A systematic look at the Very High and Low/Hard state of GX 339-4: Constraining the black hole spin with a new reflection model

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ABSTRACT
We present a systematic study of GX 339-4 in both its very high and low hard states from simultaneous observations made with XMM-Newton and RXTE in 2002 and 2004. The X-ray spectra of both these extreme states exhibit strong reflection signatures, with a broad, skewed Fe-Kα line clearly visible above the continuum. Using a newly developed, self-consistent reflection model which implicitly includes the blackbody radiation of the disc as well as the effect of Comptonisation, blurred with a relativistic line function, we were able to infer the spin parameter of GX 339-4 to be 0.935 ± 0.01 (statistical) ± 0.01 (systematic) at 90 per cent confidence. We find that both states are consistent with an ionised thin accretion disc extending to the innermost stable circular orbit around the rapidly spinning black hole.

Key words: X-rays: individual (GX 339-4) – black hole physics – accretion disc – spin

1 INTRODUCTION
X-ray spectra of Galactic black hole candidates (GBHCs) are an important tool in the studies of the inner regions of accretion flow around black holes (BHs), providing information on both the geometry of the accretion disc and on intrinsic physical parameters such as BH mass and spin.

The spectrum can be explained by the combination of a quasi-thermal blackbody component caused by radiatively efficient accretion through a disc (Shimura & Takahara 1995; Merloni, Fabian & Ross 2000), a power-law component due to inverse Compton scattering of the soft thermal disc photons in a cloud of hot electrons or “corona” (Zdziarski & Gierlinski 2004), and a reflection component (Ross & Fabian 1993). The latter arises as hard emission from the corona irradiates the cooler disc below and results in “reflection signatures” consisting of fluorescent and recombination emission lines as well as absorption features. The most prominent of these “signatures” is the broad, skewed Fe-Kα line observed in a number of GBHCs and active galactic nuclei (AGNs, see Miller 2007 for a recent review) indicative of reflection from the innermost regions of an accretion disc.

In the inner regions of an accretion disc the iron Kα line shape is distorted by various relativistic effects such as gravitational redshift, light-bending, frame-dragging and Doppler shifts, with the effects becoming more prominent the closer the line is emitted to the event horizon (Fabian et al. 1989, 2000; Laor 1991). In the case of an accretion disc around a non-spinning Schwarzschild BH, stable circular orbits can only extend down to the radius of marginal stability, \( r_{\text{in}} = 6r_g \) where \( r_g = GM/c^2 \). This radius depends on the spin parameter \( a/M \), and decreases to \( \approx 1.24r_g \) for a maximally rotating \( (a/M \approx 0.998) \) Kerr BH (Thorne 1974). By making the standard assumption that the emission region extends down to the radius of marginal stability (i.e. \( r_{\text{in}} = r_{\text{mas}} \)) one can obtain an estimate on the dimensionless spin parameter (Bardeen et al. 1972; Reynolds & Fabian 2007).

GX 339-4 is a dynamically constrained \( (M_{\text{BH}} \geq 6.0 M_\odot) \) recurrent black hole binary (BHB). Its distance has been estimated at 8 kpc (Zdziarski et al. 2004). Observations have been made on multiple occasions in various spectral states from the “low/hard” to the “very high state” (VHS; for a recent review on the different spectral states see e.g. McClintock & Remillard 2006). In both the VHS and the low/hard state (LHS) GX 339-4 shows a power-law spectra, with photon index \( \Gamma \sim 2.5-2.7 \) and 1.4-1.5 respectively (Miller et al.
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2004, 2006, hereafter M1 and M2; for a recent analysis of Suzaku observation in the “intermediate” state see Miller et al. 2008), as well as the presence of a quasi-thermal disc component, usually described by a multicolour disc blackbody model (MCD; Mitsuda et al. 1984). In both cases, the fluorescent Fe Kα features have been modelled by the addition of a LAOR relativistic line (Laor 1991) plus an ionised disc reflection component (PEXRIV, Magdziarz & Zdziarski 1995). In this manner, Miller et al. (2004, 2006) measured $r_{in} \sim 2.0-3.0r_g$ and $r_{in} \sim 3.0-5.0r_g$, for the VHS and LHS respectively.

It has long been known that the reflection in a BHB system cannot be mimicked simply by adding a blackbody component to the reflection spectrum from an otherwise cool disc. Compton broadening of the iron Kα line is of greater importance in warm accretion discs and should thus modify the spectral behaviour of BHB compared to that of AGNs. In this paper we undertake a systematic reanalysis of the VHS and LHS of GX 339-4, as reported by Miller et al. (2004, 2006). We employ the self-consistent reflection model developed by Ross & Fabian (2007), where blackbody radiation entering the accretion disc surface layers from below, as well as the effect of Comptonisation, is implicitly included in the model.

