High-density reflection spectroscopy: I. A case study of GX 339-4

Jiachen Jiang, Andrew C. Fabian, Jingyi Wang, Dominic J. Walton, Javier A. García, Michael L. Parker, James F. Steiner and John A. Tomsick

1 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
2 MIT Kavli Institute for Astrophysics and Space Research, MIT, 70 Vassar Street, Cambridge, MA 02139, USA
3 Cahill Center for Astronomy and Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
4 Dr. Karl Remeis-Observatory and Erlangen Centre for Astroparticle Physics, Sternwartstr. 7, D-96049 Bamberg, Germany
5 European Space Agency (ESA), European Space Astronomy Centre (ESAC), E-28691 Villanueva de la Cañada, Spain
6 Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720, USA

Abstract
We present a broad-band spectral analysis of the black hole binary GX 339-4 with NuSTAR and Swift using high-density reflection model. The observations were taken when the source was in low-flux (LF) hard states during the outbursts in 2013 and 2015, and in a very high-flux (HF) soft state in 2015. The high-density reflection model can explain its LF spectra with no requirement for an additional low temperature thermal component. This model enables us to constrain the density in the disc surface of GX 339-4 in different flux states. The disc density in the LF state is log (ne/cm−3) ≈ 21, 100 times higher than the density in the HF state (log (ne/cm−3) = 18.93 ± 0.12). A close-to-solar iron abundance is obtained by modelling the LF and HF broad-band spectra with variable density reflection model (ZFe = 1.50 ± 0.04Z⊙ and ZFe = 1.05 ± 0.17Z⊙, respectively).

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual (GX 339-4).

1 Introduction
The primary X-ray spectra from black holes (BHs) can be described by a power-law continuum, which originates from a high temperature compact structure external to the BH accretion disc. This high temperature compact structure is called the corona. The interaction between the primary power-law photons and the temperature compact structure external to the BH accretion disc.

In both highly variable AGNs (e.g. Mrk 335, IRAS 13224-3809, Parker et al. 2014; Jiang et al. 2018) and XRBs that show different flux states (e.g. XTE J1650-500, Reis et al. 2013).

The existence of two different flux states in XRB was first realized in the X-ray emission of the XRB Cyg X-1 (Oda et al. 1971). Its X-ray spectrum can change from a soft spectrum featured by a strong thermal component to a hard spectrum featured by a strong disc reflection component. The soft state, which is also characterized by no radio detection, is identified as the ‘high’ flux (HF) state and the hard state with associated radio detection is identified as the ‘low’ flux (LF) state due to the large flux variation during the transition. Measurements in the HF soft states of BH XRB offer good evidence that the accretion disc is extended to the innermost stable circular orbit (ISCO; e.g. LMC X-3, Steiner et al. 2010). Most of the spin measurements of soft states are based on the assumption that the inner radius is located at ISCO (e.g. Gou et al. 1997; McClintock & Narayan 1997; Narayan 2005). Although there is evidence that the disc is truncated as measured by reflection spectroscopy at X-ray luminosities Lx ≈ 0.1 per centLedd (Narayan & McClintock 2008; Tomsick et al. 2009), there is a substantial debate whether the disc is truncated in the intermediate flux hard state due to different spectral modelling or instrumental pile-up effects (see the discussion in Wang-Ji et al. 2018).

E-mail: jjj447@cam.ac.uk

© 2019 The Author(s)
Published by Oxford University Press on behalf of the Royal Astronomical Society

doi:10.1093/mnras/stz095
A common result obtained by reflection modelling of BH X-ray spectra is high iron abundance compared to solar. For example, Walton et al. (2016) found a value of $Z_{\text{Fe}} \approx 4Z_{\odot}$ in Cyg X-1 and Parker et al. (2015) obtained $Z_{\text{Fe}} \approx 4.7Z_{\odot}$ in the same source. Similarly, an iron abundance of $Z_{\text{Fe}} \approx 2 - 5Z_{\odot}$ is required for another BH XRB V404 Cyg (Walton et al. 2017). Such a high iron abundance has been commonly seen in AGNs as well (e.g. Chiang et al. 2004). GX 339-4 has shown frequent outbursts and multiple spectra during different spectral states of GX 339-4. In its hard state, its X-ray spectrum shows a broad iron emission line and a power-law continuum with a photon index

$$\Gamma \approx 1.5 \text{ and } 2.5 \text{ across different flux levels} \text{ (Miller et al. 2004, 2006, 2008). Reis et al. (2008) presented a systematic study of its high and low hard state XMM–Newton and RXTE spectra by taking the blackbody radiation from the disc into the top layer as well as the Comptonization effects into modelling, and obtained a BH spin of $a_\ast = 0.94 \pm 0.02$. More recently, Parker et al. (2016) obtained a disc iron abundance of $Z_{\text{Fe}} \approx 6.6Z_{\odot}$ for the HF state of the same source observed by the same instruments. Similar conclusions were found by analysing its stacked RXTE spectra at the LF states (García et al. 2015) and NuSTAR spectra during the outburst of 2013 (Fürst et al. 2015).

In this paper, we present a high-density reflection interpretation of both LF and HF state spectra of GX 339-4. The same NuSTAR and Swift spectra as in Parker et al. (2016) and Wang-Ji et al. (2018) are considered. In Section 2, we introduce the data reduction process. In Section 3, we introduce the details of high-density reflection modelling of the LF and HF spectra of GX 339-4. In Section 4, we present and discuss the final spectral fitting results. The high-density reflection modelling of AGN spectra are presented in a companion paper (Jiang in preparation).

