The truncated and evolving inner accretion disc of the black hole GX 339-4

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22 May 2014

ABSTRACT

The nature of accretion onto stellar mass black holes in the low/hard state remains unresolved, with some evidence suggesting that the inner accretion disc is truncated and replaced by a hot flow. However the detection of relativistic broadened iron emission lines, even at relatively low luminosities, seems to require an accretion disc extending fully to its innermost stable circular orbit. Modelling such features is however highly susceptible to degeneracies, which could easily bias any interpretation. We present the first systematic study of the iron line region to track how the inner accretion disc evolves in the low/hard state of the black hole GX 339-4. Our four observations display increased broadening of the iron line over two magnitudes in luminosity, which we use to track any variation of the disc inner radius. We find that the disc extends closer to the black hole at higher luminosities, but is consistent with being truncated throughout the entire low/hard state, a result which renders black hole spin estimates inaccurate at these stages of the outburst. Furthermore we show that the evolution of our spectral inner disc radius estimates corresponds very closely to the trend of the break frequency in Fourier power spectra, supporting the interpretation of a truncated and evolving disc in the hard state.

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

1 INTRODUCTION

Black Hole X-ray Binaries (BHXRBs) are, in the main, transient, spending the majority of their lifetime in a ‘quiescent’ state punctuated by intense outbursts which can last for months or even years. These outbursts are driven by accretion disc instabilities (see Meyer & Meyer-Hofmeister 1981; Coriat et al. 2012 and references therein) and we observe distinct spectral states revealed through the relative strength of their respective soft and hard X-ray emission (Remillard & McClintock 2006; Done et al. 2007; Belloni et al. 2011; Fender & Belloni 2012).

An outburst commences in the low/hard (hereafter ‘hard’) state, characterised by its dominant power-law component and high level of aperiodic variability. The power-law is believed to originate as a result of inverse Compton scattering of ‘seed’ photons in a thermalised, optically thin, ‘corona’, with a temperature of ∼100 keV. Present, albeit weakly, is a soft excess, generally attributed to arise from the cool and dim accretion disc. This is starkly juxtaposed with the high/soft (hereafter ‘soft’) state where a quasi-blackbody component (KT ≈ 1 keV) is now dominant and the hard power-law has steepened contributing very little to the overall luminosity. These two distinct states are ubiquitously associated with two different types of outflow: winds and jets. Narrow absorption features have been detected in numerous systems and high-resolution spectroscopy has attributed them to an accretion disc wind (Ueda et al. 1998; Lee et al. 2002; Miller et al. 2006; Díaz Trigo et al. 2007). Whilst winds are thought to be ubiquitous in BHXRBs, they are only observed in the soft state (Ponti et al. 2012; see Díaz Trigo & Boirin 2012 for a recent review) whereas a similar, but reversed, pattern is observed for the jet which is quenched in the soft state (Russell et al. 2011), but steady in the hard state (Fender et al. 2004). These two outflow phenomena may be physically linked (Neilsen & Lee 2009) or just symptoms of the state change. The transition between the hard and soft states is often referred to as the ‘intermediate’ phase, again split into two distinct regimes: the hard-intermediate (HIMS) and soft-intermediate (SIMS) states. In the HIMS the spectrum has softened as a result of a steeper power-law index (now as high as 2.5, whereas ∼1.6 in the hard state) and an increased thermal disc component. Furthermore it displays variability similar to the hard state, with increased characteristic frequencies (van der Klis 2006; Belloni et al. 2011). The SIMS spectrum is slightly softer, but not significantly, however the timing properties change abruptly displaying variability as little as a few %, marking a clearly different state.

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Also present and superimposed upon the continuum are reflection features emerging from irradiation of the accretion disc by the up-scattered seed photons \cite{ReynoldsNowak2003,Miller2007,FabianRoss2010}. Emission from the inner regions of the accretion flow will undergo both special and general relativistic effects leading to a broadened and skewed profile \cite{FabianNowak1989}. Such a profile is a result of the strong dependence of relativistic effects with distance from the central Black Hole (BH) allowing it to be used as a diagnostic of the inner accretion disc, specifically the inner radius. Furthermore, assuming the disc is at the innermost stable circular orbit (ISCO), one can essentially use the inner radius to estimate the spin of the BH since the ISCO evolves from \(r_\text{g} \) to \(\sim 1.2r_\text{g}\) for the full range of prograde spin \cite{Bardeen1973,Thorne1974}. However even given a fully robust model there is still one rather large assumption here - that the inner disc has extended all the way to the ISCO.

It is widely accepted that the inner accretion disc extends fully to the ISCO for a large fraction of the soft state \cite{GierlinskiDone2004,Steiner2010}. In quiescence however the disc is predicted and found to recede as the accretion rate diminishes \cite{McClintock1995,NarayanYi1995,Narayan1996,Esin1997,McClintock2001,Esin2001,McClintock2004}. At some stage therefore the inner accretion disc must evolve and extend itself closer to the BH, a topic which has become strongly debated in recent times.

A truncated inner accretion disc provides a geometric interpretation to explain the spectral changes observed in BHXRBs. Here the standard optically thick and geometrically thin accretion disc is replaced in the inner regions by what is essentially its converse, a hot, optically thin, geometrically thick flow \cite{Esin1997}. As the accretion rate increases the truncation radius of the disc is expected to decrease, eventually extending fully to the ISCO. However there are two distinct claims in the literature strongly arguing against this even at relatively low luminosities in the hard state. The detection of significantly broadened iron lines at low accretion rates \cite{Miller2002,Miller2006,Reis2008,Reis2010} offer evidence of relativistic effects at or near to the ISCO, although this is still strongly challenged both directly \cite{DoneGierlinski2006,Yamada2009,Done2010} and indirectly \cite{Tomsick2004,Shidatsu2011}. A geometrically thin disc with a fixed inner radius will closely follow the \(L \propto T^4\) relation \cite{Gierlinski2004,Dunn2011}, and hence deviations from this can reveal truncation of the inner disc. The debate remains unresolved with arguments for \cite{Gierlinski2006,Tomsick2008,Cabanac2009} and against \cite{Rykoff2007,Miller2006a,Reis2009,Reis2010} disc truncation. Furthermore there is evidence that the disc may also be truncated in the hard intermediate state \cite{Kubota2004,Done2008,Tamura2012}, or at the ISCO \cite{Hiemstra2011}.

GX 339-4 is a key source in the inner disc truncation debate. Investigations by \cite{Miller2006b} and \cite{Reis2008} of strongly broadened iron lines have suggested that the disc is at the ISCO in the hard state. However \cite{Done2010} suggested that these data can be largely affected by photon pile-up and presented evidence that the emission line could be significantly narrower. Studies by \cite{Tomsick2008} and \cite{Shidatsu2011} have examined the iron line region further at lower luminosities providing evidence for a truncated disc, and in the latter first hints at a correlation between the inner radius estimates and luminosity. Currently therefore our understanding of the state of the inner accretion disc in the hard state of GX 339-4 is uncertain. It is essential that we are confident of how the inner disc evolves in the hard state in order for us to measure the BH spin through the X-ray reflection method. This requires that the inner disc is at the ISCO and relies heavily on studies of the hard state where irradiation of the disc is high and the underlying continuum around 6 keV is relatively simple (see e.g. \cite{Kolehmainen2011} for issues with softer spectral states).

Besides the investigation of \cite{Shidatsu2011}, who re-analyse the data used in \cite{Tomsick2009}, each observation has been examined independently which gives rise to complications when comparing the respective results. Firstly, the parameters derived from reflection modelling can be highly degenerate and can significantly affect conclusions if not accounted for. This can be observed through the range of inclination angles fitted in the mentioned previous studies. The inclination angle of GX 339-4 has not been accurately measured and freely fitting this parameter can crucially affect the inner radius estimate \cite{Tomsick2009}. Additionally, assorted interpretations of the spectra have lead to a variety of models being applied which can again skew results. We therefore present the first systematic study of evolution of the iron line region in the hard state of GX 339-4 by fitting our selected observations simultaneously, enabling potentially degenerate parameters to be tied. This allows us to keep our analysis as consistent as possible and significantly remove the issues described before by inspecting the relative change in the inner disc evolution, specifically the ionisation and inner radius parameters. Our focus in this investigation is only GX 339-4 since it is the best sampled transient BH at the resolution we require in the hard state (see \S 2). We do note however that although transient BHs generally display the same behaviour in outburst it may be the case that the inner disc does not always vary how we find in this study.