Our method of measuring the spin of stellar mass BH is complementary to that of McClintock, Narayan & Shafee (2007). They use the soft high state when any power-law emission is minimal and fit the quasi-blackbody continuum spectrum. Their method, in contrast to ours, requires accurate measurements of the mass and distance of the black hole. In the following section, we detail our analysis procedure and results.

2 OBSERVATION AND DATA REDUCTION

GX 339-4 was observed in its VHS by XMM-Newton for 75.6 ks, starting on 2002 September 29 09:06:42 UT (revolution 514) and simultaneously by RXTE for 9.6 ks starting at 09:12:11:28 UT (M1). LHS observations were made by XMM-Newton during revolutions 782 and 783, for a total exposure of 280 ks starting on 2004 March 16 16:23:41 TT and RXTE on 2004 March 17 at 12:03:12 TT, observation 90118-01-06-00 (M2). For the 2002 observation the EPIC-pn camera (Struder et al. 2001) was operated in “burst” mode with a “thin” optical blocking filter. For the low/hard observation the EPIC-MOS1 and EPIC-MOS2 cameras (Turner et al. 2001) were operated in the standard “full-frame” mode with the “medium” EPIC optical blocking filter in place. Starting with the unscreened level 1 data files for all the aforementioned observations, we followed the reduction procedures mentioned in M1 and M2.

In essence, for the XMM-Newton observation of the VHS the Observational Data Files (ODFs) were processed using the latest XMM-Newton Science Analysis System v 7.1.0 (SAS), with events being extracted in a stripe in RAWX (31.5-40.5) vs RAWY (2.5-178.5) space. Bad pixels and events too close to chip edges were ignored by requiring “FLAG = 0” and “PATTERN ≤ 4”. The energy channels were grouped by a factor of five to create a spectrum. The standard canned burst mode response file epn_bu23.sai was used to fit the spectrum. The total good exposure time selected was 2.2 ks. Due to the high source flux, background spectra were not extracted. RXTE data for the VHS were reduced using the RXTE tools provided in the HEASOFT v 5.2 software package. Standard time filtering, including the South Atlantic Anomaly and elevation angle restriction ($\geq 10$ degs. from the earth’s limb) resulted in a net Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) exposures of 9.3 and 3.3 ks, respectively. To account for residual uncertainties in the calibration of PCU-2, we added 0.75 per cent systematic error to all its energy channels. The response matrix was made by the task “pcarsp”. The HEXTE source and background spectra were made using the standard recipes. Standard canned response were used for spectral fitting.

The XMM-Newton data from the 2004 LHS was reduced using SAS v 7.1.0. As opposed to the EPIC-pn data, the EPIC-MOS cameras in the “full frame” mode are more susceptible to photon and pattern pile-up. Pile-up occurs when several photons hit two neighbouring (pattern pile-up) or the same (photon pile-up) pixel in the CCD before the end of a read-out cycle. If this happen the events are counted as one single event having an energy equal to the sum of all their energies, thus hardening the spectra. In order to investigate the effect of pile-up suffered by the EPIC-MOS cameras, we used the SAS tool “xmmselect” to obtain spectra from annular regions of inner radius 18”, 25”, 30” and 50” and outer radius of 120” centered on the source. The events were filtered by requiring “FLAG=0” and “PATTERN ≤ 12” (single–quadruple pixel events) as well as “PATTERN=0” (only single-pixel events). Background spectra were extracted from a 60” circle near the corner of the cen-
eral chip of each MOS camera for both “PATTERN $\leq 12$” and “PATTERN = 0”. Response files for each spectrum were created using the tools rmfgen and arfgen. The FTOOL grppha was used to require at least 20 COUNTS BIN$^{-1}$. The spectra of four different extraction region and event criterion for the EPIC-MOS1 (revolution 782) observation are shown in Figure 1, fitted with a simple power-law and MCD component modified by absorption in the interstellar medium (PHABS model in XSPEC). The various parameter were tied between the spectra and a normalisation constant was allowed to float between them. It is clear from Fig. 1 that pile-up only significantly affects the spectrum created with the source extraction region with inner radius 18” and “PATTERN$\leq 12$”. All other spectra are consistent with the most conservative extraction region (inner radius 50”, single-pixel events) at energies between 0.7–10.0 keV. The overall shape of the spectrum is, however, not significantly affected by pile-up in all extraction regions and patterns, as can be seen in the lower panel of Fig. 1.

In order to maximise signal-to-noise and make use of the best calibrated response matrix for the LHS, we use the spectra extracted from the annulus with inner radius of 18” and single-pixel events throughout the analysis detailed in this work. A net exposure time of 56 and 59 ks was obtained in revolution 782 for the EPIC-MOS1 and 2 camera respectively and 58 ks for each camera in revolution 783. For the RXTE data set, the reduction procedure involved the use of the tools provided in the RXTE HEASOFT v 6.0 software package. We used the “Standard 2 mode” data from PCU-2 only. The event files and spectra were screened and the background and response files created. Systematic errors of 0.75 per cent were added to all PCU-2 energy channels. The RXTE-A cluster was operated in the “standard archive mode”. Background-subtracted spectrum and associated instrument response files were created using standard procedures. The RXTE observations resulted in net PCA and HEXTA exposures of 2.2 and 0.8 ks, respectively.