2 OBSERVATIONS AND DATA REDUCTION

The weekly MAXI hardness-intensity diagram (HID) for the 2009–2018 period of GX 339-4. The black square and the arrows correspond to the dates of the HF observations and the LF(1–11) observations analysed in this work. The arrows show the flux change during the NuSTAR monitoring of the outbursts. NuSTAR observations were taken during the rise and decay of the outburst in 2013, and only during the decay of the outburst in 2015.
by the arrow in Fig. 1. The *NuSTAR* LF observations in 2015 were taken only during the decay of the outburst. In this work, we consider all of the *NuSTAR* observations taken during these two outbursts. In March 2015, GX 339-4 was detected with strong thermal and power-law components by *Swift*, suggesting strong evidence of an HF state with a combination of disc thermal component and reflection component. One *NuSTAR* target of opportunity observation was triggered with a simultaneous *Swift* snapshot. See the black square in Fig. 1 for the flux and hardness state of the source during its HF observations. A full list of observations is shown in Table 1.

### 2.1 *NuSTAR* data reduction

The standard pipeline NUPipeline V0.4.6, part of HEASoft V6.23 package, is used to reduce the *NuSTAR* data. The *NuSTAR* calibration version V20171002 is used. We extract source spectra from circular regions with radii of 100 arcsec, and the background spectra from nearby circular regions on the same chip. The task NUPRODUCTS is used for this purpose. The 3–78 keV band is considered for both FPMA and FPMB spectra. The spectra are grouped to have a minimum signal-to-noise ratio (S/N) of 6 and to oversample by a factor of 3.

### 2.2 *Swift* data reduction

The *Swift* observations are processed using the standard pipeline XRTPIPELINE V0.13.3. The calibration file version used is x20171113. The LF observations taken in the WT mode are not affected by the pile-up effects. The source spectra are extracted from a circular region with a radius of 20 pixels\(^1\) and the background spectrum spectra are extracted from an annular region with an inner radius of 90 pixels and an outer radius of 100 pixels. The LF observations taken in the PC mode are affected by the pile-up effects. By following Wang-Ji et al. (2018) where they estimated the PSF file, a circular region with a radius of 5 pixels is excluded in the centre of the source region. The 0.6–6 keV band of all the LF *Swift* XRT spectra are considered. The HF observation was taken in the WT mode and was affected by pile-up effects. By following Parker et al. (2016), a circular radius of 10 pixels is excluded in the centre of the source region. The 0.6–1 keV of the HF *Swift* XRT spectrum at a very high state is ignored due to known issues of the RMF redistribution issues in the WT mode.\(^2\) The *Swift* XRT spectra are grouped to have a minimum S/N of 6 and to oversample by a factor of 3.

### 3 SPECTRAL ANALYSIS

XSPEC V12.10.0.C (Arnaud 1996) is used for spectral analysis, and C-stat is considered in this work. The Galactic column density towards GX 339-4 remains uncertain. The value of combined \(N_H\) and \(N_H^d\) obtained by Willingale et al. (2013) is \(5.18 \times 10^{21}\) cm\(^{-2}\). However, Kalberla et al. (2005) reported a column density of \(3.74 \times 10^{24}\) cm\(^{-2}\) in the Leiden/Argentine/Bonn survey. The Galactic column density values measured by different sets of broad-band X-ray spectra are different too. For example, Wang-Ji et al. (2018) obtained \(\approx 4 \times 10^{21}\) cm\(^{-2}\), while Parker et al. (2016) obtained a higher value of \(7.7 \pm 0.2 \times 10^{21}\) cm\(^{-2}\). We therefore fixed the Galactic column density at \(3.74 \times 10^{21}\) cm\(^{-2}\) in the beginning of our analysis and allow it to vary to obtain the best-fitting value for each set of spectra. For local Galactic absorption, the tbabs model is used. The solar abundances of Wilms, Allen & McCray (2000) are used in tbabs. An additional constant model constant has been applied to vary normalizations between the simultaneous spectra obtained by different instruments to account for calibration uncertainties.

