Study of the reflection spectrum of the bright atoll source GX 3+1 with *NuSTAR*

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**ABSTRACT**

We report on the *NuSTAR* observation of the atoll type neutron star (NS) low-mass X-ray binary GX 3+1 performed on 17 October 2017. The source was found in a soft X-ray spectral state with \(3 - 70 \text{ keV}\) luminosity of \(L_X \sim 3 \times 10^{37} \text{ ergs s}^{-1}\) (\(\sim 16\%\) of the Eddington luminosity), assuming a distance of 6 kpc. A positive correlation between intensity and hardness ratio suggests that the source was in the banana branch during this observation. The broadband \(3 - 70 \text{ keV}\) *NuSTAR* spectral data can be described by a two-component continuum model consisting of a disk blackbody \((kT_{\text{disk}} \sim 1.8 \text{ keV})\) and a single temperature blackbody model \((kT_{\text{bb}} \sim 2.7 \text{ keV})\). The spectrum shows a clear and robust indication of relativistic reflection from the inner disc which is modelled with a self-consistent relativistic reflection model. The accretion disc is viewed at an inclination of \(i \sim 22^\circ - 26^\circ\) and extended close to the NS, down to \(R_{\text{in}} = (1.2 - 1.8)R_{\text{ISCO}}\) (\(\geq 6.9 - 9.1 R_g\) or \(14 - 20.5 \text{ km}\)) which allows an upper limit on the NS radius (\(\leq 13.5 \text{ km}\)). Based on the measured flux and the mass accretion rate, the maximum radial extension for the boundary layer is estimated to be \(\sim 6.3 R_g\) from the NS surface. However, if the disc is not truncated by the boundary layer but by the magnetosphere, an estimated upper limit on the polar magnetic field would be of \(B \leq 6 \times 10^8 \text{ G}\).

**Key words:** accretion, accretion discs - stars: neutron - X-rays: binaries - stars: individual GX 3+1

1 INTRODUCTION

Neutron star low-mass X-ray binaries (NS LMXBs) are classified into two main groups based on their correlated spectral and timing behavior in X-rays [Hasinger & van der Klis 1989]. Those are the so-called Z sources, with luminosities close to or above the Eddington luminosity \((L_{\text{Edd}})\) and the atoll sources, with luminosities up to \(\sim 0.5 L_{\text{Edd}}\) (Homan et al. 2010). The name of Z and atoll sources is associated with the shape traced in the color-color diagram (CD). This shape can be divided into two main regions, corresponding to the X-ray state of the atoll sources. The harder one is related to the island state and the softer one is related to the banana state which can be further divided as lower banana and upper banana states. The source spectral and timing properties corresponding to the position on the CD are well determined by the basic parameters such as mass accretion rate (Di Salvo et al. 2001). X-ray bursts are frequently observed from atoll sources. The source GX 3+1 has been identified as an atoll source based on its spectral and variability properties (Hasinger & van der Klis 1989).

X-ray emission lines from the innermost accretion disc have been observed in different NS LMXBs [Bhattacharyya & Strohmayer 2007; Cackett et al. 2005; Pandel et al. 2008; Reis et al. 2004; Degenaar et al. 2015]. Disc lines are produced when the inner part of the accretion disc is illuminated by the hard X-ray emission. The hard X-ray emission could be thermal or non-thermal in nature. This process produces different spectral signatures including emission lines, absorption edges and a reflection hump that peaks between \(20 - 30 \text{ keV}\) (Ballantyne et al. 2001; Ross & Fabian 2007). The overall interaction is known as "disc reflection". The most prominent line produced in this process is typically an Fe K line due to its large abundance and fluorescent yield. The intrinsically narrow Fe lines appears as broad, asymmetric shape in the X-ray spectra because of the relativistic effects induced from strong gravitational field (Miller 2007; Fabian et al. 2000). This line profile is sensitive to the inner radius of the accretion disc as the relativistic effects are stronger in this area. Thus, The Fe-K emission lines are the best suited
features to diagnose the accretion flows close to the NS. The accretion disc in NS systems could be truncated by the boundary layer between the disc and the NS surface or by a strong stellar magnetic field. Thus the inner disc radius sets an upper limit to the radius of the NS and hence can constrain the NS equation of state \cite{piraino2000}. The counterpart of GX 3+1 was identified with a 2 \text{ keV} emission line around \text{Fe-K} \cite{seifina2012}. Broad Fe-K emission lines around \( \sim 6.5 \text{ keV} \) have been reported in the previous \textit{BeppoSAX}, \textit{INTEGRAL}, \textit{RXTE} and \textit{XMM-Newton} observations \cite{osterbroek2001,piraino2011}. This feature is associated with the reflection of hard photons from the inner region of the accretion disc. \cite{piraino2013} have found that the relativistic reflection is produced at a radius of \( \sim 10 R_g \) and the inclination angle of the system is consistent with \( \sim 35^\circ \). However, \cite{piraino2012} inferred an inner disc radius \( \sim 25 R_g \) and a disc inclination of \( 35^\circ < i < 44^\circ \) during the fainter phase of the source.