We begin by introducing our observation selection criteria and data reduction process in \S 2. We then analyse both the continuum (\S 3) and fits to the iron line region utilising the line and reflection modelling techniques (\S 3.1-3.3.2). Our results indicate that even at relatively high luminosities the disc appears to still be recessed in the hard state as well as a strong trend of evolution towards the ISCO at higher luminosity. Additionally we investigate whether this correlation is purely based on luminosity by analysing observations in the rise and decay of the hard state at similar flux levels (\S 3.3.3). Furthermore in \S 3.3.5 we investigate any correlation our results may have with the power spectra break frequency, which is believed to also track how the inner disc evolves. Finally we summarise our results and discuss implications for the truncated disc model and BH spin estimates in \S 4.

\section{Observations and Data Reduction}

We utilise the iron line region as a probe of disc evolution with luminosity. To undertake such a task, which requires high precision, the work presented here considers just high resolution observations with a large effective area in the iron K band. Therefore we employ only \textit{XMM-Newton} and \textit{Suzaku}, and in the case of the former utilise simultaneous \textit{RXTE} observations to increase the broadband coverage. A study by \cite{Kolehmainen2011} showed that in the case of the disc and power-law components having equal fluxes around the iron K range, fitting a broader disc component can significantly alter the line profile. Therefore we apply the additional constraint of only using observations in the hard or hard-intermediate states where the disc component contribution is not present in the range of the broadened Fe K\alpha emission line. The data we ignore restricts our sample to probe the disc evolution, however it would also lead
Table 1. Observations 2, 3, 4 were taken with XMM-Newton, whilst 1 and 2b are Suzaku datasets. Exposures correspond to that remaining after our reduction process, and hence used in our analysis. Count rates in brackets refer to before any pile-up removal was applied.

to less secure results. Additionally, a key element of this work is to probe the inner disc radius, which is already well regarded to have extended to the ISCO in the soft states.

The remainder of this section introduces our data reduction procedure and the five observations found in the archives which met our criteria are described in Table 1.

2.1 XMM-Newton

For the reduction of XMM-Newton observations we employed the Science Analysis Software (SAS) version 11.0. In this study we do not consider data from the EPIC-MOS camera (Turner et al. 2001) and instead restrict ourselves to the EPIC-pn for which the three Observations were all taken in ‘timing’ mode. For Observation 4 the EPIC-MOS data cannot be studied since only the EPIC-pn camera was operated, and the MOS dataset of Observation 3 suffers significantly from pile-up. This dataset was taken in the EPIC-pn camera was operated, and the MOS dataset of Observation 3 were all taken in ‘timing’ mode.

We apply the standard tools to create response and ancillary files (RMFGEN and ARFGEN) and use only single and double events (PATTERN\textless;4) whilst ignoring bad pixels with #XMMEA_EP and FLAG==0. Additionally all spectra are binned using the FTOOL GRPPHA to have at least 20 counts per channel. Finally we found all background regions were contaminated, indicated by spectra clearly following that of the source. However due to the high source flux in all the observations we found it acceptable to proceed without implementing any background subtraction.

Charge-transfer inefficiency (CTI) results in a gain shift hence affecting the energy spectrum and can be corrected by the SAS task EPFAST. More importantly if not allowed for CTI can shift the Fe Kα profile (see Figure 22 in the XMM-Newton Calibration Technical Note (0083)). In a recent study Walton et al. (2012) showed that the rate-dependent EPFAST correction could also lead to an incorrect profile, however they made use of a ‘burst’ mode observation at a very high count rate where the correction may not sufficient. We follow the current recommendation and apply EPFAST to all our data, but we also note that the low count rate of our observations did not result in any noticeable changes. This has also been found at similar count rates in timing mode (see e.g. Chiang et al. 2012).

2.2 Suzaku

Suzaku carries four X-ray Imaging Spectrometer detectors (XIS; Koyama et al. 2007), one of which is ‘back-illuminated’ (BI) in addition to the three ‘front-illuminated’ (FI) ones. Each covers the 50-600 keV (GSO) regions respectively.

We processed the unfiltered event files following the Suzaku Data Reduction Guide using the latest HEADAS v6.11.1 software package. We produced clean event files using the FTOOL AEPIPELINE, applying the calibration products (HXD20110913, XIS20120209 and XRT20110630). Suzaku undergoes wobbling due to thermal flexing leading to a blurring of the image. We ran the script AEATTCOR.SHI to create a new attitude file, which was then applied to each clean event file using the FTOOL XISCOORD. For the XIS XSELECT was then used to extract the spectral and background products. A source region with a radius of 200 pixels centred on the image peak was used for all observations. Observation 2b however employed the 1/4 window mode. Therefore the extraction region is larger than the window itself and hence the effective region extracted is an intersection of our circle with a rectangle of 1024 × 256 pixels. Background events were extracted using a circle of 100 pixels located away from the source.

We also check for the effects of photon pile-up using the tool PILE_ESTIMATE.SHI which creates a two-dimensional map of the pile-up fraction. In the case of Observation 2b we solve for pile-up by exchanging our source circle for an annulus with an inner region with a radius of 30 pixels which limits the effect of photon pile-up to <5%. Observation 1 was found to be free from any pile-up.

The tools XISRMFGEN and XISSIMARFGEN were used to create the response and ancillary files respectively. For our analysis we combine the two FI cameras (XIS0 and XIS3) using the FTOOL ADDASCASPEC and ignore the BI instrument (XIS1) which has a

\footnotesize

| ObsID   | State         | Net Count Rate (cts/s) | Exposure |
|---------|---------------|------------------------|----------|
| 1       | 403067010     | Hard (Decay)           | 2 ± 0.01 | 105 ks   |
| 2       | 0605610201    | Hard (Rise)            | 132 ± 0.1| 32 ks    |
| 2b      | 405063010     | HIMS (Decay)           | 20 ± 0.02 (29) | 22 ks |
| 3       | 0204750201    | Hard (Rise)            | 259 ± 0.1| 155 ks   |
| 4       | 0654130401    | Hard (Rise)            | 352 ± 0.2 (988) | 25 ks |

1. http://xmm.vilspa.esa.es/external/xmm_sw_calib/documentation.shtml
2. http://space.mit.edu/CXC/software/suzaku/aecatt.html
3. http://space.mit.edu/CXC/software/suzaku/pec.html
smaller effective area at 6 keV and is generally less well calibrated. We require a minimum of 20 counts per bin using GRPPHA.

After determining the pointing (XIS or HXD) appropriate response and tuned non-X-ray background (NXB) files were downloaded. We then applied the FTOOLS HXDPINXBFP which produces a dead time corrected PIN source spectrum plus the combined PIN background (non-X-ray and cosmic) and again a minimum of 20 counts was required. The GSO instrument is not used in our analysis.

2.3 RXTE

We performed spectral analysis using data from the Proportional Counter Array (PCA; Jahoda et al. 2006) and the High Energy X-ray Timing Experiment (HEXTE; Rothchild et al. 1998). The data were reduced using HEASOFT software package v6.11 following the standard steps described in the (RXTE) data reduction cookbook. We extracted PCA spectra from the top layer of the Proportional Counter Unit (PCU) 2 which is the best calibrated detector out of the five PCUs, although we added a systematic uncertainty of 0.5% to all spectral channels to account for any calibration uncertainties. We produced the associated response matrix and modelled the background to create background spectra.

For HEXTE, we produced a response matrix and applied the necessary dead-time correction. The HEXTE background is measured throughout the observation by alternating between the source and background fields every 32s. The data from the background regions were then merged. When possible we used data from both detector A and B to extract source and background spectra. However, from 2005 December, due to problems in the rocking motion of Cluster A, we extracted spectra from Cluster B only. On 2009 December 14, Cluster B stopped rocking as well. From this date, we thus used only PCA data in our analysis. HEXTE channels were grouped by four.