### 3.1 LF state spectral modelling

We analyse all the LF *NuSTAR* observations publicly available prior to 2018 and they have discussed in Fürst et al. (2015) and Wang-Ji et al. (2018). Fig. 2 shows the ratio plots of LF1-11 spectra fitted with a Galactic absorbed power-law model obtained by fitting only the corresponding *NuSTAR* spectra. All the LF spectra show a broad emission line feature around 6.4 keV with a Compton hump above 20 keV. They provide a strong evidence of a relativistic disc reflection component. By following García et al. (2015) and Wang-Ji et al. (2018), we model the features with a combination of relativistic disc reflection and a distant reflector for the narrow emission-line component. A more developed version of reflionx (Ross & Fabian 2005) is used to model the rest-frame disc reflection spectrum. The reflionx grid allows the following free parameters: disc iron abundance \((Z_{Fe})\), disc ionization log \((\xi)\), disc electron density \(n_e\), high-energy cut-off \((E_{cut})\), and photon index \((\Gamma)\). All the other element abundances are fixed at the solar value (Morrison & McCammon 1983). The ionization parameter is defined as \(\xi = 4\pi F/n\), where \(F\) is the total illuminating flux and \(n\) is the hydrogen number density. The photon index \(\Gamma\) and high-energy cut-off \(E_{cut}\) are linked to the corresponding parameters of the coronal emission modelled by cutoffpl in XSPEC. A convolution model relconv (Dauser et al. 2013) is applied to the rest-frame-ionized disc reflection model reflionx to apply relativistic effects. A simple power-law-shaped emissivity profile is assumed \((e^{\xi r^q})\) and the emissivity index \(q\) is allowed to vary during the fit. Other free parameters are the disc viewing angle \(i\) and the disc inner radius \(r_{in}/ISCO\). The ionization of the distant reflector is fixed at the minimum value \(\xi = 10\). The other parameters of the distant reflector are linked to the corresponding parameters in the disc reflection component. The BH spin parameter \(a_\ast\) is fixed at its maximum value 0.998 (Kerr 1963) to fully explore the \(r_{in}\) parameter. We use cflux, a simple convolution model in XSPEC, to calculate the 1–10 keV flux of each model component. For future reference and simplicity, we define an empirical reflection fraction as \(F_{ref}/F_{tot}\) in the 1–10 keV band, where \(F_{ref}\) and \(F_{tot}\) are the flux of the disc reflection component and the coronal emission calculated by cflux. Note that this is not the same as the physically defined reflection fraction discussed by Dauser et al. (2016). The final model is tbabs * (cflux * (relconv * reflionx) + cflux * reflionx + cflux * cutoffpl) in XSPEC format. This model can fit all LF spectra successfully with no obvious residuals. For example, it offers a good fit for the LF1 spectra with C-stat = 1043.52/948. A ratio plot of LF1 spectra fitted with this model is shown in the top panel of Fig. 3. The best-fitting values of some key parameters that affect the spectral modelling below 3 keV are following: \(N_H = 3.4^{+0.2}_{-0.1} \times 10^{21}\) cm\(^{-2}\), log \((\xi/\text{erg cm s}^{-1}) = 3.18^{+0.07}_{-0.06}\), and log \((n_e/\text{cm}^{-3}) = 20.6 \pm 0.3\). Our best-fitting column density is consistent with the Galactic column density measured in Kalberla et al. (2005).

---

1\(^1\) pixel \(\approx 2.36\) arcsec.

2\(^2\)See following website for more XRT WT mode calibration information. http://www.swift.ac.uk/analysis/xrt/digest_cal.php
We notice that previously the spectral modelling requires a low temperature multicolour disc thermal component diskbb \(kT = 0.46\) keV when using the model with the disc electron density \(n_e\) fixed at \(\log(n_e/\text{cm}^{-3}) = 15\) for LF1 observation (Wang-Ji et al. 2018). However, the normalization of this component is very low and weakly constrained. Similarly, a weak thermal component is also required in the analysis of its XMM–Newton hard state observations (Reis et al. 2008) and other earlier NuSTAR observations (Reis et al. 2013). The difference in spectral modelling may result from the following two reasons: one is the high density reflection model, where a blackbody-shaped emission arises in the soft band when the disc electron density \(n_e\) becomes higher than \(10^{15}\) cm\(^{-3}\); the other is the uncertain neutral absorber column density, which was measured to be \(N_{\text{H}} = 4.12_{-0.12}^{+0.08} \times 10^{21}\) cm\(^{-2}\) in Wang-Ji et al. (2018) and higher than our best-fitting value for the LF1 spectra.

In order to test for an additional diskbb component, we first fit the spectra with \(N_{\text{H}}\) fixed at the highest Galactic column density \(N_{\text{H}} = 5.18 \times 10^{21}\) cm\(^{-2}\) obtained by Willingale et al. (2013) rather than the value from Kalberla et al. (2005). An additional diskbb component improves the fit by only \(\Delta$$C$$\text{-stat} = 1.1\). See the middle panel of Fig. 3 for the corresponding ratio plot. Only an upper limit of the diskbb normalization is of \(N_{\text{diskbb}} < 1.5 \times 10^{20}\) found. Compared with the result in Wang-Ji et al. (2018), a lower disc inner temperature of \(kT = 0.24_{-0.10}^{+0.16}\) keV is required in this fit. Secondly, we fit LF1 spectra with the absorber column density as a free parameter (the bottom panel of Fig. 3). A contour plot of C-stat distribution on the \(N_{\text{H}}\) versus \(N_{\text{diskbb}}\) parameter plane is calculated by STEPPAR function in XSPEC and shown in Fig. 4. It clearly shows a strong degeneracy between the absorber column density and the normalization of the diskbb component. The fit is only improved by \(\Delta$$C$$\text{-stat} = 3\) with two more free parameters after including this diskbb component. See Fig. 3 for ratio plots against different continuum models. By varying the Galactic column density, it only slightly changes the fit of the Swift XRT spectrum. Therefore, we conclude that an additional diskbb component is not necessary for LF1 spectral modelling when the disc density parameter \(n_e\) is allowed to vary. In order to visualize the spectral difference with different \(n_e\), we show the best-fitting reflection model component for LF1 in Fig. 5 in comparison with the best-fitting model for the same observation assuming \(\log(n_e/\text{cm}^{-3}) = 15\) cm\(^{-3}\) in Wang-Ji et al. (2018). With a disc density as high as \(\log(n_e/\text{cm}^{-3}) = 20.6\), a quasi-blackbody emission arises in the soft band and accounts for the excess emission below 2 keV. Similar conclusions are found for the other sets of LF spectra. Future pile-up free high S/N observation below 2 keV, such as from NICER, may help constrain more detailed spectral shape of LF states of GX 339-4.