Broadband energy coverage of the \textit{NuSTAR} \cite{harrison2013} observation of the source GX 3+1 allows us to study the source broadband spectrum and to constrain the reflection component properties such as the broad Fe emission line along with the Compton hump. These studies are important to infer the properties of the accretion flow close to the NS. In this paper, we report on a detailed study of the reflection features and the fit, with a self-consistent reflection model. In this way, this study allows us to constrain the stellar radius and/or inner accretion disk radius. We also comment on the geometry of the boundary layer between the accretion disc and the stellar surface. We organize the paper in the following way. First, we describe the observations and the details of data reduction in sec. 2. In sec. 3 and sec. 4, we describe the temporal and spectral analysis, respectively. Finally, in sec.5, we discuss our findings.

2 \textbf{OBSERVATION AND DATA REDUCTION}

The source GX 3+1 was observed with \textit{NuSTAR} on 2017 October 17 (MJD 5804.3731) for a total exposure time of \( \sim 13.7 \text{ ks} \) (Obs. ID: 30363001002). \textit{NuSTAR} data of the source GX 3+1 were collected with the two co-aligned grazing incidence hard X-ray imaging telescopes (FPMA and FPMB) in the 3 – 79 keV band.

We reprocessed the data using the standard \textit{NuSTARDAS} data analysis software (\textit{NuSTARDAS v1.7.1}) and \textit{CALDB (v20181030)}. We used the \texttt{nupipeline} (version v 0.4.6) to filter the event lists. We used a circular region with a radius of 100 arcsec to extract the source events. We also extracted background events from the corner of the detectors devoid of any sources using circular region of similar size as the source region. We employed the task \texttt{nuproduct} to create lightcurve, spectra and response files for the FPMA and FPMB. We grouped the FPMA and FPMB spectral data with a minimum of 100 counts per channel and fitted the two spectra simultaneously.

3 \textbf{TEMPORAL ANALYSIS}

Left panel of Figure 1 shows the 3–79 keV \textit{NuSTAR}/FPMA light curve of GX 3+1 with a binning of 100 sec and spans \( \sim 14 \text{ ks} \). The source was detected at an average intensity of \( \sim 200 \text{ counts s}^{-1} \). No X-ray bursts were observed during this observation. We also extracted the 3–8 keV and
8 – 20 keV light curve separately with 100 s bins and produced the corresponding hardness ratio (HR) which is displayed in the right panel of Figure 1. The HR value, which is a measure of the spectral shape, stayed quite constant at ∼ 0.28 after 5 ks from the beginning of the observation. It suggests that the spectral shape of the source is stable during the whole span of the observation. In Figure 2 we show the hardness intensity diagram (HID), in which the HR (3 – 8 keV and 8 – 20 keV) is plotted as a function of the source intensity (3 – 20 keV). In this observation, we found that HR is positively correlated with intensity for this source. In the case of atoll sources, the positive correlation between the hardness and the intensity is characteristic to the banana branch (Asai et al. 1993; Hasinger & van der Klis 1989). This means that the source stayed in the banana branch during this observation. Our HID and the conclusion based upon this is consistent with that of Asai et al. (1993) where they calculated HID with the Ginga/Large Area Counter (LAC) data with the almost similar definition of hardness ratio and intensity as mentioned above (see Figure 2 of Asai et al. 1993). However, it may be noted that the island state has so far not been observed from GX 3+1.