For the variability analysis in §3.3 only the PCA data was used. We utilised the data modes GoodXenonL2s and E_{125us} > 54M_{11} Ls depending on the case. Power density spectra (PDS) were computed following the procedure reported in Belloni et al. (2006) using stretches 1024s long and PCA channels 0–95 (2–40 keV).

3 ANALYSIS AND RESULTS

The iron line region in some of our observations, or contemporaneous ones, has previously been analysed (see e.g., Tomskic et al. 2009, Done & Diaz Trigo 2016, Shidatsu et al. 2011, Cassatella et al. 2013). This is the first work however to make use of Observations 2b and 4. Quite simply one can compare the results from each previous analysis to probe any correlation between the iron line region and luminosity. However such a process introduces many issues which could bias results and hence conclusions. For example, the use of different models; the effects of degeneracies in the models; and the range of values of constant parameters like inclination, are just a few of these potential complications.

To gain a real insight into evolution throughout outburst one must keep analysis between each observation as consistent as possible. This is the key approach of this work. We fit observations simultaneously hence applying the same model to each dataset.

Furthermore we are then able to tie degenerate parameters such as inclination (see Figure 3. of Tomskic et al. 2009), allowing us to not only more accurately constrain their measurement but also reduce the effect of such issues. To this end we stress that it is not our aim to present what the exact inner radius value is for each observation. Instead we investigate the relative change of parameters between each observation. This is a crucial step towards an accurate investigation of the iron line region. We are aware that our results may well suffer from degeneracies. However the relative effect between observations should be significantly less and thus allow us the most accurate description yet of the evolution of the iron line region throughout the hard state.

3.1 Our Selected Models

The X-ray spectrum of BHXRBs can generally be described by three components. Two of these are a thermal blackbody component originating from the accretion disc and a power-law likely due to Compton up-scattered seed photons. The third, known as the ‘reflection spectrum’ (Fabian & Ross 2010), occurs due to the irradiation of the disc by the up-scattered photons, resulting in, but not exclusively, X-ray fluorescence. The most prominent signature of this is Fe Kα emission due to its high abundance and fluorescent yield.

The hard state itself is dominated by the power-law component, whilst the disc is weak (kT < 0.5 keV) above 1 keV (Miller et al. 2006a, Reis et al. 2010). Because of this we ignore the region below 4 keV above which the disc contribution is negligible, thereby simplifying our spectrum to just 2 components. However we check for consistency using a full bandpass in [4, 20] keV. We model the interstellar absorption using the model PHABS fixed at 0.5 × 10^{-22} cm^{-2}. There are two reason for this. Firstly, by only fitting above 4 keV our ability to constrain the column freely is reduced. Secondly, the neutral hydrogen value towards GX 339-4 is well resolved to be within the range (0.4 − 0.6) × 10^{22} cm^{-2} (Kong et al. 2009). We hence fix its value at the centre of these limits, noting that the effect of such a range above 4 keV is negligible. We also note that variability in the absorption has been suggested (Cabanac et al. 2009), however this was found not to be the case when fitting individual photoelectric absorption edges in high-resolution X-ray spectra (Miller et al. 2009).

To model the reflection there are two methods we can use: (1) Fit the prominent Fe Kα emission line blurred due to relativistic effects (Fabian et al. 1989, Laor 1993) or (2) Reproduce the entire reflection spectrum for an illuminated accretion disc (Ross et al. 1999, Ross & Fabian 2005) whilst blurring relativistically (Brenneman & Reynolds 2006, Dauser et al. 2010). Each method is extensively applied in the literature and hence we implement them both in our analysis. To model the Fe Kα line (method 1) and apply relativistic blurring in method 2 we employ the REFLINEX and RELCONV models of Dauser et al. (2010) respectively. For the reflection spectrum we use the code XILLVER (García & Kallman 2010, García et al. 2011), which goes beyond the resolution of the most widely used publicly available model REFLEXN (Ross & Fabian 2005). However we do include REFLINEX to allow comparison with previous investigations and ensure our results with XILLVER are consistent. For this work we use XSPEC version 12.8.0 and all quoted errors are at the 90% confidence level unless otherwise stated.
Observation 3 ratio and is in a different spectral state to the others. The line profile is however displayed in Figure 6. The flux has units of erg cm\(^{-2}\) s\(^{-1}\) and calculated in the 0.5 – 10 keV energy range using the model CFLUX.

### Table 2.

| Observation | \(\Gamma\) | \(N_{PL}\) | Flux | \(\chi^2/\nu\) |
|-------------|----------|-----------|------|----------------|
| 1           | 1.565\(\pm 0.012\) | 0.011\(\pm 0.001\) | 0.82 | 777/791 |
| 2           | 1.437\(\pm 0.008\) | 0.098\(\pm 0.001\) | 8.30 | 714/668 |
| 2b          | 1.807\(\pm 0.009\) | 0.144\(\pm 0.003\) | 8.46 | 882/789 |
| 3           | 1.476\(\pm 0.003\) | 0.186\(\pm 0.001\) | 15.05 | 812/666 |
| 4           | 1.647\(\pm 0.004\) | 0.919\(\pm 0.006\) | 59.61 | 765/658 |

### 3.2 The Continuum

To begin we fit each observation individually, removing the iron line region from the fit (5 – 8 keV) in order to accurately estimate the continuum emission upon which the reflection is superimposed. At this point we want to test two properties of the continuum: (1) Whether an absorbed power-law is an acceptable description of the continuum and (2) that our description of the continuum is consistent with the PCA when the reflection is modelled. It is imperative that our continuum is correctly modelled since the shape of the reflection spectrum is strongly dependent upon it, hence we use this initial analysis as a sanity-check for the later sections. To this end the motivation for fitting each observation individually at first is that it allows us to extend our broadband coverage. Our main focus, the EPIC-pn and XIS cameras, will only be covering the 4 – 5 keV and 8 – 10 keV regions to constrain the continuum. We add simultaneous PCA-HEXTE observations to the EPIC-pn and make use of the PIN on-board Suzaku to extend the range up to 100 keV and 50 keV respectively. A constant normalisation factor must be allowed between each detector, however the only one well calibrated enough to be fixed is between the XIS and PIN (both of our Observations were taken in the XIS nominal position, hence we fix the constant to be 1.16). The cross-normalisation between the PCA, HEXTE and PN are all uncertain so the PCA constant is fixed to be 1 and the PN and HEXTE datasets are allowed a free constant. These were \(\sim 0.85\) and \(\sim 0.8\) for the PN and HEXTE respectively. We note again that we fit each epoch individually in this section since given that we have 5 detectors from three separate missions this would potentially render the results degenerate if all datasets were fitted simultaneously.

It has been recently noted (see [Hiemstra et al. 2011](#), [Kolehmainen et al. in preparation](#)) that the cross-calibration between the PCA and EPIC-pn is uncertain, showing an energy-depdendant discrepancy at least below \(\sim 7\) keV. We therefore fit the PCA in the energy range 7 – 30 keV and the HEXTE between 20 – 100 keV. For Observation 4 the HEXTE was now not operational, hence we only fit the PCA data but extend its range up to 50 keV given it is a significantly longer and brighter exposure. The PIN spectra added to the XIS observations are fitted in the 15 – 50 keV range as recommended by the HXD instrument team.

We fit a single absorbed power-law to the whole broadband spectrum, tying the photon index and normalisation parameters be-
between detectors whilst allowing a constant to float between them as described before. Our continuum model is found to be a good fit to all of the observations (Table 2 and no cut-off is required at high energies, although this may exist beyond our upper energy limit. A significant smeared edge is required for Observation 4 suggesting a large amount of reflection is present. The majority of residuals lie beyond 10 keV, the likely source of which is a Compton ‘hump’ from the reflection of hard X-rays by the cool accretion disc. Interestingly this isn’t present in Observations 1 and 2, suggesting that the reflection has increased in the higher luminosity observations. Given the good description of the continuum by this model we use it as the base continuum in the later sections.