We restrict our spectral analyses of the XMM-Newton EPIC-pn data to the 0.7–9.0 keV band. For a preliminary constraint on the blackbody temperature of the LHS we use XMM-Newton EPIC-MOS data in the range 0.5–2.0 keV as we expect the temperature to be low, however for the rest of the analyses XMM-Newton EPIC-MOS is used in the range 0.7–9.0 keV, similarly to the VHS, unless stated otherwise. The PCU-2 spectrum is restricted to the 2.8–25.0 keV band with an edge at 4.78 keV ($\tau = 0.1$) to account for the strong Xe L edge. HEXTA spectrum is analysed between 20.0–100.0 keV. A Gaussian line at 2.31 keV is introduced when fitting the EPIC-pn spectrum due to the presence of a feature at this energy that resembles an emission line. This feature is likely to be caused by Au M-shell edges and Si features in the detectors (M1). When fitting the RXTE spectra as well as the four spectra from the XMM-Newton low/hard observation, (MOS1 and 2 for revolution 782 and 783), a joint fit is achieved by allowing a normalisation constant to float between the various spectra. All parameters in fits involving different instruments were tied. XSPEC v 11.3.2 (Arnaud 1996) was used to analyse all spectra. The quoted errors on the derived model parameters correspond to a 90 per cent confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$ criterion), unless otherwise stated.

3 ANALYSIS AND RESULTS

3.1 Fits to RXTE Data: 2.8–100.0 keV Continuum

We first analyse the RXTE PCU-2 and HEXTA spectra in order to constrain the power-law continuum of the two states. By considering the simplest power-law plus MCD model, modified by absorption in the interstellar medium (PHABS model in XSPEC) with an equivalent neutral hydrogen column density fixed at $N_H = 5.3 \times 10^{21}$ cm$^{-2}$ (Kong et al. 2000), resulted in a poor fit for both states, with $\chi^2/\nu = 279.5/74$ and 273.0/76 for the VHS and LHS respectively. In the case of the LHS the addition of a MCD component did not affect the fit. Significant residual features are present in the region around the Fe Kα fluorescence line. In order to phenomenologically model a disc reflection line we initially added a Gaussian emission line and smeared edge components (SMEDGE in XSPEC) to the model. This significantly improved the fit with $\chi^2/\nu = 68.7/68$ and 88.9/70 for the VHS and LHS respectively. The parameters measured in the VHS for this model are $\Gamma_{PL} = 2.56^{+0.12}_{-0.10}$, $R_{PL} = 2.7^{+0.5}_{-0.4}$, $kT = 0.87^{+0.02}_{-0.06}$ keV, $R_{MCD} = 2200^{+300}_{-100}$, $E_{gauss} = 6.0^{+1.0}_{-1.0}$ keV, FWHM = $2.6^{+1.0}_{-1.0}$ keV, $R_{gauss} = 0.02^{+0.02}_{-0.01}$, EW = 220 ± 100 eV, $E_{smedge} = 8.8^{+0.5}_{-1.7}$ keV, $\tau_{smedge} = 0.2^{+0.2}_{-0.2}$, $W_{smedge} = 2.0^{+1.0}_{-1.0}$ keV, (where $R$ is the normalisation for each function). The equivalent parameters for the LHS are $\Gamma_{PL} = 1.48 \pm 0.01$, $R_{PL} = 0.20^{+0.005}_{-0.007}$, $E_{gauss} = 5.9^{+1.2}_{-0.6}$ keV, FWHM = $0.9^{+0.6}_{-0.5}$ keV, $R_{gauss} = 1.7^{+2.8}_{-1.0} \times 10^{-3}$, EW = 110 ± 40 eV, $E_{smedge} = 7.1^{+0.6}_{-0.2}$ keV, $\tau_{smedge} = 0.3^{+0.2}_{-0.1}$, $W_{smedge} = 2.3 \pm 2.0$ keV. The values obtained for both states are in agreement with those in M1 and M2.