4 SPECTRAL ANALYSIS

We fitted the FPMA and FPMB spectra simultaneously as initial fits revealed a good agreement between these two spectra. We performed the fit over the 3 – 70 keV energy band using XSPEC v. 12.9. A constant was floated between the spectra to account for uncertainties in the flux calibration of the detectors. The constant was set 1 for FPMA and left it free for FPMB. A value of 1.02 was measured for FPMB. For each fit, we included the tbabs model to account for interstellar absorption along the line of sight. Abundances was set to wilm (Wilms et al. 2000) and cross-section with vern (Verner et al. 1996). We fix the absorption column density to the Dickey & Lockman (1990) value of $1.16 \times 10^{22}$ cm$^{-2}$ as the NuSTAR data only extend down to 3 keV and found it difficult to constrain from our spectral fits. All the errors in this work are quoted at 90% confidence level unless otherwise stated.

4.1 Continuum modeling

For NS LMXBs in their soft states, the X-ray spectra above 7 keV are typically modelled as either a hot (23 keV) black body or thermal Comptonization. We fitted 3 – 70 keV NuSTAR continuum to a model consisting of a disc blackbody component (diskbb in XSPEC) and a single-temperature blackbody component (bbody in XSPEC). This model can be simply interpreted in terms of emission from the accretion disc and boundary layer between the accretion disc and the NS surface. This combination of models gave a particularly poor fit ($\chi^2$/dof=2481/850) because of the presence of the strong disc reflection features in the spectrum which is evident in Figure 3. Emission from the boundary layer can also be modelled via low-temperature, optically thick Comptonization. To test this, we replaced the single-temperature blackbody component by the Comptonization model comptt (Titarchuk 1994).
But in this combination of models, the \texttt{compTT} parameters are poorly constrained, particularly seed photon temperature and optical depth have taken some arbitrary large values. We note that for the earlier continuum model \texttt{tbabs}(diskbb+bbody) all the continuum parameters are well constrained and thus we continued with this continuum model. We added a power-law component with the existing continuum model as this combination of spectral models, \texttt{tbabs}(diskbb+bbody+powerlaw), is also frequently used for the soft state spectra of many NS LMXBs \cite{Cackett2010, Lin2007}. However, the addition of the power-law component was found to be statistically insignificant. Therefore, we proceeded with the simpler continuum model \texttt{tbabs}(diskbb+bbody) as it describes the continuum fairly well and this combination of models have been widely used to fit the spectra of different NS LMXBs \cite{Cackett2010, Lin2007}. We have shown the fitted continuum model \texttt{tbabs}(diskbb+bbody) and the \( \chi \) residuals in Figure 3.

4.2 Reflection Model

The continuum model consisting of a disk blackbody and a single-temperature blackbody left large positive residuals around \( \sim 5 - 8 \) keV and \( 10 - 20 \) keV (see Figure 3). The broad feature \( \sim 5 - 8 \) keV is consistent with Fe K\( \alpha \) emission and the flux excess in the \( 10 - 20 \) keV is the corresponding Compton back-scattering hump. As these features are the clear signature of disk reflection, we proceeded by modeling our data with physical reflection models. We employed \texttt{reflionx} \cite{Ross2005} model which describes reflection from an ionized disc.

Our broadband continuum fits prefer a blackbody model over a Comptonized model to describe the spectrum at higher energies. Moreover, it is clear in Figure 3 that most of the flux capable of ionizing Fe comes from the blackbody component. We therefore included a modified version of the \texttt{reflionx} model that assumes the disc is illuminated by a blackbody, rather than a power law (see e.g. \cite{Cackett2010, King2016, Degenaar2016}). The parameters of the \texttt{reflionx} model are as follows: the disc ionization parameter \((\xi)\), the iron abundance \((N_{\text{Fe}})\), the temperature of the ionizing black body flux \(kT_{\text{ref}}\), and a normalization \(N_{\text{ref}}\). We convolved \texttt{reflionx} with \texttt{relconv} \cite{Dauser2010} in order to account for relativistic Doppler shifts and gravitational redshifts. The emissivity of the disk in the model \texttt{relconv} is described as a broken powerlaw in radius (e.g., \( r \propto r^{-3} \)), giving three parameters: inner emissivity index \((q_{\text{in}})\), outer emissivity index \((q_{\text{out}})\), and break radius \((R_{\text{break}})\). Here we used a constant emissivity index (fixed slope) by fixing \( q_{\text{out}} = q_{\text{in}} \) (obviating the meaning of \( R_{\text{break}} \)) as the slope is not constrained by the data. The fit parameters of the \texttt{relconv} model are as follows: the emissivity index \((q)\), the inner and outer disk radius \(R_{\text{in}}\) and \(R_{\text{out}}\), the disk inclination \((i)\) and the dimensionless spin parameter \((a)\).