For our initial analysis we only consider the hard state spectra. We display the continuum data to model ratio with the iron line region added back into the plot (i.e. ‘noticed’ in XSPEC) for the hard state observations in Figure 1. Immediately one can see a distinct evolution of the iron line region. At higher luminosities the profile extends further in both the red and blue wings. Additionally the peak appears to shift to higher energies. A higher spin and inclination would mean a larger concentration of emission from multiple ionisation stages which can both contribute an overall broadening of the profile (García & Kallman 2010, 2011), thus extending the blue wing. Also, larger ionisation results in increased Compton scattering and emission from multiple ionisation stages which can both contribute an overall broadening of the profile (García & Kallman 2009; see also García & Kallman 2010 and García et al. 2011). Furthermore any variation in the illuminating source would only strongly affect the emissivity for the very inner regions of the disc (<2rg), which for the spin estimated for GX 339-4 isn’t applicable (Fabian et al. 2012). Thus inner radius variation should dominate the red wing variation we observe. The shift in the peak of the profile is almost certainly due to an increase in the disc ionisation. A more ionised disc means emission from higher rest energies, hence a shift in the peak. Also, larger ionisation results in increased Compton scattering and emission from multiple ionisation stages which can both contribute an overall broadening of the profile (García & Kallman 2009; see also García & Kallman 2010 and García et al. 2011), thus extending the blue wing.

Therefore visual inspection of Figure 1 just by eye implies that at higher luminosities in the hard state the accretion disc is extending closer to the BH and becoming more ionised.

3.3 The Iron Line Region
3.3.1 Line Modelling
To gain a more accurate description of how the disc is evolving we next model the iron line region and we begin by fitting the Fe Kα line, applying the model RELLINE (Dauser et al. 2010). For our initial analysis we focus upon the four hard state observations in Table 1 to probe how the reflection evolves just within this state. We fit these simultaneously, tying the inclination between each observation and fix the emissivity and spin to be r−3 and 0.9 respectively, and the outer radius of the disc is fixed at 1000rg. We use the absorbed power-law continuum described in Table 2, applying those results as the initial parameter values. Our results are presented in Table 3. We find a satisfactory best fit of χ²/ν = 1.30, with the majority of residuals remaining in the Fe Kα band, as displayed in Figure 2. The feature around 7 keV in Observation 1 is likely to be Fe Kβ emission, consistent with the near-neutral Fe Kα fit of 6.46±0.02 keV. A similar residual is also seen in Observation 2 but below 7 keV, which possibly arises from emission from a higher ionisation stage (H-like at 6.97 keV) or Compton scattering broadening the profile. However Fe Kβ emission cannot be ruled out. The effect of multiple ionisation stages is also seen in Observation...
The emissivity index and spin parameters are fixed to be 3 and 0.9 respectively, whilst the outer continuum flux. Both are calculated using Table 3.

The equivalent width of the lines in the rise data increases with luminosity, approaching the upper limit of the allowed range (6.97 keV; H-like Fe Kα emission) for Observations 3 and 4. This hence predicts that the disc surface layers are more ionised at higher luminosities, adding weight to the second and third of our predictions by eye. The tied inclination parameter is found to be $18\degree$, which is consistent with previous analysis using a single Fe line [Miller et al. 2006b; Reis et al. 2010; Done & Diaz Trigo 2010]. We note however that an inclination lower than $\sim 40\degree$ looks unfeasible since it will result in BH mass of $\geq 20 M_\odot$ (assuming the constraints reported in Hynes et al. 2003 and Muñoz-Darias et al. 2008), although the inner disc may not be aligned with the binary inclination [Maccarone 2002].

The equivalent width of the lines in the rise data increases with luminosity, indicating a larger area of reflection (i.e. a smaller inner radius). However, Observation 1, which is in decay, doesn’t fit this trend. It is likely though that this is the only profile well described by one ionisation stage, and hence would yield a larger value compared to other observations, which instead leave significant resid-

| Model   | Parameter | 1         | 2         | 3         | 4         |
|---------|-----------|-----------|-----------|-----------|-----------|
| POWERLAW | $\Gamma$ | 1.59$\pm$0.02 | 1.42$\pm$0.01 | 1.47$\pm$0.01 | 1.64$\pm$0.01 |
|         | $N_{PL}$ | 0.011$\pm$0.001 | 0.096$\pm$0.001 | 0.18$\pm$0.01 | 0.91$\pm$0.01 |
| RELLINE | E (keV) | 6.46$\pm$0.02 | 6.54$^{+0.02}_{-0.03}$ | 6.94$^{+0.02}_{-0.03}$ | 6.97$^{+0.01}_{-0.01}$ |
|         | $\theta$ (°) | 18$\pm$1 | 36$^{+3}_{-6}$ | 54$^{+9}_{-27}$ | 54$^{+9}_{-22}$ |
|         | $r_{in}$ (risco) | 79$^{+68}_{-26}$ | 36$^{+11}_{-8}$ | 37$^{+2}_{-1}$ | 3.0$^{+0.2}_{-0.1}$ |
|         | $N_R$ (10$^{-6}$) | 0.37$\pm$0.05 | 2.61$\pm$0.22 | 7.85$^{+0.30}_{-0.25}$ | 59.3$^{+3.0}_{-3.0}$ |
|         | E.W. (eV) | 61$^{+10}_{-7}$ | 40$^{+4}_{-5}$ | 75$^{+1}_{-5}$ | 154$^{+13}_{-6}$ |
| $\chi^2/\nu$ | 6608/5100 | |

| POWERLAW | $\Gamma$ | 1.72$^{+0.15}_{-0.03}$ | 1.44$\pm$0.01 | 1.47$\pm$0.01 | 1.60$\pm$0.01 |
|         | $N_{PL}$ | 0.013$\pm$0.0002 | 0.087$\pm$0.0004 | 0.16$\pm$0.01 | 0.37$^{+0.06}_{-0.04}$ |
| RELCONV | $\theta$ (°) | 42$^{+11}_{-6}$ | 295$^{+131}_{-163}$ | 137$^{+71}_{-92}$ | 67$^{+60}_{-23}$ |
|         | $r_{in}$ (risco) | $>344$ | 2.5$^{+0.03}_{-0.40}$ | 2.61$^{+0.02}_{-0.01}$ | 2.89$^{+0.03}_{-0.02}$ |
|         | $N_R$ (10$^{-6}$) | 6.50$^{+25.6}_{-3.91}$ | 3.31$^{+0.27}_{-0.24}$ | 4.82$^{+0.15}_{-0.14}$ | 20.6$^{+0.09}_{-0.07}$ |
|         | RF | 0.13$\pm$0.05 | 0.13$\pm$0.03 | 0.14$\pm$0.01 | 1.29$\pm$0.25 |
| $\chi^2/\nu$ | 5467/5100 | |

| POWERLAW | $\Gamma$ | 1.66$\pm$0.03 | 1.45$\pm$0.01 | 1.49$\pm$0.01 | 1.53$^{+0.03}_{-0.07}$ |
|         | $N_{PL}$ | 0.012$\pm$0.0001 | 0.097$\pm$0.0001 | 0.18$\pm$0.01 | 0.44$^{+0.12}_{-0.13}$ |
| RELCONV | $\theta$ (°) | 36$^{+3}_{-6}$ | 410$^{+12}_{-277}$ | 54$^{+9}_{-22}$ | 31$^{+18}_{-9}$ |
|         | $r_{in}$ (risco) | $>321$ | 2.38$^{+0.02}_{-0.01}$ | 2.47$^{+0.03}_{-0.01}$ | 3.36$^{+0.01}_{-0.01}$ |
|         | $N_R$ (10$^{-6}$) | 2.47$\pm$0.31 | 8.38$^{+1.00}_{-0.51}$ | 8.44$^{+0.84}_{-0.93}$ | 6.57$^{+0.38}_{-0.35}$ |
|         | RF | 0.10$\pm$0.03 | 0.06$\pm$0.03 | 0.06$\pm$0.01 | 0.73$\pm$0.21 |
| $\chi^2/\nu$ | 5482/5100 | |

Table 3. Results from fitting the four hard state observations simultaneously with the RELLINE line profile (top section) and a blurred reflection model RELCONV*XILLVER (middle section), RELCONV*REFLIONX (bottom section). The photon index in the reflection models is tied to that of the continuum power-law and the iron abundance is assumed to be solar. The emissivity index and spin parameters are fixed to be 3 and 0.9 respectively, whilst the outer radius of the disc is fixed to be 1000 $r_g$. We calculate the reflection fraction (RF) as the ratio of the flux from the reflected emission and the power-law continuum flux. Both are calculated using CFLUX in the 4 – 10 keV band. If an upper or lower limit is not shown this indicates that the parameter has reached a hard limit. In some cases the inner radius parameter has reached the largest tabulated value in the model (1000 $r_g$), therefore we only present the lower limit in this case.