3.2 Fits to XMM-Newton EPIC-pn and MOS data

3.2.1 Verifying the presence of a quasi-blackbody component

Whilst fitting XMM-Newton data for both VHS and LHS, the power-law index was constrained to lie within $\Delta$T $\leq 0.1$ from the values obtained in the RXTE fits. We began by considering a simple power-law continuum plus blackbody component in the form of a MCD. The hydrogen column density was fixed at $N_H = 5.3 \times 10^{21}$ cm$^{-2}$ for both states. A fit to the VHS EPIC-pn data in the range 0.7–3.0 keV ($\chi^2/\nu = 14489.9/462$) shows the presence of a blackbody component with temperature of $\approx 0.76$ keV (Fig. 2, top). We used EPIC-MOS data in the range 0.5–2.0 keV to verify the presence of a MCD component in the LHS. Fig. 2 (bottom) shows the data/model ratio (extended to an energy range of 5.0 keV) without a blackbody component for the LHS. The best fit model requires a disc blackbody with a temperature of $\approx 0.22$, with $\chi^2/\nu = 1137.8/389$. The best fit without a quasi-blackbody gives $\chi^2/\nu = 120617.2/389$, which clearly indicates the need for this component. Recently, similar results have been obtained for the low/hard state of GX 339-4, where an optically thick disc with a temperature of $\approx 0.2$ keV has been reported (Tomsick et al. 2008).

3.2.2 Simple Model: 0.7–9.0 keV

We fit both the VHS and LHS simultaneously with a power-law plus MCD component. Only the value of $N_H$ was tied between the states. The best-fit value found for $N_H = 5.170 \pm 0.001 \times 10^{21}$ cm$^{-2}$ is in accordance with that of Kong et al. 2000. We restricted the value of $N_H$ to 5.1–5.3 times $10^{21}$ for the remainder of this work. Figure 3 shows the spectra with the data/model ratio. The formally unacceptable fit ($\chi^2/\nu = 10279.4/3860$) can be seen to be due mainly to the broad iron line and soft energy residuals, and for the VHS, a large Fe Kα absorption edge.

To provide a physically realistic description of the Fe line region we initially added a relativistic Fe line (LAOR, Laor 1991) to the MCD and power-law continuum and, for the VHS, a smeared
edge to phenomenologically model the iron Kα absorption edge. The LAOR model describes a broad line from an accretion disc surrounding a rotating Kerr BH, with an emissivity profile described by a power-law of the form $\epsilon(r) = r^{-\delta}$. The outer disc radius was fixed at the maximum allowed value of 400 $r_g$. The inner radius of the disc, $r_{\text{in}}$, emissivity index, $q$, disc inclination, $i$, and the normalisation were free to vary. It should be noted that constraining the spin based on the LAOR model, although robust, is only an approximation since the identification of $r_{\text{in}}$ as determined from LAOR assumes a hard wired spin parameter of $a = 0.998$. The way that the inferred BH spin depends on the position of the inner radius was explored by Dovciak, Karas & Yaqoob (2004), and was shown to be consistent with the “true” spin as one considers more rapidly rotating black holes (see their Figure 2). We fit both the VHS and LHS individually, restricting the value of $N_H$ to $5.2 \pm 0.1 \times 10^{21}$ cm$^{-2}$. The fit parameters are given in Table 1.

Adding both a LAOR and SMEDGE components significantly improved the fit for the VHS, with $\chi^2/\nu = 2478.1/1652$ and the LHS with $\chi^2/\nu = 3069.7/2376$ (Fig. 4). For the LHS, residuals below 2.0 keV indicate that the simple power-law plus MCD components, predominant in this range, is not an accurate description of the continuum, and a more complex reflection component should be present. If data below 2.0 keV does not affect the direct measurement of the Fe Kα line profile since the LAOR function used to model the line only extends down to an energy of $\approx 3.5$ keV (see Fig. 4). We note that the parameters values found here differ slightly from those of similar models in M1 and M2 likely due to the restriction imposed on the neutral hydrogen column density, $N_H$ and on improved calibration.

### 3.2.3 More Complex Models: Very High State

In all our previous fits, the presence of a broad iron emission line has been determined and successfully modelled by the LAOR kernel. The presence of a possible edge at $\approx 7.1$ keV found for the VHS is consistent with that predicted from absorption due to Fe K-shell transition in partially ionised, “warm”, material (Ross & Fabian 1993; Ross et al. 1996). To date, BHB spectra have been modelled by a combination of a line model such as LAOR or KERRDISK (Bremer & Reynolds 2006), a separate reflection function such as PEXRIV and a multicolour disc, since no self-consistent reflection model had been available. Here, we use the reflection model developed by Ross & Fabian (2007, REFHIDEN) to model those components jointly for the VHS. The parameters of the model are the number density of hydrogen in the illuminated surface layer, $N_H$, inclination, and power-law index to $5.1 \pm 0.006$ keV (Fig. 5). We note that the parameters values found here differ slightly from those of similar models in M1 and M2 likely due to the restriction imposed on the neutral hydrogen column density, $N_H$ and on improved calibration.