We introduced a few reasonable conditions when making fits with \texttt{reflionx} and \texttt{relconv}. We set the emissivity to \( q = 3 \), in agreement with a Newtonian geometry far from the NS \cite{Cackett2010}. Following \cite{Braje2004}, the dimensionless spin parameter \( a \) can be approximated as \( a \approx 0.47/P_{\text{ms}} \) where \( P_{\text{ms}} \) is the spin period in ms. But the spin period of the source GX 3+1 is not known. The fastest known NSs spin at \( \sim 1.5 \) ms which corresponds to \( a \approx 0.3 \) \cite{Galloway2008}. The innermost stable circular orbit (ISCO) is then located at

\[
E_{\text{ISCO}} = 5\,\text{keV}
\]

Figure 3. NuSTAR (FPMA in black, FPMB in red) unfolded spectra. The spectral data were rebinned for visual clarity. Continuum is fitted with the model consisting of a multicolour disk blackbody and a single temperature blackbody. Model used: \texttt{TBabs}\times(diskbb+bbody). It revealed un-modelled broad emission line \( \sim 5 - 8 \) keV and a hump like feature \( \sim 10 - 20 \) keV. The prominent residuals can be indentified as a broad Fe-K emission line and the corresponding Compton hump. The red wing of the Fe-K emission line extends down to \( \sim 5 \) keV while the blue wing drops \( \sim 7 \) keV.
$R_{\text{ISCO}} = 5.05 R_g$, where $R_g = GM/c^2$ is the gravitational radius [Degenaar et al. 2016a]. For $a = 0$ the position of the ISCO is at $R_{\text{ISCO}} = 6 R_g$. Thus there is a small shift in the position of the ISCO compared to the Schwarzschild metric ($a = 0$). We performed the fit with $a = 0$ as well as $a = 0.3$. We note that both the fit yielded similar results as expected. We also fixed the outer radius $R_{\text{out}} = 1000 R_g$. Further, we fixed the $A_F$ to unity (compatible with the solar value) as the fit was almost insensitive to this parameter.

The addition of the relativistic reflection model improved the spectral fits significantly ($\chi^2/\text{dof}=899/845$). The best-fit parameters for the continuum and the reflection spectrum are shown in Table 1. Our fits suggest that the inner disc is located close to the NS at $R_{\text{in}} = (1.2 - 1.8) R_{\text{ISCO}} (\approx 6.1 - 9.1 R_g$ or $14 - 20.5$ km). The inclination angle is found to be $i = 24 \pm 2$ degree in agreement with the fact that neither dips nor eclipses have been observed in the light curve of GX 3+1. The reflection component has an intermediate disc ionization of $\xi \approx 151 - 236$ erg s$^{-1}$ cm which is the typical range observed in both black holes and NS LMXBs ($\log \xi \sim 2 - 3$). The fitted spectrum with relativistically blurred reflection model and the residuals are shown in Figure 4.

5 DISCUSSION

We report on the NuSTAR observation of the bright atoll type NS LMXB GX 3+1. The source was in a soft spectral state with the $3 - 70$ keV luminosity of $L_X \sim 2.84 \times 10^{37}$ ergs s$^{-1}$, assuming a distance of 6 kpc. This corresponds to $\sim 16\%$ of the Eddington luminosity, confirming predictions from the theoretical modelling of the X-ray spectra of bright sources like GX 3+1 (Psaltis & Lamb 1998). From the hardness-intensity diagram (HID), it is confirmed that the source was in the so-called banana branch during the present observation. The broad-band $3 - 70$ keV NuSTAR spectral data can be described by a continuum model consisting of a disk blackbody ($kT\text{disk} \sim 1.8$ keV) and a single temperature blackbody model ($kT\text{bb} \sim 2.7$ keV). Thermal emission from the accretion disc is prominently detected in the X-ray spectrum. The hot blackbody emission provides most of the hard X-ray flux that illuminates the accretion disc and produces the reflection spectrum. The spectral data required a significant reflection component, characterized by the broad Fe-K emission line $\sim 6 - 7$ keV and a Compton hump around $10 - 20$ keV. Studying reflection spectra provides valuable insight into the accretion geometry, such as the inner radius of the accretion disc, inclination of the accretion disk and height of the illuminating X-ray source.