So far we have achieved the best-fitting model for the LF spectra individually. We also undertake a multi-epoch spectral analysis with disc iron abundance \(Z_{\text{Fe}}\) and disc viewing angle \(\alpha\) linked between LF1-11 spectra. All the other parameters are allowed to vary during the fit. A table of all the best-fitting parameters is shown in Table 2. The best-fitting models and corresponding ratio plots are shown in Fig. 6. We allow the column density of the neutral absorber to vary in different epochs to investigate any variance. A slightly higher column density \(N_{\text{H}} \approx 4.1\times10^{21}\text{ cm}^{-2}\) is required for LF6,7. The emissivity index of the relativistic reflection spectrum is weakly constrained in LF3-6 observations but largely consistent with the Newtonian value \(q = 3\), except for the LF1 observation. We can also confirm that the disc is not truncated at a significantly large radius, such as \(r = 100\text{r}_g\) (Plant et al. 2015). A slight iron over abundance compared to solar is required \((Z_{\text{Fe}} = 1.5_{-0.13}^{+0.12})\) for the spectral fitting. The power-law continuum is softer in the first two observations taken at higher flux levels but remains consistent at 90 per cent confidence during the rest of the decay in 2015. The photon index in LF7-10 during the outburst in 2013 is consistent at 90 per cent confidence as well. The reflection fraction decreases with the decreasing total flux during the flux decay in 2015. This is likely caused by a receding inner disc radius at the very LF states or a change of the coronal geometry (e.g. its height above the disc). Moreover, the multi-epoch spectral analysis of all LF observations shows tentative evidence for an anticorrelation between disc density and X-ray band flux. For example, the disc density increases from \(\log(n_e/\text{cm}^{-3}) = 20.6_{-0.12}^{+0.09}\) in the highest flux state (LF1) to \(\log(n_e/\text{cm}^{-3}) = 21.45_{-0.11}^{+0.08}\) in the lowest flux state (LF6). The flux level of the cold reflection component remains consistent, indicating that this emission arises from stable material at a large radius from the central BH. We will discuss other fitting results, such as the electron density measurements, in Section 4.

### Table 1. NuSTAR and Swift observations of GX 339-4 in 2013 and 2015. WT: window timing mode; PC: photon counting mode.

| Obs | NuSTAR obsID | Date | exp. (ks) | Swift obsID | Date | exp. (ks) | Mode |
|-----|--------------|------|----------|-------------|------|----------|------|
| HF  | 8001015003   | 2015-03-04 | 30.9 | 00081429002 | 2015-03-04 | 1.9 | WT |
| LF1 | 8010210102   | 2015-08-28 | 21.6 | 00032898124 | 2015-08-29 | 1.7 | WT |
| LF2 | 80102011004 | 2015-09-02 | 18.3 | 00032898126 | 2015-09-03 | 2.3 | WT |
| LF3 | 80102011006 | 2015-09-07 | 19.8 | 00032898130 | 2015-09-07 | 2.8 | WT |
| LF4 | 80102010108 | 2015-09-12 | 21.5 | 00081534001 | 2015-09-12 | 2.0 | PC |
| LF5 | 80102010110 | 2015-09-17 | 38.5 | 00032898138 | 2015-09-17 | 2.3 | WT |
| LF6 | 80102010112 | 2015-09-30 | 41.3 | 00081534005 | 2015-09-30 | 2.0 | PC |
| LF7 | 8001013002 | 2013-08-11 | 42.3 | 00032490015 | 2013-08-12 | 1.1 | WT |
| LF8 | 8001013004 | 2013-08-16 | 47.4 | 00080180001 | 2013-08-16 | 1.9 | WT |
| LF9 | 8001013006 | 2013-08-24 | 43.4 | 00080180002 | 2013-08-24 | 1.6 | WT |
| LF10| 8001013008 | 2013-09-03 | 61.9 | 00032898130 | 2013-09-02 | 2.0 | WT |
| LF11| 8001013010 | 2013-10-16 | 98.2 | 00032988001 | 2013-10-17 | 9.6 | WT |
spectra. A multicolour disc blackbody component `diskbb` is used to account for the strong disc thermal component. The full model is `tbabs * (cflux*reconv*reflionx + cflux*reflionx + cflux*cutoffpl + diskbb)` in XSPEC format. This model provides a good fit with C-stat/ν=1048.68/971. The best-fitting model is shown in the last panel of Fig. 6 and the best-fitting parameters are shown in the last column of Table 2. A disc density of \( \log (n_e/\text{cm}^{-3}) = 18.93^{+0.12}_{-0.16} \) is found in HF observations which is 100 times lower than the best-fitting value in LF observations.

