XMM-Newton observations of the ultraluminous X-ray source NGC 1313 X-1

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Abstract. Ultraluminous X-ray sources (ULXs) are extra-galaxtic, non-nuclear sources with the X-ray luminosity in excess of the Eddington limit for a $10M_{\odot}$ black hole. Although some ULXs could be candidates for intermediate mass black holes accreting matter at sub-Eddington rate, it is thought that the majority population of ULXs are stellar mass black holes accreting matter at super-Eddington state. In this work, we examine the high quality X-ray spectra of the ULX NGC 1313 X-1 observed by *XMM-Newton*. The modeling results suggest that the data could be explained well using the super-Eddington model. Moreover, the X-ray spectral evolution of the ULX could be explained successfully in the context of accretion in the super-Eddington state.

1. Introduction

Ultraluminous X-ray sources (ULXs) are extra-galactic X-ray point sources with the observed X-ray luminosity ($L_{\rm X}$) in excess of the Eddington limit for $10M_{\odot}$ black hole ($L_{\rm X} > 10^{39}$ erg s^{-1}) [1]. Although some ULXs remain good candidates for intermediate mass black holes accreting material at sub-Eddington rate [2], currently, it is thought that the majority of ULXs are stellar mass black hole which are accreting material at super-Eddington state [3, 4]; indeed, this is the state in which the outward radiation pressure exceeds the inward gravitational force. The studies of ULX X-ray spectra have been active for the last two decades. It has been shown that the ULX spectra presenting *an ultraluminous state* would compose of two components in which the higher energy component could pronounce the curvature called *high energy curvature* [3, 5]. Later, Sutton et al. 2013 [4] have proposed that the super-Eddington ULX spectra could be classified into three regimes: (i) single component, broadened disc spectra, (ii) two component, hard ultraluminous state and (iii) two component, soft ultraluminous state (see fig. 1 of reference [4]). NGC 1313 X-1 is one of the nearby (d ∼3.7 Mpc) and bright ULXs [3]. Indeed, its spectra fall in regime of the hard ultraluminous state, and also show the variability with time [6]. Although it has been purposed that this ULX is the stellar mass black hole accreting matter at super-Eddington state [3, 5], the physical processes providing the source to accrete at this extreme rate are still unclear. Thus, ULX NGC 1313 X-1 is one of the good candidate for study. In this work, we will revisit the NGC 1313 X-1 data observed by *XMM-Newton* observatory. Here, the data will be obtained from the public data archive; by selecting only the highest quality data, the observed spectra will be analysed by the range of models in order to understand more the underlying physics of super-Eddington ULXs.

2. Observations and Data Reduction

We began searching for the ULX data from the *XMM-Newton* Science Archive[1]. As discussed in earlier studies (e.g. [3, 7]), some spectral feature such as the high energy curvature can be seen only in the good quality spectra; here, only on-axis observations (the source position is $<$ $1'$ off from focal point of the telescope) which the exposure time is $>$ 40 ks were selected as the basis for this study, in order to obtain the best quality spectra. The detail of observations used in this study is shown in Table 1.

We performed the data reduction and create the science products using the standard procedure following the *XMM-Newton* data analysis guide.[2] The source spectra were generated from the source extraction regions where the circular areas are centred at the position of NGC 1313 X-1 on the detectors; the radial size of the areas is shown in the column 4 of Table 1. The background spectra were generated from the $60''$ circular, source-free area where is on the same CCD chip (and the same off-axis angle if possible) to that of the source spectra. All spectra obtained from pn, MOS1 and MOS2 detectors[3] were grouped to have a minimum of 25 counts per bin to utilise the χ^2 minimisation method during spectral modeling. The total number of spectral bins from pn, MOS1 and MOS2 is shown in the column 5 of Table 1

Table 1. Observations and spectral properties of NGC 1313 X-1

Obs. ID	Obs. date	Exposure time (ks)	Extraction radius (arcmin)	Spectral bins	L_X (10^{39} erg s^{-1})
0106860101	2000-10-17	42.2	25	267	4.72
0693850501	2012-12-16	125.2	30	445	5.23
0693851201	2012-12-22	125.2	30	432	5.43
0742590301	2014-07-05	63.0	25	433	8.18