3 where a feature at 6.4 keV remains, most likely due to neutral emission from the outer disc, and a broad residual is seen beyond 7 keV as scattering is not modelled. In Observation 4 the disc is likely to be more ionised removing the former issue, however the latter becomes even more significant as a result. A large smeared edge is also clearly present.

Our results indicate consistently that the inner accretion disc is more recessed at lower luminosities. We see evolution from $79 r_{isco}$ to $3 r_{isco}$ over less than two magnitudes of $L_{Edd}$. However we stress that our recorded values may not be a true indication of the inner disc radius as it is possible degeneracies in the model could skew its accuracy. Furthermore we can see from Figure 2 that the reflection is not well fitted by a single line. The key result here is the strong relative trend, which we can be confident about, of a disc extending closer to the BH at higher luminosities. This confirms the first of our predictions using Figure 1. Additionally we note the rest energy of emission also increases with luminosity, approaching the
As noted in the previous section and displayed in Figure 2, although the much lower value found by the single Fe line method is highly unlikely given the constraints on the binary parameters of the system. We therefore compare our results from line modelling to RELCONV* [3.3.2] to be a more accurate method to draw any conclusions from the relative flux between components.

3.3.2 Full Reflection Fitting

As noted in the previous section and displayed in Figure 2, although the fit was satisfactory when line modelling was applied, there were residuals remaining in the Fe band. This suggests that the reflection is more complex than just Fe Kα emission at one ionisation stage. Such a shortcoming is likely to arise due to Comptonisation and emission from regions of the disc with different physical conditions. Both would generate further broadening and structure in the resolved emission line and these mechanisms are not taken into account by a Fe line model. Therefore such a model, if these processes were present, would either artificially broaden in order to fit, for example by over-predicting the relativistic effects present, or leave the additional broadening not modelled and consequently residuals in the spectra.

We therefore compare our results from line modelling to that of relativistically blurred reflection from an ionised disc. The model we employ, on top of our standard continuum, is RELCONV* [3.3.2] to be a more accurate method to draw any conclusions from the relative flux between components.

The much larger values recorded for the inner radii can be driven by two effects. A much larger inclination is found \((42^\circ \text{ vs. } 18^\circ)\) and the smaller doppler shifts at low inclinations would require a smaller inner radius to recover the same profile width \([\text{Done} \& \text{Diaz Trigo} 2010]\). However, as discussed in the previous section, the much lower value found by the single Fe line method is highly unlikely given the constraints on the binary parameters of the system.

Figure 3. The unfolded spectral fit and data/model ratios of the simultaneous fitting of the four hard state observations in Table 1 using the blurred reflection model RELCONV*XILLVER. The up-scattered disc emission is indicated by the red lines and the composite model is overlaid in orange. We present the reflection in two ways: the blue solid lines show the blurred reflection as fitted, whilst the green dashed lines display the reflection spectrum when the relativistic blurring (RELCONV) is removed. Please note that the green dashed lines are not part of the fit, they are purely to allow the evolution of the profile due to ionisation and relativistic effects to be viewed separately. All of the spectra have been re-binned for the purposes of plotting.
Inner accretion disc evolution in GX 339-4

3.3.3 Markov Chain Monte Carlo Analysis

The three different models we have applied have unanimously observed the same trends, however applying $\chi^2$ fitting to such a large number of free parameters (21; Table 3) across four datasets brings with it the considerable possibility that a local minimum is mistaken for the global best fit. Furthermore, as discussed previously, the precise resolution required in reflection fitting and the subtle effects parameters have is highly susceptible to degeneracies, which can force the parameter space a fit occupies. In order to assess this possibility we apply a Markov Chain Monte Carlo (MCMC) statistical analysis to our results with XILLVER. This technique has recently been successfully used by Reynolds et al. (2012) to constrain the black hole spin of NGC 3783 which also required a large number of free parameters.

Starting a random perturbation away from our best fit (Table 3) we run four 55,000 element chains, of which the first 5000 elements of each chain are discarded (‘burnt’). The chain proposal is taken from the diagonal of the covariance matrix calculated from the initial best fit. For this we assume probability distributions which are Gaussian and a rescaling factor of $10^{-3}$ is applied. We can use the resultant 200,000 element chain to determine the probability distribution for each parameter and compare to the results found through the standard XSPEC ERROR command. For observations 1 to 4 the best fit inner radii and MCMC-determined 90% confidence intervals are $>302, 295^{+125}_{-120}, 137^{+84}_{-24}$ and $67^{+52}_{-15}$ respectively, hence being very consistent with those quoted in Table 3.

Figure 3 (top panels) displays the values of the inner radius for the four observations from every 200th step of the 200,000 elements. Each distribution shows no sign of significant deviation or trend thus suggesting that the global minimum has in fact been found, offering even more certainty to the inner radius evolution we have uncovered. The lower panels of Figure 3 show the probability distribution for the inner radius, in-keeping with Table 3. For each observation the inner disc being at the ISCO is clearly ruled out.

Another benefit of MCMC analysis is that it allows one to reveal any correlations between parameters. In Figure 3 we present two-dimensional probability distributions of the inner radius with inclination and ionisation. Each axis is chosen for clarity rather than to span the entire parameter space of the model, but still encompasses the full probability distribution for both parameters. Each distribution shows little sign of a correlation, indicating that no significant parameter degeneracies are at play and that we have indeed found the global best fit.

3.3.4 Does Disc Evolution Monotonically Track Luminosity? - Comparing Rise and Decay

So far we have only analysed the four hard state observations, ignoring the 2011 hard-intermediate dataset (Observation 2b). This observation took place in decay at a very comparable luminosity to Observation 2, which was taken whilst GX 339-4 was in its rise through the hard state. Therefore if disc evolution is solely a trend with luminosity then one should expect to obtain similar results between the two observations. The middle panel of Figure 3 shows the data/model ratio of the continuum fit to Observation 2b. We find a strongly broadened Fe line, much more asymmetric than the hard state profiles, indicating relativistic broadening is more significant. We fix the inclination to that found in Table 3 to probe this conclusion, and the results are presented in Table 3. The same fixed values are used for the spin (0.9), emissivity index (3) and disc outer radius (1000 $r_g$).
We find that for both the line and reflection fitting techniques the inner accretion disc radius is estimated to be significantly smaller for the intermediate state observation. This strong contrast in the inner radius of the disc suggests a possible hysteresis in how the inner disc evolves throughout the outburst. Furthermore, the disc inner radius found through both methods is smaller than for all of the hard state observations at 90% confidence. Therefore this strongly suggests that the disc is truncated throughout the hard state, even in Observation 4 which is at $\sim 0.15 L_{\text{Edd}}$ (assuming a BH mass and distance of $8 M_\odot$ and 8 kpc respectively). This conclusion is further supported by the small difference in fit between the two methods (only $\Delta \chi^2 = +7$ for no additional degrees of freedom using REELLINE; Table 4), meaning that the profile is now dominated by relativistic effects from emission close to the BH.

The ionisation parameter is similar ($\sim \log(2.6)$), although slightly larger in decay. The decay spectrum is softer (as defined by the hard-intermediate state) since there is more thermal emission from the disc (compare e.g. [Hiemstra et al. 2011] with [Reis et al. 2010]). This will lead to increased heating of the surface layers of the disc where the reflection spectrum originates from, and therefore display broader line profiles ([Ross & Fabian 2007]), similar to that of a larger ionisation parameter. The current publicly available models do not take this into account (see [4] for further discussion of this) and it is likely that the hard-intermediate state observation would then require a larger ionisation parameter to solve for this.