![Figure 2](image-url)  
*Figure 2. Top: Best fit spectra for the VHS showing the presence of a quasi-blackbody with a temperature of $\approx 0.76$ keV (see text). Bottom: Data/model ratio without a quasi-blackbody component for the LHS. Resolution 782 and 783 are shown in red and blue respectively (the data are combined for plotting purposes only). It is clear from these plots that a semi-blackbody component is present in both states.*

### Table 1. Results of Fits to XMM-Newton EPIC-pn (VHS) and EPIC-MOS (LHS) Data.

| Parameter | VHS | LHS |
|-----------|-----|-----|
| $N_H$ ($10^{21}$ cm$^{-2}$) | $5.300 \pm 0.004$ | $5.100 \pm 0.006$ |
| $kT$ (keV) | $0.721 \pm 0.001$ | $0.235 \pm 0.02$ |
| $R_{\text{MCD}}$ | $2890^{+10}_{-20}$ | $8100 \pm 800$ |
| $E_{\text{Laor}}$(keV) | $6.97 \pm 0.01$ | $6.97^{+0.01}_{-0.06}$ |
| $q_{\text{Laor}}$ | $6.82^{+0.03}_{-0.04}$ | $3.23^{+0.05}_{-0.26}$ |
| $\tau_{\text{in}}(r_g)$ | $1.91^{+0.02}_{-0.01}$ | $2.8 \pm 0.1$ |
| $i$(deg) | $18.2^{+0.3}_{-0.5}$ | $10.0^{+2.0}_{-0.5}$ |
| $R_{\text{Laor}}(\times 10^{-3})$ | $130 \pm 2$ | $3.75 \pm 0.15$ |
| $E_{\text{smedge}}$(keV) | $7.16^{+0.01}_{-0.01}$ | ... |
| $\tau_{\text{smedge}}$ | $2.3^{+0.1}_{-0.6}$ | ... |
| $W_{\text{smedge}}$ | $4.1 \pm 0.2$ | ... |
| $\chi^2/\nu$ | $2478.1/1652$ | $3069.7/2376$ |
Figure 3. Top: Data/model ratio for a simple model consisting of a power-law and MCD components only. The XMM-Newton EPIC-pn data for the VHS is shown in black. Spectra for the combined EPIC-MOS (LHS) revolution 782 and 783 are shown in red and blue respectively (the data are combined for plotting purposes only). Bottom: Blowup of the EPIC-pn (black) and EPIC-MOS1 (revolution 782, red) spectrum showing the broad iron line and Fe Kα edge region. The data have been re-binned for visual clarity. The EPIC-pn spectrum has been extended to 10 keV for illustration purposes only.

Figure 4. Left: LHS data/model ratio for a model consisting of a simple power-law and MCD components, as well as a LAOR line (Model 1). Spectra for the combined EPIC-MOS revolution 782 and 783 are shown in red and blue respectively. The data are combined and re-binned for plotting purposes only. Right: Model components for MOS 1 revolution 782.
Table 2. Result of more complex fits to XMM-Newton EPIC-pn data for GX 339-4 in the Very High State.

| Parameter | Model 2 | Model 3 |
|-----------|---------|---------|
| \(N_H\) \((10^{21} \text{ cm}^{-2})\) | 5.16 ± 0.02 | 5.17 ± 0.03 |
| Ic | 2.7 ± 0.01 | 2.7 ± 0.02 |
| \(R_{\text{eff}}\) | 1.45 ± 0.25 | 2.8 ± 0.2 |
| \(kT\) \((\text{ keV})\) | 0.519 ± 0.006 | 0.554 ± 0.044 |
| \(H_{\text{eff}}\) \((10^{21} \text{ cm}^{-3})\) | 4.05 ± 0.2 | 4.52 ± 0.4 |
| \(I_{\text{low/BB}}\) | 4.4 ± 0.4 | 2.0 ± 0.1 |
| \(R_{\text{REFHIDEN}}\) | 4.4 ± 0.2 | 2.7 ± 0.1 |
| \(q_{\text{in}}\) | 6.84 ± 0.1 | 7.6 ± 0.3 |
| \(q_{\text{out}}\) | ... | 3.7 ± 0.3 |
| \(r_{\text{break}}(r_g)\) | ... | 4.9 ± 0.6 |
| \(r_{\text{in}}(r_g)\) | 1.804 ± 0.008 | 2.03 ± 0.025 |
| i \((\text{deg})\) | 19.5 ± 0.5 | 19.98 ± 0.02 |
| \(\chi^2/\nu\) | 2348.8/1655 | 2237.8/1653 |

Notes.- Model 2 is described in XSPEC as \((\text{PHABS} \times (\text{PL} + \text{REFHIDEN}))\). Model 3 assumes the accretion disc has a broken-power law emissivity profile described by the function KDBLUR in XSPEC. The value of \(N_H\), inclination, and power-law index was constrained to 5.1–5.3 \(10^{21} \text{ cm}^{-2}\), 10–20 degrees and 2.5–2.7, respectively in both models.

The data/model ratio for the VHS. Top: Model assumes a broken-power-law emissivity profile and constitute of a power-law and the disc reflection function \(\text{REFHIDEN}\). The presence of a O VIII edge at 0.86 keV and a possible narrow emission line at \(\approx 6.4\) keV can be seen. Bottom: Same as above but with an additional narrow Gaussian line and a O VIII edge at 0.86 keV. The data have been re-binned for visual clarity.