5.1 Inner radius and the inclination of the accretion disc

We fitted the reflection features with a relativistically blurred reflection model reflionx to investigate the accretion geometry of GX 3+1. It is generally believed that in the soft X-ray spectral state when the luminosity of the source is $\geq 10\%$ of the Eddington limit, the accretion disc extends to/near the ISCO (e.g. Esin et al. 1997). We found that the inner edge of the accretion disc extended inwards to $R_{\text{in}} = (1.2 - 1.8) R_{\text{ISCO}}$. Given that $R_{\text{ISCO}} \approx 5.05 GM/c^2$ for a NS spinning at $a = 0.3$, this would correspond to
Figure 5. Left panel shows the variation of $\Delta \chi^2 (= \chi^2 - \chi^2_{min})$ as a function of disk inclination angle obtained from the relativistic reflection model. We varied the disc inclination angle between 10 degree and 35 degree. Right panel shows the variation of $\Delta \chi^2 (= \chi^2 - \chi^2_{min})$ as a function of inner disc radius (in the unit of $R_{ISCO}$) obtained from the relativistic reflection model. We varied the inner disc radius as a free parameter up to $2.5 R_{ISCO}$. Horizontal lines in both the panels indicate 2σ and 3σ significance level.

$R_{in} = (6.1 - 9.1) R_g$ or $(14 - 20.5)$ km for a $1.5 M_\odot$ NS. The inferred inner disc radius is consistent with high luminosity implied during this observation. Similar inner disc radius is also obtained by Ludlam et al. (2017) and Degenaar et al. (2016a) when they analyzed the NuSTAR spectra of NS LMXB Aquila X-1 and IRAX J180408.9 – 342058, respectively in their soft spectral states. Moreover, our estimated inner disc radius for GX 3+1 is within the range obtained for several other NS LMXBs ($R_{in} \simeq 5 - 20 G M/c^2$; see Cackett et al. 2010, Degenaar et al. 2015, Di Salvo et al. 2012, Miller et al. 2011, Papitto et al. 2013).

We compared the inner disc radius from the Fe line fitting with that implied from the diskbb fits. The normalization component of the diskbb is defined as $N_{diskbb} = (R_{in, diskbb}/D_{10})^2 \cos i$ (where $R_{in, diskbb}$ in km and $D_{10}$ is the distance in units of 10 kpc), which can be used as an important probe to constrain the inner radial extent of the accretion disk. Different correction factors such as inner boundary assumptions (Gierliński et al. 1999), spectral hardening (Merloni et al. 2000), absolute flux calibration of the instrument or the spectral model need to be taken into account to calculate the true inner disk radii from diskbb fits. From our best fit diskbb normalization, we obtained an inner disk radius of $R_{in, diskbb} \simeq 4.3 - 5.3$ km for an inclination of $i = 22 - 26$ degree and distance of 6 kpc. However, if we corrected it with the hardening factor $\simeq 1.7$ (e.g. Kubota et al. 2001, Reynolds & Miller 2013), then it yielded $R_{in, diskbb} \simeq (12.5 - 15.4)$ km. This is consistent with the location of the inner disc inferred from our reflection fits ($R_{in} = 14 - 20.5$ km).

We found that the inner disc has a relatively low viewing angle ($i \approx 24$ degree). It is consistent with the fact that neither dips nor eclipses have been observed in the light curve of GX 3+1. This lower value of the disc inclination is also consistent with Pintore et al. (2015) and Piraino et al. (2012).