### parameters

| Parameter         | Line Only | Full Reflection |
|-------------------|-----------|-----------------|
| $\Gamma$          | 1.84±0.02 | 1.85±0.04       |
| $N_{PL}$          | 0.15±0.01 | 0.13±0.03       |
| E (keV)           | 6.97±0.06 |                 |
| $r_{in}(r_{isco})$| 2.3±0.3   | 12.5±7.2        |
| $N_L (10^{-4})$   | 6.69±1.05 |                 |
| log($\xi$)        | 2.65±0.22 | 1.50±0.50       |
| $N_R (10^{-6})$   | 1.50±5.00 |                 |
| E.W. (eV)         | 152±29    |                 |
| RF                | 0.23±0.12 |                 |
| $\chi^2/\nu$     | 1563/1518 | 1556/1518       |

### Table 4

Results from fitting Observation 2b with the REELLINE (left section) and RELCONV*XILLVER (right section) models respectively. The inclination and outer radius parameters are frozen to those found in the hard state for the respective model used (see Table 4).

#### 3.3.5 Power Density Spectra

The power spectra of BHs in the hard state display similar characteristics ([van der Klis 1995, 2006]). Typically they are described by a flat region of power $P(\nu) \propto \nu^0$ below a frequency $\nu_0$, known...
as the ‘break frequency’. Above $\nu_b$ the power spectra steepens to roughly $P(\nu) \propto \nu^{-1}$. This break frequency is coupled with the BH mass and accretion rate (McHardy et al. 2006; K"ording et al. 2007) and gradually increases as the source progresses through the hard state (see e.g. Migliari et al. 2005). Furthermore a number of correlations have been found, notably with a steepening of the Comptonised spectrum and an increasing amount of reflection (Gilfanov et al. 1999). Both of these trends can be interpreted as an increasing penetration of the cool accretion disc into the inner hot flow which gives more seed photons to cool the flow. Therefore it has been suggested that $\nu_b$ is associated with the truncation radius of the inner disc (Gilfanov et al. 1999, Churazov et al. 2001).

For each of the hard state observations listed in Table 1 we analyse the power density spectra (PDS) of a simultaneous RXTE observation. Where more than one observation is available we chose the one with the best signal-to-noise. Unfortunately the nearest observation to Observation 2b was not of sufficient quality to be used, and hence this epoch is ignored. Figure 7 displays the PDS follows the expected trend to higher frequencies with luminosity which is the exact trend we find. However, as we described before, other correlations have been found and its not certain which is the driving the break. Again, as an example, both the softening power-law photon index and increasing reflection fraction trends are both consistent with a decreasing inner radius of the disc. Mass accretion rate may also influence the change is more moderate. The break frequency follows this same pattern suggesting it too tracks the inner radius of the disc, extending closer to the BH as it progresses through the hard state. To see of which could be tracking the inner radius) for accretion onto a BH are proportional to $R^{3/2}$. Therefore we should expect to find that the $\nu_b$ increases with luminosity which is the exact trend we find. Nevertheless the evolution is remarkably similar. We see for both the line and reflection methods the evolution from Observations 1 to 2 and 3 to 4 is quite steep, whereas from 2 to 3 the change is more moderate. The break frequency follows this same pattern suggesting it too tracks the inner radius of the disc, extending closer to the BH as it progresses through the hard state. To see

![Figure 5. Two-dimensional probability distributions of the inclination (top) and ionisation (bottom) parameters with the inner radius. For each upper panel we plot contour levels at $p(\theta, r_{in}) = (1, 10, 30) \times 10^{-5}$, such that for being in the range $\theta = \theta + \delta \theta$ and $r_{in} = r_{in} + \delta r_{in}$ the probability is defined as $p(\theta + \delta \theta, r_{in} + \delta r_{in})$. For the lower panels the contour levels are displayed at $p(\xi, r_{in}) = (1, 10, 30) \times 10^{-4}$ for Observation 1, which has poorer constraint on the ionisation parameter, and $p(\xi, r_{in}) = (2, 20, 60) \times 10^{-4}$ for the remaining observations. Each plot contains the full distribution for the whole parameter range with the axis reduced for clarity. In all eight distributions there no indication of a significant correlation between the parameters.](image-url)
In this work we have analysed the iron line region of GX 339-4 and applied it as a probe of how the inner accretion disc evolves, presenting evidence that the iron line profile changes with luminosity. Our results indicate that even at relatively high luminosities the inner disc radius is still somewhat truncated, although following a trend of decreasing radius with increasing luminosity. This brings into question at which point, if any, the inner disc has reached the ISCO in the canonical hard state. Such a finding has a direct impact upon the use of reflection features to measure BH spin. The entire range of prograde BH spin is spanned within the inner 5 gravitational radii of the disc, and hence even a slight truncation, much smaller than the extent we present, will have a profound impact upon the confidence of spin determination.

We investigate the use of both the line and full reflection fitting methods and find at all stages the disc is predicted to be significantly more recessed using the latter technique. Full reflection modelling takes into account Comptonisation and multiple ionisation stages which themselves broaden the line profile. These effects are a consequence of disc ionisation, and hence a degeneracy could...
occur between relativistic broadening, for example the inner disc radius, and the ionisation parameter. We record a trend of increase in the ionisation parameter with luminosity. On the HID (Figure 1) the hard state track is near-vertical, keeping a roughly constant hardness. Most of the power thus is consistently going mainly into the hard, illuminating, component rather than the soft disc. By definition the ionisation parameter is proportional to the flux of the illuminating component, and therefore it should be expected to increase with luminosity.

One major issue currently with the publicly available reflection models is that they describe the illumination of an otherwise cold slab of gas. This assumption is acceptable for use in fitting the spectra of AGN where the disc is relatively cold. However in the case of BHXRBs the hotter surface layers of the disc will have a significant effect upon the reflection spectrum (Ross & Fabian 2007). Additionally we have the presence of the thermal disc component in the soft bandpass which may be mistaken as reflection by the model. This problem is further compounded by better statistics at lower energies which hence can drive the fit in this range rather than the more revealing iron line region. We remove the latter issues by fitting only above the energy range where the disc is significant and hence our continuum description is a much simpler absorbed power-law. The effects of the hotter disc is not so straightforward to determine. The increased ionisation has clear broadening effect on the line profile as discussed in (Ross & Fabian 2007), however its effect should be fairly consistent between observations due to the small range in hardness in Figure 1. Therefore the effect of ionisation not due to irradiation should be roughly constant between each observation.

It is however significant and likely to be treated in two ways by our model. Either the ionisation parameter or the relativistic effects will be increased to reproduce the additional broadening in the line profile. If the outcome is the latter we should yield inner disc radii values closer to the BH than would be apparent for a self-consistently modelled BH XRB. Therefore, in such a case, we expect the disc to be more truncated than what we record in this investigation.

Although we have displayed distinct evolution of the inner disc in the hard state of GX 339-4 we are still currently limited by our sampling of other BH sources. Although many sources show similar behaviour (see e.g. Dunn et al. 2010) some for example do not show full state transitions (e.g. Swift J1753.5-0127; Soleri et al. 2013) and hence it may be the case that the inner disc evolves differently in the hard state of otherBHs.

4.1 The Effect of the Emissivity and Spin Parameters

Throughout our analysis we have made two, rather important, assumptions. That is, that the disc follows an emissivity law of $r^{-3}$ for all the observations, and the spin of the BH in GX 339-4 is $a = 0.9$.

We tie the emissivity parameter between each observation due to the high level of degeneracy it has with the inner radius parameter. A larger emissivity index yields increased emission from the inner regions of the disc, hence increasing the significance of the relativistic effects upon the overall profile. This is somewhat analogous to having an inner disc radius closer to the BH where the influence of relativity becomes stronger. We acknowledge that such an assumption may be incorrect and the emissivity profile may evolve throughout the outburst depending on the geometry of the hard X-ray source. Given that little is conclusively known about the ‘corona’ it is difficult to analyse such an issue other than to fit each emissivity parameter freely, which would highly reduce the confidence in our inner radius values.

The value of 3 that we use for the emissivity parameter is the value for a Newtonian disc. In General Relativity though one would expect the hard X-ray source to be more focused on the inner regions because of light-bending, resulting in a steeper fall off with radius (i.e. a larger emissivity index; Miniutti et al. 2003). Therefore a broken power-law profile may be needed to describe the contrasting emission from the inner region. However, as discussed in Fabian et al. (2012), it is only in the innermost region ($< 2r_g$) where a steep inner profile is needed. Thus such a description is not expected to significantly affect the relative difference in the inner radius between observations. An emissivity profile of $r^{-3}$ should be a crude lower limit given that it describes a Newtonian disc, hence if a steeper emissivity index was actually required we expect a more truncated disc to counter this when fitting the spectra. Furthermore, at the inner radii values we estimate, there should be no significant deviation from $q = 3$. A recent study by Wilkins & Fabian (2012) investigates further emissivity profiles for different coronal geometries, the general trend being towards a value of roughly 3 from radii much smaller than what we find in this study. Thus even if the geometry of the corona were to evolve between our observations, this is not expected to alter our assumption.