3.2.4 More Complex Models: Low/Hard State

The effective temperature of around 0.15 keV and hydrogen number density \(H_{\text{den}} > 2 \times 10^{21} \text{ H cm}^{-3}\) expected for the LHS falls outside the parameter range of the \(\text{REFHIDEN}\) model. However, the model is being developed and an analyses of the LHS with \(\text{REFHIDEN}\) is left for future work. The disc-blackbody in the LHS has a negligible effect on the iron-\(K\alpha\) features above 2 keV (see Figure 4). For comparison with our results for the VHS, we use \(\text{REFLIONX}\) to analyse \(\text{XMM-Newton EPIC-MOS}\) data for the LHS in the range 2.0–10.0 keV with a model similar to \(\text{REFHIDEN}\) but lacking the intrinsic blackbody disc component. The model \(\text{REFLIONX}\) is a revised version of \(\text{REFLION}\) (Ross & Fabian 2005) used to describe reflection from accretion disc in AGN systems where the blackbody emission is at too low an energy to affect the Fe Kα emission. It should be stressed that the reflection features above 2 keV are unlikely to be significantly affected by the change from \(\text{REFHIDEN}\) to \(\text{REFLIONX}\). The parameters of the model are the iron abundance (set to solar), photon index of the illuminating power-law, ionisation parameter, \(\xi\), and the normalization. The disc reflection spectra is convolved with the relativistic blurring kernel, KDBLUR. The power law index in \(\text{REFLIONX}\) is tied to that of the hard component. We constrain the value of the inclination, and power-law index to 10–20 degrees and...
The hydrogen column density, \( N_H \), is fixed at \( 5.17 \times 10^{21} \text{ cm}^{-2} \), the best fit value found for the VHS, as we do not expect it to vary. The best fit obtained with the blurred REFLIONX model is shown in Fig.7 and detailed in Table 3. This model gives \( \chi^2/\nu = 2242.5/2031 \) with an emissivity index of 3.065 ± 0.05 indicating a standard “lamp-post” emissivity profile. The value found for the inclination of 20–17 deg. is in agreement with that for the VHS. The low disc ionisation parameter, \( \log(\xi) \approx 3 \), is consistent with that expected for low disc temperatures. At 90 per cent confidence, this model gives constraint on the innermost stable radius of \( r_{in} = 2.08^{+0.17}_{-0.10} r_g \) (see Fig. 8). If we include the energy band 0.7–2.0 keV to the above fit, a large low energy residual is present due to the disc emission. By modeling this with a DISKBB component, a best fit of \( \chi^2/\nu = 3070.9/2388 \) is achieved in the full 0.7–10.0 keV range with a disc temperature of 0.201 ± 0.003 keV as in §3.2.1.

### 3.3 Joint XMM-Newton – RXTE spectrum analysis

#### 3.3.1 Very High State: 0.7–100.0 keV

In order to check the robustness of our results, we extended the fit from the EPIC-pn spectrum to include the energy range 0.7–100.0 keV, using RXTE data. PCU-2 data was fitted between 8.0–25.0 keV. This resulted in a poor fit, with \( \chi^2/\nu = 4017.0/1727 \). It should be stressed that the quality of the EPIC-pn data far outweighs that of RXTE and thus a statistically worst fit is inevitable in the full range. However, most of the residuals are accounted for by allowing the power-law index to vary. The best fit value of \( \Gamma = 2.583 \pm 0.007 \) is in accordance to that found in section 3.1 for the RXTE continuum. The parameters for fits to the combined EPIC-pn and RXTE spectrum are listed in Table 4 and shown in Fig. 9 (left). It is clear that the model is a very good description of the spectrum (see Fig. 9), with \( \chi^2/\nu = 2549.3/0.1718 \) in the full 0.7–100.0 keV range. Most importantly, the value for the inner radius, \( r_{in} \) found here of 2.02^{+0.02}_{-0.06} r_g \) is similar to that found in section 3.2.3.
Notes. — VHS was modelled with REFHIDEN and a broken power-law model, REFLIONX was used, and the spectra was fitted in the range from 0.7 to 100 keV. The best fit indicates a value for $r_{\text{in}}$ of $2.02_{-0.06}^{+0.02} r_g$ and $2.04_{-0.02}^{+0.07} r_g$ for the VHS and LHS respectively. EPIC-MOS/pn data are shown in black. RXTE-PCU-2 and HEXTE data are shown in red and blue respectively. The data have been re-binned for visual clarity.