So far we have obtained a good fit for the HF spectrum of GX 339-4. A higher column density is required for the neutral absorber \( (N_H = 6.2 \pm 0.2 \times 10^{21} \text{ cm}^{-2}) \) compared to the LF observations \( (N_H \approx 3.4 \times 10^{21} \text{ cm}^{-2}) \). Parker et al. (2016) obtained a higher column density of \( N_H = 7.2 \pm 0.2 \times 10^{21} \text{ cm}^{-2} \) for the same observation assuming \( n_e = 10^{15} \text{ cm}^{-3} \) for the disc. Both our result and Parker et al. (2016) are higher than the Galactic absorption column density estimated at other wavelengths (e.g. Kalberla et al. 2005), indicating a possible extra variable neutral absorber along the line of sight. Only an upper limit of the flux of the distant cold reflector is achieved \( \log (F_{\text{dis}}) < -10.89 \). The 1–10 keV band flux values of the disc reflection component and the coronal emission increase by a factor of 13 and 6, respectively, compared to LF1. The best-fitting broad-band model shows the highest reflection fraction among all the observations considered in this work, indicating a geometry change of the disc corona system such as a small inner disc radius. A solar iron abundance \( (1.05^{+0.17}_{-0.15}) \) is required for the HF spectra, which is lower than the value obtained by Parker et al. (2016), where a disc density of \( n_e = 10^{15} \text{ cm}^{-3} \) is assumed.
component. The HF spectral modelling requires a 100 times lower normalization parameter plane for LF1 spectra when fitted with (red solid line), 2
It shows a clear degeneracy between two parameters. The lines show the 1 σ contours (green dash–dotted line). An additional diskbb component is required to fit the broad-band spectra in Wang-Ji et al. (2018).

4 RESULTS AND DISCUSSION

We have obtained a good fit for the LF and the HF spectra of GX 339-4. The LF spectral modelling requires a high disc density of \( \log (n_e / \text{cm}^{-3}) \approx 21 \) with no additional low-temperature thermal component. The HF spectral modelling requires a 100 times lower density \( \log (n_e / \text{cm}^{-3}) \approx 18.93^{+0.12}_{-0.16} \) compared to LF observations.

In this section, we discuss the spectral fitting results by comparing with previous data analysis and accretion disc theories.

4.1 Comparison with previous results

First, the most significant difference from previous results is the close-to-solar disc iron abundance. Previously, Parker et al. (2016) and Wang-Ji et al. (2018) obtained a disc iron abundance of \( Z_{\text{Fe}} = 6.6^{+0.3}_{-0.3} \) and \( Z_{\text{Fe}} \approx 8 Z_{\odot} \), respectively, by analysing the same spectra considered in this work. Similar result was achieved by Fürst et al. (2015). A high iron abundance of \( Z_{\text{Fe}} = 5 \pm 1 Z_{\odot} \) was also found by analysing stacked RXTE spectra (García et al. 2015). All of their work was based on the assumption for a fixed disc density \( n_e = 10^{19} \text{cm}^{-3} \). By allowing the disc density \( n_e \) to vary as a free parameter during spectral fitting, we obtained a close-to-solar disc iron abundance \( Z_{\text{Fe}} = 1.50^{+0.12}_{-0.04} \) for LF observations and \( Z_{\text{Fe}} = 1.05^{+0.37}_{-0.15} Z_{\odot} \) for HF observations. The best-fitting disc iron abundance for the LF spectra is slightly higher than the value for the HF spectra at 90 per cent confidence. However, they are consistent within 2 \( \sigma \) confidence range. See the left-hand panel of Fig. 7 for the constraints on the disc iron abundance parameter. A similar conclusion was achieved by analysing the intermediate flux state spectra of Cyg X-1 (Tomsick et al. 2018) with variable density reflection model. However, a fixed solar iron abundance was assumed in their modelling.

Secondly, the best-fitting disc viewing angle measured for GX 339-4 is different in different works. The middle panel of Fig. 7 shows the constraint of the disc viewing angle given by multi-epoch LF spectral analysis and HF spectral analysis. The two measurements are consistent at the 90 per cent confidence level (\( i = 34 \pm 2 \) deg for the LF observations and \( i = 35.9^{+1.5}_{-2.0} \) deg for the HF observations). Although our best-fitting value is lower compared with the measurement in Wang-Ji et al. (2018) (\( i = 40^\circ \)) and higher than the measurement in Parker et al. (2016) (\( i = 30^\circ \)), all the previous reflection based measurements are consistent with.
our results at 2σ level. Similarly Tomsick et al. (2018) measured a
different viewing angle for Cyg X-1 compared with previous works.
It indicates that a slightly different viewing angle measurement might be common when allowing the disc density \( n_c \) to vary as a
free parameter during the spectral fitting.