The spin parameter is calculated from the ISCO itself, spanning $6 - 1.235 r_g$ for the prograde range of spin ($a = 0 - 0.998$). The key assumption is that the disc is at the ISCO and in testing this assumption the inner disc and spin parameters become highly degenerate with each other. Therefore since we wish to investigate the inner disc radius we fix the value of the spin to be $a = 0.9$ to keep our analysis consistent. As alluded to in 3.3.1 this is the upper limit found by Kolehmainen & Dong (2010) using the continuum method. It is also close to values obtained previously by reflection fitting (Reis et al. 2008; Miller 2008).

However defining a spin value has in fact very little effect upon our overall conclusions. A larger spin allows the disc to extend closer to the BH, but this isn’t an intrinsic effect of the spin itself. Increased spin will have some influence due to frame dragging, but this is quite minimal, and only relevant for the very inner regions of the accretion disc (Dauser et al. 2010). To put this into other words, a change in spin has little or no effect upon a largely truncated accretion disc.

4.2 Testing the Full Bandpass

As discussed before we have restricted our analysis so far to above 4 keV since this is where we can be sure there is no contribution from the thermal disc component in the bandpass. This allows us to fit a simpler continuum model in the computationally intensive task of fitting four datasets simultaneously. Another issue is that the weak thermal component can be mistaken for the soft excess in the reflection model. Also the lower part of the bandpass contains strong edges in the effective area and is hence generally less well calibrated. Since the statistics are better at lower energies these features could drive the reflection fit rather than the more revealing Fe K emission, thus we ignored the data below 4 keV, restricting our bandwidth but also our calibration dependence. This is standard practice in the AGN community where the majority of X-ray reflection studies have taken place, be it in systematic investigations (see e.g. Nandra et al. 2007; de La Calle Pérez et al. 2010) or single observations (see e.g. Fabian et al. 2002; Ponti et al. 2009). However, ideally one would fit the entire bandpass, and the spectrum there could play a significant role in fitting the reflection.
this section we demonstrate how consistent our results are when fitting the whole bandpass with an additional thermal component (DISKBB) included.

We now fit each observation individually since jointing fitting with the extra disc model and additional bandpass is computationally too intensive. Since the inclination is measured from the sharper blue wing of the Fe Kα profile this should be well determined even if the analysis above 4 keV is in error. Therefore we fix the inclination to the value determined with XILLVER (Table 3). As discussed before calibration at low energies is brings with it uncertainties, the most significant being features at ~ 1.8 and ~ 2.2 keV which are likely to be of instrumental origin. We therefore ignore the 1.75 – 2.35 keV region in the XMM-Newton data to prevent this driving the fit. The issue is more severe for the Suzaku XIS camera so the excluded region is extended to 1.7 – 2.4 keV. Furthermore “soft excesses” have been reported in binaries with moderate to high column densities, the origin of which remains uncertain and appears to not be limited to the timing mode (see the XMM-Newton Calibration Technical Note (0083) and references therein). We also find a significant residual below 1 keV which severely affects the fit and hence follow [Hiemstra et al. 2011] and Reis et al. [2011] in ignoring data below 1.3 keV, considerably improving the fit. We allow the XIS datasets to extend down to 0.7 keV since they display no such residual.

With the added disc component our full model is now PHABS(DISKBB+POWERLAW+RELCONV*XILLVER). We fit each dataset individually with the additional parameters for the inner disc temperature and normalisation fitted freely. The column density is now also allowed to be free and results can be found in Table 6. Unfortunately due to the lower cut-off of 1.3 keV used for the PN data the weak disc component cannot be constrained in Observations 2 and 3. The remaining observations are all well fitted by the added disc model, all reporting a reduced chi-squared of ≤ 1.10 except for Observation 3. The main cause of the poor fit to Observation 3 is in the soft region of the bandpass (< 4 keV), and is probably due to some un-modelled thermal emission being present there. The Fe line is still well modelled.

For all of the observations we find that each parameter remains consistent at the 90% confidence level with those in 3.3.2 and clearly indicates that our results in that section were not driven by fitting only above 4 keV. In particular the inner radius parameter shows little change and the trend of the disc extending closer to the BH with increasing luminosity still remains. Additionally the power-law photon index shows very little variation indicating that the continuum was still very well constrained when we restricted the fit to above 4 keV. Furthermore if a broad red wing from a disc at the ISCO was present then it is possible this could have been masked by a harder photon index when fitting only above 4 keV. However little variation found when fitting the full bandpass confirms that the profiles in the hard state show little relativistic broadening, consistent with a truncated disc throughout the hard state.

4.3 How Well Constrained is the Inner Radius?

Much of the focus in this paper is on how the inner radius of the disc is evolving in the hard state. If we just examine absolute values then this would suggest that the disc is always substantially truncated. However given how degenerate the unknown inclination parameter is with the inner radius, we cannot be sure of this and instead concentrate more on the trend between observations. At first sight the magnitude of the confidence limits on the inner radius would suggest that our analysis is uncertain, perhaps even flawed, but this is simply due to the decreasing relativistic effect at large radii. For example, the fits to the Fe Kα line with RELLINE (Table 3) find confidence limits a factor of over 100 larger for Observation 1 than Observation 4. The fit is just as well constrained, and as well as the other parameters, it is just the smaller effect on the spectrum at large radii that drives the increasing limits.

Although we are not focusing upon the absolute values of the inner radius we are still interested in how well they represent the true value. One test of this is to calculate whether the EW we see matches that expected for a reflecting slab truncated to the radius we infer. A disc will subtend a solid angle of $\Omega = 2\pi(\cos \theta_{in} - \cos \theta_{out})$, where the respective angles are to the radii corresponding to the inner and outer radii from the centre of the disc. These are calculated as $\theta = \arctan(R/h)$, where $R$ is the respective disc radius and $h$ is the height above the disc of the observer. In our case we take the observer to be the illuminating source, and use a height of 20$r_g$. Given that $R_{out} \gg h$ we can use $\theta_{out} = 90$. We estimate expected EW values from [Garcia et al. 2013] using the values for the ionisation parameter we fitted using XILLVER (Table 3). Assuming isotropic emission the ratio of the EW calculated with RELLINE to the expected value should be equivalent to $\Omega/2\pi$.

We find reasonable agreement in each case, with the EW ratio factors of 1.17, 0.94, 0.82 and 1.14 larger than the solid angle for Observations 1 to 4 respectively. Each observation is consistent with the EW ratio within the limits on the inner radius parameter. Although this is a good indication that our absolute value of the inner radius is reasonable some uncertainties still remain. For example the expected EW is calculated from the whole Fe K region, where Fe Kβ emission could contribute up to ~ 15% of the EW depending on the ionisation stage. Also flaring of the outer disc is expected (see e.g. Corral-Santana et al. 2013 and references therein) which could significantly increase the EW observed.

5 CONCLUSIONS

We have systematically analysed how the inner accretion disc evolves in the canonical hard state of GX 339-4 using the iron line region. Our results have shown that the inner accretion disc moves closer to the black hole at higher luminosities, consistent with the broader profile found in the spectra. The poor fit to each spectrum using a single line model points to a reflection spectrum not dominated by relativistic effects, with significant broadening also arising as a result of ionisation. When this is taken into account we find an improved fit and much larger inner radii, with the two lowest luminosity observations consistent with no relativistic broadening at the 90% confidence level. However the absolute values found by modelling reflection features can be affected by degeneracies between parameters, and this is the motivation for our systematic analysis. Therefore the key result is the strong trend to smaller inner radii at larger luminosities, which should be largely independent of such effects.