![Figure 9](image-url)  
**Figure 9.** XMM-Newton and RXTE spectra of GX 339-4 fit jointly with a disc reflection model convolved with the relativistic blurring kernel, KDBLUR. Left: VHS spectrum in the 0.7–100.0 keV range. Right: LHS spectrum in the 2.0–100.0 keV range. The best fit indicates a value for $r_{\text{in}}$ of $2.02_{-0.06}^{+0.02} r_g$ and $2.04_{-0.02}^{+0.07} r_g$ for the VHS and LHS respectively. RXTE-PCU-2 and HEXTE data are shown in red and blue respectively. The data have been re-binned for visual clarity.

| Parameter | Very High State | Low/Hard State |
|-----------|----------------|----------------|
| $N_H (10^{21} \text{ cm}^{-2})$ | $5.100_{-0.004}^{+0.004}$ | 5.17 |
| $\Gamma$ | $2.583_{-0.007}^{+0.007}$ | $1.43_{-0.005}^{+0.005}$ |
| $R_{\text{PL}}$ | $2.61_{-0.09}^{+0.13}$ | $0.09_{-0.004}^{+0.004}$ |
| $kT (\text{keV})$ | $0.585_{-0.001}^{+0.001}$ | ... |
| $H_{\text{lev}}(\times 10^{21} \text{ H cm}^{-3})$ | $6.6_{-0.2}^{+0.2}$ | ... |
| $H_{\text{lev}}/BB$ | $1.00_{-0.02}^{+0.02}$ | ... |
| $\xi (\text{erg cm s}^{-1})$ | $> 10000$ | $1330_{-60}^{+70}$ |
| $R_{\text{REFHIDEN}}$ | $1.92_{-0.06}^{+0.02}$ | ... |
| $R_{\text{REFLIONX}}(10^{-6})$ | ... | $4.4_{-0.2}^{+0.4}$ |
| $q_{\text{in}}$ | $7.05_{-0.20}^{+0.05}$ | $3.16_{-0.05}^{+0.05}$ |
| $q_{\text{out}}$ | $3.0_{-0.1}^{+0.1}$ | ... |
| $r_{\text{break}}(r_g)$ | $6.0_{-1}^{+2}$ | ... |
| $r_{\text{in}}(r_g)$ | $2.0_{-0.0}^{+0.02}$ | $2.04_{-0.02}^{+0.07}$ |
| $i$ (deg) | $20.0_{-3}^{+0.2}$ | $20.0_{-1.3}^{+0.2}$ |
| $\chi^2/\nu$ | $2549.3/1718$ | $2316.6/2095$ |

Notes. — VHS was modelled with REFHIDEN and a broken power-law emissivity profile, as described in the text. For the LHS, the disc reflection model REFLIONX was used, and the spectra was fitted in the range 2–100 keV.

3.3.2 Low/Hard State: 2–100 keV

A similar extension on the energy range of the LHS was made, with RXTE data being used in conjunction with EPIC-MOS. A best fit of $\chi^2/\nu = 2316.6/2095$ over the full 2.0–100.0 keV energy band is found. The various parameters are shown in Table 4 and the resulting spectra in Fig. 9 (right). The value for the inner radius, $r_{\text{in}}$, found here of $2.04_{-0.02}^{+0.07} r_g$ is similar to that found in section 3.2.4.

4 DISCUSSION

The spectral modelling of the VHS suggests that the surface layer of the accretion disc is highly ionised, with $\xi \sim 10^4 \text{ erg cm s}^{-1}$. In this state, the iron in the outer layer of the disc is fully ionised and regions $\lesssim 2$ Thomson mean free paths below the surface produces a strong iron-K absorption edge. Narrow $K\alpha$ line emission from this region is then Compton-broadened as it scatters out of the disc. The strong presence of the iron-K edge in the VHS can be seen in Fig. 3 and quantitatively appreciated by the high optical depth ($\tau = 2.3_{-0.8}^{+0.4}$) of the (phenomenological) component SMEDGE in Model 1. The best-fit REFHIDEN model clearly shows the large K-shell absorption feature and weak $K\alpha$ emission line characteristic of the VHS in GX 339-4 (Fig. 10, left).

Note that similar features have also been observed in the VHS of Cygnus X-1 (Done et al. 1992). The ionisation parameter found for the LHS, $\xi = 1350_{-100}^{+100} \text{ erg cm s}^{-1}$, is consistent with the disc being moderately ionised and having a low apparent temperature. In this state, the illuminated accretion disc results in a strong $Fe-K\alpha$ emission line from the top layers. Compton-broadening, although present, cannot explain the highly broadened and skewed line shape (see Fig. 3), where the low energy red wing extend down to $\approx 4$ keV. Figure 10 (right) shows the best-fit REFLIONX model, prior to (top) and after blurring (bottom), for the LHS. As opposed to the VHS, in the low/hard state the Fe-$K\alpha$ line is clearly seen. The value for the ionisation parameter for the low/hard state of $\xi = 10^4 \text{ erg cm s}^{-1}$ reported by Tomsick et al. (2008) is an order of magnitude higher than the present result. At these values, the iron is fully ionised and should not produce an iron $K\alpha$ reflection line (Matt, Fabian & Ross 1993; Young, Ross & Fabian 1998).