Thirdly, a high BH spin (\( a_+ > 0.93 \)) is given by the disc reflection
modelling in the HF spectral analysis. Due to the lack of precise
measurement of the source distance and the central BH mass, we
can only give a rough estimation of the inner radius through the
normalization of the diskbb component in the HF observations. The
normalization parameter is defined as \( N_{\text{diskbb}} = (r_a / D_{10\,\text{kpc}})^2 \cos i \),
where the \( D_{10\,\text{kpc}} \) is the source distance in units of 10kpc and \( i \) is the
disc viewing angle. The best-fitting value is \( N_{\text{diskbb}} = 1649^{+76}_{-90} \),
corresponding to an inner radius of \( r_a \approx 45 \, \text{km} \approx 3r_g \), assuming \( M_{\text{BH}} = 10M_\odot \) and \( D = 10 \, \text{kpc} \). We also fitted the thermal component with \( \text{kerrbb} \) model (Li et al. 2005) as in Parker et al. (2016). \( \text{kerrbb} \) is a multicolour blackbody model for a thin disc around a
Kerr BH, which includes the relativistic effects of spinning BH. The
BH spin and the disc viewing angle are linked to the corresponding
parameters in relconv. However, we found the source distance and the
central BH mass parameters in \( \text{kerrbb} \) are not constrained during the spectral fitting. \( \text{kerrbb} \) model gives a slightly worse
Figure 6. Top: the first 11 panels show the best-fitting models obtained by fitting LF1-11 spectra simultaneously. The last panel shows the best-fitting model obtained by fitting only HF spectra. Red solid lines: total model; blue dotted lines: relativistic reflection model; purple dashed lines: coronal emission; green dash–dotted lines: distant reflection component; orange dash-dot-dot lines: disc thermal spectrum (only needed in the HF spectral modelling). Bottom: ratio plots against the corresponding best-fitting models shown in the upper panels. Red circles: XRT; blue crosses: FPMA; green crosses: FPMB.

Figure 7. C-stat contour plots for the disc iron abundance and the relativistic reflection parameters obtained by fitting LF 1-11 spectra simultaneously (solid lines) and only the HF spectra (dashed line). The solid lines show the 1σ, 2σ, and 3σ ranges.
fit with ΔC-stat≈7 and 2 more free parameters compared to the diskbb model. Since the BH mass and distance measurement is beyond our purpose, we decide to fit the thermal spectrum in the HF observation with diskbb for simplicity. See Parker et al. (2016) for more discussion concerning the BH mass and the source distance measurements obtained by fitting with kerrbb. In conclusion, the high spin result in this work is obtained by modelling the relativistic disc reflection component in the HF state of GX 339-4 and consistent with previous reflection-based spectral analysis (e.g. García et al. 2015; Plant et al. 2015; Parker et al. 2016; Wang-Ji et al. 2018). Kolehmainen & Done (2010) found an upper limit of $\alpha < 0.9$ by analysing RXTE spectra. However, they assumed the disc viewing angle is the same as the binary orbital inclination, which is not necessarily the case (e.g. Tomsick et al. 2014; Walton et al. 2016).

Fourthly, there is a debate whether the disc is truncated at a significant radius in the brighter phases of the hard state. Compared with the results obtained by the same model with $n_e = 10^{15}$ cm$^{-3}$ and an additional diskbb component (Wang-Ji et al. 2018), we find larger upper limit of the inner radius in the LF2-5 observations. For example, an upper limit of $r_{\text{in}} < 8R_{\text{ISCO}}$ is obtained for the LF2 observation, larger than $r_{\text{in}} = 1.8^{+0.5}_{-0.4}R_{\text{ISCO}}$ found by Wang-Ji et al. (2018). Such difference could be due to different modelling of the disc reflection component. The constraints on the inner radius $r_{\text{in}}$ are shown in the top right panel of Fig. 8. Nevertheless, we confirm that the inner radius is not as large as $r_{\text{in}} \approx 100r_g$ as proposed by previous analysis (e.g. Plant et al. 2015).

### 4.2 High density disc reflection

The LF and HF NuSTAR and Swift spectra of GX 339-4 can be successfully explained by high density disc reflection model with a close-to-solar iron abundance for the disc. In the LF hard states, no additional low-temperature diskbb component is required in our modelling. Instead, a quasi-blackbody emission in the soft band of the disc reflection model fits the excess below 2 keV. At higher disc density, the free–free process becomes more important in constraining low energy photons, increasing the disc surface temperature, and thus turning the reflected emission in the soft band into a quasi-blackbody spectrum. See Fig. 5 for a comparison between the best-fitting high-density reflection model for LF1 observation and a constant disc density model ($n_e = 10^{15}$ cm$^{-3}$).

In LF states of GX 339-4, a disc density of $n_e \approx 10^{21}$ cm$^{-3}$ is required for the spectral fitting. Our multi-epoch spectral analysis shows tentative evidence that the disc density increases from $\log(n_e/\text{cm}^{-3}) = 20.60_{-0.23}^{+0.21}$ in the highest flux state (LF1) to $\log(n_e/\text{cm}^{-3}) = 21.45_{-0.13}^{+0.06}$ in the lowest flux state (LF6) during the decay of the outburst in 2015, except for LF5 observation. See Table 2 for $n_e$ measurements. Similar pattern can be found in LF7-10 observations. In HF state of GX 339-4, we measure a disc density of $n_e \approx 10^{19}$ cm$^{-3}$ by fitting the broad-band spectra with a combination of high density disc model and a multicolour disc blackbody model. The disc density in HF state is 100 times lower than that in LF states. The 0.1–100 keV band luminosity of GX 339-4 in HF state ($L_X \approx 0.28L_{\text{Edd}}$) is 10 times the same band luminosity in LF states ($L_X \approx 0.01 - 0.03 L_{\text{Edd}}$). While the accretion rate is rather small, the anticorrelation between the disc density and the X-ray luminosity $\log(n_e/\text{cm}^{-3}) \propto -2\log(L_X/L_{\text{Edd}})$ is found to agree with the expected behaviour of a standard radiation-pressure-dominated disc (e.g. Shakura & Sunyaev 1973; Svensson & Zdziarski 1994). See Section 4.3 for more detailed comparison between the measurements of the disc density and the predictions of the standard disc model.