The trend we find thus fully supports the truncated disc model of the hard state. Furthermore when extending our analysis to the hard-intermediate state we find even smaller inner radii such that the disc is consistent with being truncated throughout the entire hard state. It has also been suggested that the break frequency found in the power density spectra of the hard state corresponds to the inner radius of the disc ([Gilfanov et al. 1999]). Upon comparing this to our results from spectral fitting we find a remarkably similar trend. Together these two independent conclusions provide very strong evidence in favour of disc truncation in the hard state.
Table 6. Results from fitting the four hard state observations individually with PHABS(DISKBB+POWERLAW+RELCONV*XILLVER). The photon index in the reflection models is tied to that of the continuum power-law and the iron abundance is assumed to be solar. The same fixed values are used as for Table 3. In some cases the inner radius parameter has reached the largest tabulated value in the model (\(r_{\text{in}}\)), therefore we only present the lower limit in this case.

This result implies that the current sample of spin estimates in the hard state are inaccurate. Therefore any distinct conclusions drawn from these estimates, such as the spin-powering of relativistic jets, may well be biased.

ACKNOWLEDGEMENTS

The authors are very grateful to Javier Garcia for the use of the reflection model XILLVER, and Stefano Bianchi for useful discussion. This research has made use of the General High-energy Aperiodic Timing Software (GHATS) package developed by T.M. Belloni at INAF - Osservatorio Astronomico di Brera. It has also made use of data obtained with the XMM-Newton, Suzaku and RXTE satellites. DSP acknowledges financial support from the STFC. GP acknowledges support via an EU Marie Curie Intra-European fellowship under contract no. FP-PEOPLE-2012-IEF-331095. TMD acknowledges funding via an EU Marie Curie Intra-European fellowship under contract no. 2011-301355.

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This result implies that the current sample of spin estimates in the hard state are inaccurate. Therefore any distinct conclusions drawn from these estimates, such as the spin-powering of relativistic jets, may well be biased.
APPENDIX A: SPECTRAL CHECKS OF PILE-UP IN EPIC-PN DATA

The effect of pile-up upon the Fe line profile is uncertain. Simulations by Miller et al. (2010) suggest that it leads to the narrowing of line profiles, however spectral studies appear to display broadening (see, e.g., Done & Diaz Trigo 2010; Ng et al. 2010). With more certainty we can say that pile-up will lead to an overall spectral hardening as low energy photons are in essence shifted to higher energies. One can therefore use this to verify that a chosen level of pile-up correction is sufficient.

The standard process utilised to deal with pile-up is to remove the brighter central region (i.e. that centred on the source) which is more susceptible to this issue, replacing, for example, a circular extraction region with an annulus. In fact a strong indicator of pile-up is a cavity centred on the source where a significant amount of flux is lost as the pile-up leads to reduced photons and a larger fraction exceeding the energy-threshold of the detector. The EPIC-pn timing mode collapses the data into a one-dimensional row, hence the extraction region becomes a box. In the case of pile-up treatment brighter rows around and including that centred on the source are removed, leaving in essence two boxes separated by the excluded brighter rows around and including that centred on the source are

In this section we compare the spectra extracted using regions with increasing central sections removed, as listed in Table A1.
and photon index fixed as determined with the optimal datasets but alternative extraction regions (Table A1), keeping the column density standard when fitting the continuum. We then add spectra with normalising each spectra to be equal between 1.3-1.75 keV. This allows us to then see at what energies any changes in the spectra are occurring.

We fit a simple absorbed power-law between 1.3-10 keV to Observations 2 and 3 with full extraction regions, and Observation 4 with the three central columns removed. These optimal extraction regions were chosen using the registered count rate and pile-up level estimated by the SAS task EPATPLOT, as described in §2.1. We removed the 1.75-2.35 keV region which contains instrumental edges, and we choose the lower bound of 1.3 keV due to calibration problems at energies below this (see §4.2 for more information). The 5-8 keV band is also removed to avoid fitting the Fe line as it is expected to be due to pile-up which should show a gradual hardening of abundances, whilst the line profile remains consistent, hence again we conclude that the full extraction region can be used for this observation.

Observation 2 shows little deviation between the three spectra. Above 8 keV there is some softening, however this is not expected to be due to pile-up which should show a gradual hardening of affected data throughout the bandpass. When each spectra is fitted individually the photon index variation is very small (<0.05). Instead we later suggest this is due to calibration uncertainties. The line profile itself appears unaffected and hence we conclude that the full extraction region can be used for this observation.

Observation 3 is very similar to Observation 2 with some softening above 8 keV when columns are removed. It shows no significant hardening in the spectra using a full extraction region and the line profile remains consistent, hence again we confirm that a full extraction region is free of pile-up as concluded in §2.1. For Observation 4 we fit to the spectra with 3 columns removed since a full region was found be modified by pile-up by EPATPLOT whilst also having a count rate above the recommended threshold. We see in Figure A1 that the spectra with a full extraction region is significantly harder and shows a much different line profile. The fitted spectra with three columns removed shows a drop above 8 keV, however this is due to a strong Fe edge emphasised by the large reflection fraction (Table 3 see also §3.3). Spectra with 5 and 7 columns removed look very similar to the fitted data, albeit showing some further softening above 8 keV consistent with the other observations. The Fe profile appears unchanged and in all this suggests that the removal of three columns leaves the data free from pile-up as determined before.

We plot the data/model ratios for these three observations in Figure A1. Piled-up data will be harder, hence having a roughly constant increasing excess at higher energies as compared to spectra with less or no pile-up present. The fit itself is not expected to be precise as X-ray reflection and, if present in the bandpass, the thermal disc component are not being modelled. However the deviation from a single power-law allows the effects of pile-up to be easier to detect.

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The small softening effects seen above 8 keV are due to calibration uncertainties in the determination of the effective area for PSF with central holes (this has been confirmed by the XMM-Newton EPIC calibration team). It is also important to note that the variation is less than 10% and the most recent EPIC calibration status quotes the uncertainty in the effective area to be ±5%. The consistency of the softening, regardless of observation (i.e. count rate) or column removal, serves to support this interpretation.

Finally we test the softening seen above 8 keV as more columns are removed. We investigate this by fitting Observation 4 with 5 columns removed in order to compare to our results to those listed in Table 3 which used the dataset with 3 columns removed. For this we applied the model XILLVER for the reflection, fixing the inclination at 42° to be in line with the value fitted jointly by Ne et al. but otherwise letting all parameters fit freely. The result is extremely consistent, with the inner radius being exactly the same (67.1T). The only parameter not consistent at 90% confidence was the photon index, although only the slightest difference is present: 1.63±0.01 (5 columns) vs 1.60±0.01 (3 columns). Such a small variation does not ultimately make much difference, and pile-up is expected to create a much more severe discrepancy (see Ne et al. 2010 for examples of strong pile-up in spectra). The modelled re-

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Table A1. A comparison of net count rates for the EPIC-pn datasets after correcting for pile-up. A full column corresponds to the region 31-45 in RAWX. Removal of the inner 3, 5 and 7 columns refers to the regions of 37-39, 36-40 and 35-41 being excluded. We only include the latter region for Observation 4 as a means to compare two larger regions to the extraction region used in this study.

|   | Full Column | Inner 3 | Inner 5 | Inner 7 |
|---|-------------|---------|---------|---------|
| 2 | 132 ± 0.1   | 47 ± 0.1| 26 ± 0.1|
| 3 | 259 ± 0.1   | 93 ± 0.1| 53 ± 0.1|
| 4 | 988 ± 0.1   | 352 ± 0.1| 194 ± 0.1| 114 ± 0.1|

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Figure A1. A comparison of pile-up effects in the EPIC-pn datasets using various extraction regions. The top, middle and lower panels refer to Observations 2, 3 and 4 respectively (Table 3). All spectra are extracted from a region of 31-45 in RAWX. Red, green and blue indicate that the inner 3, 5 and 7 columns have been removed. The black spectra utilises the full strip. In this study we use the full strip for Observations 2 and 3, and Observation 4 has the inner three columns removed, hence we fit to these datasets and compare how the other spectra match-up after normalising the 1.3-1.75 keV region to be equal. If pile-up is present the spectra is expected to be systematically harder, i.e. increasing data/model ratio towards higher energies, and modify the Fe profile.
flection is unaffected which is of most importance to this study. Therefore any uncertainty due to removing columns in Observation 4 has no bearing on our conclusions in this study.