The apparent inconsistency in their results can be attributed to the use of PEXRIV (Magdziarz & Zdziarski 1995) as the reflection model. This model does not account for diffusion of photons in the disc and thus rectify broadening caused by Comptonisation by increasing the ionisation parameter.

The obvious differences in the resulting spectra of the two states can be ascribed to the different ionisation states of the disc. Previous attempts to model the spectra of Galactic BHB used the relativistic blurring of the $K\alpha$ line to obtain the innermost radius, $r_{\text{in}}$, and thus the spin parameter. In the present work, the full reflection spectra for the two extreme states was convolved, and the blurring parameters were obtained not just from the $K\alpha$ line but from all of the reflection features. This is particularly important in the case of the VHS, where the Fe-$K\alpha$ emission line is not the dominant feature of the reflection component and Compton scattering needs to be fully accounted in the reflection model. In this state, a steep inner disc emissivity index of $q_{\text{in}} = 6.0_{-0.6}^{+0.3}$ within a radius $r_{\text{break}} = 4.9_{-0.7}^{+0.6} r_g$ is required, indicating that the corona is...
centrally concentrated. The model constrains the inner radius of the accretion disc to $r_{\text{in}} = 2.03^{+0.025}_{-0.035} r_g$ at the 90% confidence level. It should be noted that the value for $r_{\text{in}}$ quoted above for the XMM-Newton observation is consistent with that found for the full RXTE fits, indicating that the model is an accurate description of both the reflection features as well as the underlying continuum. Assuming that emission within the innermost stable orbit is negligible (see Reynolds & Fabian 2007), the value of $r_{\text{in}}$ found here translates to a black hole spin of $0.939^{+0.004}_{-0.003}$ for the VHS. In the LHS, spectral fitting using the model REFLIONX resulted in an inner radius of $r_{\text{in}} = 2.08^{+0.17}_{-0.10} r_g$. This translates to a spin parameter of $0.93^{+0.015}_{-0.02}$ for the LHS.

The value for the spin parameter found for both states of GX 339-4 are within one per cent of one another and falls within one sigma error. It has been argued that bleeding of the iron line emission to regions inside the innermost stable radius may cause systematic errors in the derived value of the spin parameter (Reynolds & Begelman 1997; Krolik 1999). Using a high-resolution 3-D MHD simulation of a geometrically-thin accretion disc, Reynolds & Fabian (2007) have shown that the ionisation edge is within $0.5 r_g$ of the innermost stable circular orbit for a non-spinning BH. However, it was shown by the same authors that this bleeding decreases as the position of the innermost radius approaches the event horizon, and hence the spin inferred from the position of $r_{\text{in}}$ becomes much closer to the true spin as one considers more rapidly rotating black holes. Similar results were reported by Dovciak, Karas & Yaqoob (2004, see their Figure 2). In order to verify our results against any systematic variation, we modelled the VHS with a KERRDISK line profile (Brenneman & Reynolds 2006). The spin, which is a free parameter of the model, was found to be $0.952^{+0.005}_{-0.004}$, lying within $\pm 1$ per cent of the value inferred from the innermost radius.

The reflection model, REFHIDEN, assumes a single-temperature accretion disc. Although this is not a realistic claim, we believe it unlikely to have any significant effect on the inferred innermost radius of emission. In order to verify this hypothesis, we approximated a “real” disc with inner radius increasing logarithmically from $2 r_g$ to $6.78 r_g$. Each point on the disc was assumed to radiate like a blackbody with an effective temperature that scales with radius as $r^{-3/4}$ starting at 0.9 keV. Within this region, the illuminating flux scaled as $r^{-5/3}$. Using the EPIC-pn response file, we modelled 1 ks of simulated data with a single temperature REFHIDEN. As expected, the model constrained the various parameter, with an effective temperature of $\approx 0.52$ keV and an inner radius of $2.041^{+0.004}_{-0.020} r_g$. As a further check on any inconsistency that may arise from using a single temperature disc reflection model to constrain the spin of the black hole, we investigated the VHS with a different thermal model, (KERRBB, Li et al. 2005), which includes relativistic smearing in a disc with radial temperature gradient. The black hole spin, a free parameter in the KERRBB model, was found to be $0.93 \pm 0.02$, consistent with that inferred from the single temperature REFHIDEN model.
5 CONCLUSIONS

We have analysed XMM-Newton spectra of GX 339-4 in both its very high and low/hard states. Looking at the difference in the spin parameter between the two states, as well as that derived from the various independent models for the VHS, we can estimate the systematic error in the iron line method to be about 1 per cent. By using a reflection model which intrinsically accounts for Comptonisation and blackbody emission, we infer that the spin parameter of GX 339-4 is $0.935 \pm 0.01$ (statistical) $\pm 0.01$ (systematic).

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