### 4.3 Accretion rate and disc density

Svensson & Zdziarski (1994, hereafter SZ94) reconsidered the standard accretion disc model (Shakura & Sunyaev 1973, hereafter SS73) by adding one more parameter to the disc energy balance condition – a fraction of the power associated with the angular momentum transport is released from the disc to the corona, denoted as $f$. Only $1-f$ of the released accretion power is dissipated in the colder disc itself.
where $K = 2^{-7/2} \left( \frac{22\pi}{45} \right)^{3/10} \left( \frac{m_p}{m_e} \right)^{9/10} \left( \frac{e_1}{r_e} \right)^{3/10}$. $\alpha_f$ is the fine-structure constant; $m_p$ is the proton mass; $m_e$ is the electron mass; $r_e$ is the classical electron radius. An example of a gas-pressure-dominated disc solution for $R = 2R_S$ and $f = 0.01$ is shown by the black line in Fig. 9 for comparison. For a gas-pressure-dominated disc, the disc density increases with increasing accretion rate.

The best-fitting disc density and accretion rate values obtained by fitting GX 339-4 LF1-11 and HF spectra with high-density reflection model are shown by black points in Fig. 9. The accretion rate is calculated using $\dot{m} = L_{\text{BD}}/\epsilon L_{\text{Edd}} \approx L_{0.1-100\text{keV}}/\epsilon L_{\text{Edd}}$, where $\epsilon$ is the accretion efficiency and $L_{0.1-100\text{keV}}$ is the 0.1–100 keV band absorption corrected luminosity calculated using the best-fitting model. According to Novikov & Thorne (1973) and Agol & Krolik (2000), an accretion efficiency of $\epsilon = 0.2$ per cent is assumed for a spinning BH with $a_*=0.95$ measured in Section 3.2. A BH mass of $10 M_\odot$ and a source distance of 10 kpc are assumed.

The 0.1–100 keV band luminosity in the HF state of GX 339-4 is approximately 10 times the same band luminosity in the LF states. The disc density in the HF state is two orders of magnitude lower than the density in the LF1-6 states. The anticorrelation between its density and accretion rate is expected according to the radiation-pressure-dominated disc solution in SZ94 (log($n_e$) $\propto -2 \log(\dot{m})$, as in equation 1). However, the disc density measurements for GX 339-4 are lower than the predicted values for corresponding accretion rates. See Fig. 9 for comparison between measurements and theoretical predictions in SZ94. Following are possible explanations for the mismatch: (1) The disc density shown in equation (1) is assumed to be constant throughout the vertical profile of the disc (SS73). The $n_e$ parameter we measure using reflection spectroscopy is however the surface disc density within a small optical depth (Ross & Fabian 2007). For example, three-dimensional MHD simulations show that the vertical structure of radiation-pressure-dominated disc density is centrally concentrated (e.g. Turner 2004; Hirose, Krolik & Stone 2006). (2) The accretion rate might be underestimated by assuming $L_{\text{BD}} \approx L_{0.1-100\text{keV}}$, although we do not expect other bands of GX 339-4 to make a large contribution to its bolometric luminosity. (3) There is a large uncertainty on the BH mass, the disc accretion efficiency, and the source distance measurements for GX 339-4. For example, the most recent near-infrared study shows that the central BH mass in GX 339-4 could be within 2–10$M_\odot$ (Heida et al. 2017). Nevertheless, the use of the high-density reflection model enables us to estimate the density of the disc surface in different flux states of an XRB and an anticorrelation between $n_e$ and $L_X$ has been found in GX 339-4.

### 4.4 Future work

In our work, we conclude that the high-density reflection model can explain both the LF and HF spectra of GX 339-4 with a close to solar iron abundance. No additional blackbody component is statically required during the spectral fitting of the LF states. On one hand, the strong degeneracy between the disc and the disc component and the absorber column density is due to the low S/N of the Swift XRT observations. More pile-up free soft band spectra are required to obtain a more detailed spectral shape at the extremely LF state of GX 339-4, such as from NICER. On the other hand, more detailed spectral modelling is required. For example, a more physics model, such as Comptonization model, is required for the coronal emission modelling in the broad-band spectral analysis. The disc thermal photons from the disc to the reflection layer need to be taken into account. For this purpose, the blackbody model should be used with the disc temperature as the free parameter.
ACKNOWLEDGEMENTS

JJ acknowledges support by the Cambridge Trust and the Chinese Scholarship Council Joint Scholarship Programme (201604100032), DJW acknowledges support from an STFC Ernest Rutherford Fellowship. ACF acknowledges support from the Alexander von Humboldt Foundation. This work made use of data from the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center and the California Institute of Technology. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester. We acknowledge support from European Space Astronomy Center (ESAC).