3. Spectral Analysis and Discussion

We started modeling the spectra using the simple double component model: multi-colour disc blackbody (MCD) plus power-law model (DISKBB + POWERLAW in XSPEC). This model is based on the assumption that the low energy spectral component is the emission from the standard accretion disc [8] whilst the high energy component could be represented by the power-law component. In fact, this model is successfully used to classify the ULX spectra observed by *XMM-Newton* into three spectral states: broadened disc, hard ultraluminous and soft ultraluminous [4]. The modeling results from this model are shows in Fig. 1 and Table 2. Indeed, the model seems to not provide a good statistic (the final reduce χ^2 ~1.09 – 1.38). However, using the ULX classification method proposed by the reference [4], the results from this model imply that the ULX spectra extracted from the observations 0106860101, 0693850501 and 0693851201 are in the hard ultraluminous regime whilst that is extracted from the observation 0742590301 is in the soft ultraluminous regime. We will discuss more about this later at the end of the section.

We then modified the two component model by replacing the power-law component with the Comptonisation model (COMPTT model in XSPEC). As suggested by the previous studies (e.g. references [3, 7]), the high energy spectral component could pronounce the curvature clearly seen in the good quality spectra, so that need the curved spectral component such as COMPTT to explain. In this model, we tied the corona seed photon temperature to the temperature of the MCD component. The modeling results are shown in Fig. 1 and Table 2; it is obvious that

[1] http://nxsa.esac.esa.int

[2] https://www.cosmos.esa.int/web/xmm-newton/sas-threads

[3] *XMM-Newton* has three X-ray detectors simultaneously operating during the observations.

Table 2. Spectral fitting results

Model parameter	Observation ID			
	0106860101	0693850501	0693851201	0742590301
	MCD + power-law model			
$N_{\rm H}$ (cm^{-2})	0.25 ± 0.04	0.28 ± 0.02	0.29 ± 0.02	0.38 ± 0.03
$T_{\rm in,MCD}$ (keV)	$0.21^{+0.03}_{-0.02}$	0.22 ± 0.01	0.20 ± 0.01	0.16 ± 0.01
$\Gamma_{\rm power-law}$	1.70 ± 0.07	1.77 ± 0.03	1.82 ± 0.03	2.34 ± 0.02
Reduced χ^2	1.09	1.18	1.15	1.38
	MCD + Comptonisation model			
$N_{\rm H}$ (cm^{-2})	$0.22^{+0.05}_{-0.04}$	0.25 ± 0.02	0.26 ± 0.02	0.20 ± 0.01
$T_{\rm in,MCD}$ (keV)	0.21 ± 0.03	0.22 ± 0.01	0.21 ± 0.01	$0.16^{+0.02}_{-0.01}$
$kT_{\rm e,Compton.}$ (keV)	$2.60^{+2.65}_{-0.55}$	$2.58^{+0.35}_{-0.24}$	$2.76^{+0.56}_{-0.33}$	$2.24^{+0.21}_{-0.16}$
$\tau_{\rm e,Compton.}$	$7.32^{+.166}_{-1.68}$	$7.13^{+0.60}_{-0.63}$	$6.59^{+0.65}_{-0.77}$	$5.89^{+0.34}_{-0.38}$
Reduced χ^2	1.08	1.11	1.11	1.14
	Blackbody + DISKPBB *model*			
$N_{\rm H}$ (cm^{-2})	$0.18^{+0.04}_{-0.03}$	0.19 ± 0.02	0.22 ± 0.01	0.27 ± 0.01
$kT_{\rm blackbody}$	0.18 ± 0.02	0.20 ± 0.01	0.18 ± 0.01	0.18 ± 0.01
$T_{\rm in,DISKPBB}$ (keV)	$5.99^{+1.22}_{-2.79}$	$3.72^{+0.46}_{-0.40}$	$5.50^{+0.49}_{-0.48}$	$2.37^{+0.09}_{-0.08}$
$p_{\rm DISKPBB}$	$0.55^{+0.03}_{-0.01}$	$0.57^{+0.02}_{-0.01}$	0.54 ± 0.01	≤ 0.50
Reduced χ^2	1.07	1.08	1.08	1.19

