plotted with the background (blue) in detector counts. The shape of the background clearly mimics that of the source, indicating that much of the extracted ‘background’ is in fact contaminated by the source (see also Done & Diaz Trigo 2010 for similar issues in EPIC pn timing mode, and Guainazzi et al. 2010a). We attempt to constrain the true background by subtracting a scaled version of the source spectrum from the extracted background. We set the scale by assuming that the true background is negligible in the 1–2 keV bandpass. The remaining background is still a slight overestimate of the true background as high energy photons are preferentially scattered into the wings of the point spread function, so the spectrum at large off-axis angles will be slightly harder than the on-axis source spectrum. We plot the resulting background estimate as unfolded ($\nu F_\nu$) spectra in the lower panel of Fig. A1.

The background above 5 keV from singles in the pn full frame mode is typically at a level of 0.1 counts/s/keV, with a strong copper line superimposed (Freyberg et al. 2006: XMM-SOC-CAL-TN-0068). Adding the doubles (burst mode loses one spatial dimension, so cannot distinguish between singles and doubles in the compressed direction) would increase this by a factor $\sim 2$. This is roughly the level seen at 10 keV in all the spectra (upper panel) except for the one with the strongest tail (Obs. 4). The lower panel shows the source subtracted $\nu F_\nu$ looks similar to that expected from the background, with a strong copper line at 8 keV in all the disc dominated spectra. However, the ‘background’ level is progressively larger, swamping the line, in the spectra with stronger tails. This probably indicates that there is residual contamination from the source, and this contamination gets stronger for stronger hard spectra.

Thus the residual background in the faintest disc dominated spectrum is probably closest to the ‘true’ background for singles plus doubles in burst mode. This is 20% of the source flux at 8–10 keV. The bright disc dominated spectra are a factor $\sim 3–4$ brighter at 10 keV (see Fig 2), so a similar background here would give a 5% excess at high energies in the pn. The residuals to the best fit model appear to be slightly larger than this (Fig 5) which may indicate remaining cross-calibration uncertainties between the pn and PCA (Guainazzi et al. 2010, Weisskopf et al. 2010).

The clear conclusion is that the background in burst mode is not necessarily negligible, especially for very soft spectra. There is no way to estimate this reliably from the data, so offset pointings are required.
Figure A1. Background analysis for the EPIC pn burst mode. Top panel: The source spectrum (in red), plotted with the extracted background (blue) in detector counts. The shape of the background plainly follows the shape of the source, indicating that much of the 'background' is in fact contaminated by the source. Bottom panel: The background spectrum (in blue) corrected with the source spectrum. Observations 1 and 2 show the clearest copper lines at $\sim 8$ keV, while the 'background' level in observation 4 is clearly strongest of the sample.