REFERENCES

Agol E., Kroll J. H., 2000, ApJ, 528, 161
Arnaud K. A., 1996, in George H. J., Jeannette B., eds, Astronomical Data Analysis Software and Systems V, A.S.P. Conference Series, Vol. 101, p. 17
Barr P., White N. E., Page C. G., 1985, MNRAS, 216, 65P
Chiang C.-Y., Walton D. J., Fabian A. C., Wilkins D. R., Gallo L. C., 2015, MNRAS, 446, 759
Dauser T., García J., Wilms J., Böck M., Brenneman L. W., Falanga M., Fukumura K., Reynolds C. S., 2013, MNRAS, 430, 1694
Dauser T., García J., Walton D. J., Eikmann W., Kallman T., McClintock J., Wilms J., 2016, A&A, 590, A76
Esin A. A., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
Fabian A. C. et al., 2009, Nature, 459, 540
Fürst F. et al., 2015, ApJ, 808, 122
García J., Kallman T. R., 2010, A&A, 718, 1972–1982 (2019)
García J. A., Steiner J. F., McClintock J. E., Remillard R. A., Grinberg V., 2010, ApJ, 718, L117
García J. A., Fabian A. C., Kallman T. R., Dauser T., Parker M. L., McClintock J. E., Remillard R. A., Grinberg V., Dauser T., 2015, ApJ, 813, 84
George I. M., Fabian A. C., 1991, MNRAS, 249, 352
Gou L. et al., 2014, ApJ, 790, 29
Grupe D., Komossa S., Leighly K. M., Page C. G., 2010, ApJS, 186, 64
Heida M., Jonker P. G., Torres M. A. P., Chiavassa A., 2017, ApJ, 846, 132
Hynes R. I., Steeghs D., Casares J., Charles P. A., O’Brien K., 2003a, ApJ, 573, A120
Hynes R. I., Steeghs D., Casares J., Charles P. A., O’Brien K., 2003b, ApJ, 583, L95
Jiang J., Walton D. J., Fabian A. C., Parker M. L., 2019, MNRAS, 483, 2958
Jiang J. et al., 2018, MNRAS, 477, 3711
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R., Pöppel W. G. L., 2005, A&A, 440, 775
Kerr R. P., 1963, Phys. Rev. Lett., 11, 237
Kolehmainen M., Done C., 2010, MNRAS, 406, 2206
Li L.-X., Zimmerman E. R., Narayan R., McClintock J. E., 2005, ApJS, 157, 335
Matsuoka M. et al., 2009, PASJ, 61, 999
Miller J. M., Homan J., Steeghs D., Rupen M., Hunstead R. W., Wijnands R., Charles P. A., Fabian A. C., 2006, ApJ, 653, 252
Miller J. M. et al., 2004, ApJ, 606, L131
Miller J. M. et al., 2008, ApJ, 679, L113
Morrison R., McCammon D., 1983, ApJ, 270, 119
Muñoz-Darias T., Casares J., Martínez-Païs I. G., 2008, MNRAS, 385, 2205
Narayan R., 2005, Ap&SS, 300, 177
Narayan R., McClintock J. E., 2008, New Astron. Rev., 51, 733
Novikov I. D., Thorne K. S., 1973, in Dewitt C., Dewitt B. S., eds, Black Holes (Les Astres Occlus), Gordon and Breach, New York, NY (USA), p. 343
Oda M., Gorenstein P., Gursky H., Kellogg E., Schreier E., Tananbaum H., Giaacioni R., 1971, ApJ, 166, L1
Parker M. L., Miller J. M., Fabian A. C., 2018, MNRAS, 474, 1538
Parker M. L. et al., 2014, MNRAS, 443, 1723
Parker M. L. et al., 2015, ApJ, 808, 9
Parker M. L. et al., 2016, ApJ, 821, L6
Plant D. S., Fender R. P., Ponti G., Muñoz-Darias T., Coriat M., 2015, A&A, 573, A120
Reis R. C., Fabian A. C., Ross R. R., Miniutti G., Miller J. M., Reynolds C., 2008, MNRAS, 387, 1489
Reis R. C., Miller J. M., Reynolds M. T., Fabian A. C., Walton D. J., Cackett E., Steiner J. F., 2013, ApJ, 763, 48
Reynolds C. S., Brenneman L. W., Lothian M. H., Trippe M. L., Miller J. M., Fabian A. C., Nowak M. A., 2012, ApJ, 755, 88
Reynolds C. S., Nowak M. A., 2003, Phys. Rep., 377, 389
Ross R. R., Fabian A. C., 2005, MNRAS, 358, 211
Ross R. R., Fabian A. C., 2007, MNRAS, 381, 1697
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337 (SS73)
Steiner J. F., McClintock J. E., Remillard R. A., Gou L., Yamada S., Narayan R., 2010, ApJ, 718, L117
Svensson R., Zdziarski A. A., 1994, ApJ, 436, 599 (SZ94)
Tanaka Y. et al., 1995, Nature, 375, 659
Tomisick J. A., Yamaoka K., Corbel S., Kaaret P., Kalemci E., Migliari S., 2009, ApJ, 707, L87
Tomisick J. A. et al., 2014, ApJ, 780, 78
Tomisick J. A. et al., 2018, ApJ, 855, 3
Turner N. J., 2004, ApJ, 605, L45
Walton D. J. et al., 2016, ApJ, 826, 87
Walton D. J. et al., 2017, ApJ, 839, 110
Wang-Ji J. et al., 2018, ApJ, 855, 61
Wang H., Zhou H., Yuan W., Wang T., 2012, ApJ, 751, L23
Willingale R., Starling R. L. C., Beardmore A. P., Tanvir N. R., O’Brien P. T., 2013, MNRAS, 431, 394
Wilms J., Allen A., McCray R., 2004, MNRAS, 351, 791
This paper has been typeset from a TeX/XeTeX file prepared by the author.