5.2 Mass accretion rate

From the persistent flux ($F_p$) and the distance ($d$) of the source, we can also estimate the accretion rate ($\dot{m}$) per unit area at the NS surface (Galloway et al. 2008). Here we used equation 2 of Galloway et al. (2008).

\[
\dot{m} = 6.7 \times 10^7 \left( \frac{F_p c_{bol}}{10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}} \right) \left( \frac{d}{10 \text{ kpc}} \right)^2 \left( \frac{M_\odot}{1.4 M_\odot} \right)^{-1} \times \left( \frac{1 + z}{1.31} \right) \left( \frac{R_{NS}}{10 \text{ km}} \right)^{-1} \ \text{g cm}^{-2} \text{ s}^{-1},
\]

where $c_{bol}$ is the bolometric correction which is $\approx 1.38$ for the nonpulsing sources (Galloway et al. 2008). $M_{NS}$ and $R_{NS}$ are the NS mass and radius, respectively. $z$ is the surface redshift and $1 + z = 1.31$ for a NS with mass 1.4 $M_\odot$ and radius 10 km. We determine the mass accretion rate using $F_p = 0.66 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ to be $\sim 5.1 \times 10^{-9} M_\odot$ y$^{-1}$ during this observation. This inferred value of $\dot{m}$ is consistent with den Hartog et al. (2003) and Kuikers & van der Klis (2006). Moreover, it is consistent when the source is in the banana branch.

5.3 Geometry of the boundary layer

Our upper limits on $R_{in}$ suggests that the disc is truncated substantially above the NS surface itself. It allows us to consider that the disc may be truncated by a boundary layer extending from the stellar surface (Ludlam et al. 2017). Equation (2), given by Popham & Sunyaev (2001), provides a way to estimate the maximum radial extent ($R_{max}$) of the bound-
The outer radius of the reflecton spectral component was fixed to 1000 $R_G$ and the spin parameter was set to $a = 0.3$ and $q = 3$. Iron abundance ($A_F$) was set to 1. $^a,^b$ denotes the normalization component of the bbody and reflecton model, respectively. Assumed a distance of 6 kpc and a mass of $1.5 M_{\odot}$ for calculating the luminosity. $^*$ All the fluxes are calculated in the energy band 3.0 – 79.0 keV.

5.4 NS radius constraints

If the disc extends closer to the surface of the NS, then the reflection modelling can be used to place constraints on the NS radius. Reflection modelling permit us to put a lower limit on the gravitational redshift from the NS surface. Gravitational redshift is given by $1 + z = 1 / \sqrt{1 - 2GM/R_{\text{NS}}^2}$. For $R_{\text{NS}} = 1.5 R_{\text{ISCO}} (\approx 7.6 G M/c^2)$, implied by our reflection fit would constrain the NS radius to $R_{\text{NS}} \lesssim 17$ km, hence the gravitational redshift to $z \geq 0.16$ for an assumed mass of $M = 1.5 M_{\odot}$. Our measurement for $R_{\text{in}}$ does extend down to $1.2 R_{\text{ISCO}}$. If this were the case, then it would constrain the NS radius to $R_{\text{NS}} \lesssim 13.6$ km for the gravitational redshift $z \geq 0.22$. This constraint on the radius of the NS is consistent with the result obtained from the analysis of the type-I X-ray bursts [den Hartog et al. 2003].

5.5 Magnetic field strength

The inner part of the accretion disc may have also been truncated by the associated magnetic field of the NS. We can thus use our measured inner disc radius from the reflection fit to estimate an upper limit of the magnetic field strength of the NS. We used the following equation of Cackett et al. (2009), which was a modified version of the formulation of Ibrahimov & Poutanen (2009) to calculate the magnetic dipole moment.

$$
\mu = 3.5 \times 10^{23} k_A^{-7/4} \bar{z}^{7/4} \left( \frac{M}{1.4 M_{\odot}} \right)^2 \times \left( \frac{\eta}{f_{\text{ann}}} \right) \left( \frac{F_{\text{bol}}}{10^{-9} \text{erg cm}^{-2} \text{s}^{-1}} \right)^{1/2} \frac{D}{3.5 \text{kpc}} \text{G cm}^3
$$

where $\eta$ is the accretion efficiency in the Schwarzschild metric, $f_{\text{ann}}$ is the anisotropy correction factor. The coefficient $k_A$ depends on the conversion from spherical to disk accretion (numerical simulation suggest $k_A = 0.5$ whereas theoretical model predict $k_A < 1.1$). Cackett et al. (2003) modified $R_{\text{in}}$ as $R_{\text{in}} = x GM/c^2$. We estimated flux in the $0.01 – 100$ keV range (extrapolating NuSTAR spectral

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Table 1. Best-fit spectral parameters of the NuSTAR observation of the source GX 3+1 using model: TBabs × (diskbb + bbody + reflecton × reflionx).