using the curved COMPTT component to fit with the spectral high energy component can help to improve the final statistic (reduce $\chi^2 \sim 1.08 - 1.14$ for this model). Interestingly, similar corona properties found in the previous ULX works using this model [3, 6, 9] were also obtained in our analysis; the Comptonising corona is optically thick ($\tau_{\rm e} \sim$ 6–7) and cool ($kT_{\rm e}$ ~2.5 keV). In fact, this corona behavior is in contrast with the nature of corona seen in Galactic black hole, in which it is optically thin ($\tau_{\rm e} \lesssim 1$) and hot ($kT_{\rm e} \gtrsim$50 keV). Although the previous work [3] has explained physically this corona behavior in the context of super-Eddington accretion in which the material is blown off in form of an outflowing wind forming the optically cool and thick corona, this is inconsistent with the results from theoretical and simulation-based works which study on accretion in supercritical regime (e.g. [10, 11]); indeed, the studies suggest that the spectral high energy component might be the emission from the hot accretion disc with a large colour correction, instead of the corona.

Finally, we alternatively modeled the ULX spectra using a super-Eddington model; here we used a simple blackbody emission model (BB) to represent the emission from the putative outflowing wind whilst the direct emission from the inner part of the disc is represented by the DISKPBB component. In brief, the DISKPBB is the MCD model in which the exponent of the radial dependence of the disk temperature – parameter p – can be varied.[4] Although we found that the model does not improve significantly the fitting results comparing to the previous MCD plus Comptonisation model (see Fig. 1 and Table 2), the physical interpretation extracted from the model is consistent with the theoretical prediction; in fact, the parameter p obtained from the DISKPBB component is constrained to be ~0.5, consistent with the prediction that ULXs have a slim accretion disc geometry [12]. Moreover, as this model could explain well the ULX spectra, we used this model to study the spectral variability with the ULX luminosity. The best fitted spectra obtained from the model are plotted in Fig. 2. It is clear that as the luminosity increases, the spectra change from the hard ultraluminous spectrum to the soft ultraluminous spectrum. This could be explained in the context of super-Eddington model [11] in which, assuming that the NGC 1313 X-1 is observed at high inclination angle, increasing in the mass

[4] see more on https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node164.html

accretion rate could also increase the degree that the high energy photons from the inner disc would be obscured by the outflowing wind, resulting in softer spectra and the drop in the number of high energy photons as luminosity increases [13].

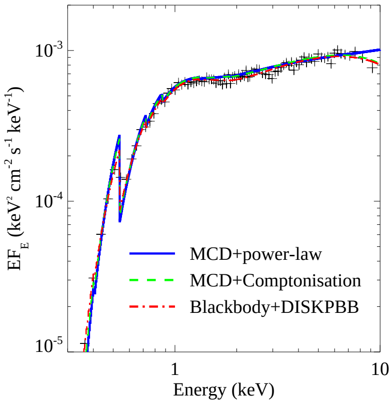

Figure 1. The comparison of simulated spectra from each model best fitting to the observation 0693850501 spectrum.

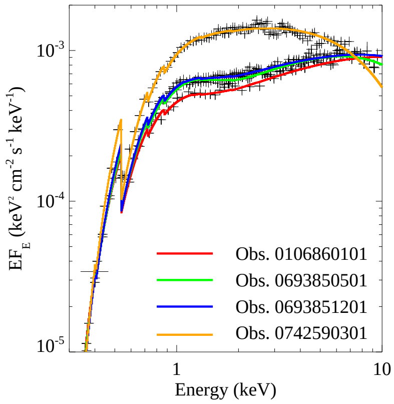

Figure 2. The evolution of the X-ray spectra with X-ray luminosity obtained from the blackbody + DISKPBB model.

4. Conclusion

In this work, we analysed the X-ray spectra of the ULX NGC 1313 X-1 using the best quality data observed by *XMM-Newton* observatory. The range of models were used to fit with the data. We show that the MCD plus power-law model cannot explain the spectra well; in contrast, both MCD plus Comptonisation model and BB plus DISKPBB model can explain the ULX spectra equally well. However, we argue that the MCD plus Comptonisation model does not provide the reasonable physical interpretation since it suggests that the ULX corona is optically thick and cool. Therefore we purpose that the BB plus DISKPBB model gives more realistic interpretation in which it implies that the ULX is super-Eddington accretor. In fact, the super-Eddington model supports well the behavior of spectral variability seen in this object.

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