| Component | Parameter (unit)                  | Value |
|-----------|-----------------------------------|-------|
| TBABS     | $N_H (10^{22} \text{cm}^{-2})$   | 1.16(f) |
| DISKBB    | $kT_{\text{disc}}$ (keV)         | 1.53±0.13 |
|           | $N_{\text{diskbb}} [(\text{km}/10 \text{ kpc})^2 \text{cos}]$ | 58±11 |
| BBODY     | $kT_{\text{bb}}$ (keV)           | 2.03 ± 0.08 |
|           | $N_{\text{bb}}$ ($10^{-2}$)     | 3.44 ± 0.45 |
| RELCONV   | $i$ (degrees)                    | 24 ± 2 |
|           | $R_{\text{in}} (\times R_{\text{ISCO}})$ | 1.51±0.24 |
| REFLIONX  | $\xi$ (erg cm$^{-1}$)           | 191±45 |
|           | $kT_{\text{refl}}$ (keV)         | 2.60±0.10 |
|           | $N_{\text{refl}}$ $^b$           | 2.48±0.22 |
|           | $F^*_{\text{total}}$ ($10^{-8}$ ergs/cm$^2$) | 0.66 ± 0.01 |
|           | $F_{\text{diskbb}}$ ($10^{-8}$ ergs/cm$^2$) | 0.31 ± 0.01 |
|           | $F_{\text{bbody}}$ ($10^{-8}$ ergs/cm$^2$) | 0.28 ± 0.01 |
|           | $F_{\text{refl}}$ ($10^{-8}$ ergs/cm$^2$) | 0.07 ± 0.01 |
|           | $L_{3-79\text{keV}}$ ($10^{-37}$ ergs/s) | 2.84 ± 0.01 |

The height of the ionizing source above the disc is defined as

$$Z^2 = \frac{L_{\text{BL}}}{n_e \xi} - R_{\text{in}}^2,$$

where $L_{\text{BL}}$ is the boundary layer luminosity, $n_e$ is the electron density, $\xi$ is the ionization parameter and $R_{\text{in}}$ is the inner accretion disc radius. From spectral fitting and reflection modelling we determine $L_{\text{BL}}$, $\xi$ and $R_{\text{in}}$. We estimated $n_e$ of the accretion using the relation $\xi = L_X / (n_e r^2)$. Since we find that $L_X \approx 2.84 \times 10^{37}$ ergs s$^{-1}$, we obtain $n_e \sim 0.51 \times 10^{23}$ cm$^{-3}$ following $r = 17$ km and $\xi = 191$ erg cm$^{-1}$ (best-fit values). Thus, for $\xi = (151–236)$ erg cm$^{-1}$, $L_{\text{BL}} \sim 1.28 \times 10^{37}$ ergs s$^{-1}$ and $R_{\text{in}} = (14–20.5)$ km, we find $Z = (9.5 – 15)$ km which is equivalent to $(4.2–6.8 R_g)$. The small height of the ionizing source inferred from our reflection fit could refer to the boundary layer between the accretion disc and the NS surface as the primary source of the illuminating hard X-rays (see Sanna et al. 2013; Degenaar et al. 2012).

We now further examined the conception that the boundary layer is the source of ionizing flux. We determined the maximum height of the boundary layer for a disc extending close to the NS surface. Following Equation (6) of Cackett et al. (2010), the height of the ionizing source above the disc is defined as
fit) is of \( F_{\text{bol}} = 7.97 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \). We assumed \( D = 6 \text{ kpc}, M = 1.5 M_\odot \) and \( R = 10 \text{ km} \). Using \( R_{\text{in}} \leq R_9 \) from the NuSTAR spectral fit, along with the assumptions \( k_A = 1, f_{\text{ang}} = 1 \) and \( \eta = 0.1 \), leads to magnetic field strength of \( B \leq 6 \times 10^9 \text{ G} \) at the magnetic poles. Moreover, if we assume \( k_A = 0.5 \) \citep{Long2003}, then the magnetic field strength at the poles would be \( B \leq 2 \times 10^8 \text{ G} \).

**POSTSCRIPT**

After completing this manuscript, it has come to our notice that the same NuSTAR observation (Obs. ID: 30363001002) of this source along with some other sources have also been analysed by \cite{ludlam2019}.

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