

Unveiling the disc structure in ultraluminous X-ray source NGC 55 ULX-1

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ABSTRACT

Ultraluminous X-ray sources (ULXs) are the most extreme among X-ray binaries in which the compact object, a neutron star or a black hole, accretes matter from the companion star, and exceeds a luminosity of 10^{39} erg s^{−1} in the X-ray energy band alone. Despite two decades of studies, it is still not clear whether ULX spectral transitions are due to stochastic variability in the wind or variations in the accretion rate or in the source geometry. The compact object is also unknown for most ULXs. In order to place constraints on to such scenarios and on the structure of the accretion disc, we studied the temporal evolution of the spectral components of the variable source NGC 55 ULX-1. Using recent and archival data obtained with the XMM-Newton satellite, we modelled the spectra with two blackbody components which we interpret as thermal emission from the inner accretion flow and the regions around or beyond the spherization radius. The luminosity–temperature (L – T) relation of each spectral component agrees with the $L \propto T^4$ relationship expected from a thin disc model, which suggests that the accretion rate is close to the Eddington limit. However, there are some small deviations at the highest luminosities, possibly due to an expansion of the disc and a contribution from the wind at higher accretion rates. Assuming that such deviations are due to the crossing of the Eddington or supercritical accretion rate, we estimate a compact object mass of 6–14 $M_{\odot}$, favouring a stellar-mass black hole as the accretor.

Key words: Accretion, accretion discs – X-rays: binaries – X-rays: individual: NGC 55 ULX-1.

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are empirically defined as bright, non-nuclear, point-like, mainly extragalactic sources with an X-ray luminosity $L_X > 10^{39}$ erg s^{−1} (Kaaret, Feng & Roberts 2017). They are brighter than the Eddington luminosity limit for a 10 $M_{\odot}$ black hole (BH) and can even reach luminosities in excess of 10^{41} erg s^{−1} in the canonical X-ray band (0.3–10 keV; Walton et al. 2021).

Many conjectures have been made to account for the high luminosity of these sources. Initially, ULXs were thought to be powered by black holes with masses greater than 10 $M_{\odot}$ and, potentially, intermediate-mass black holes (IMBHs, 10^2 – $10^5 M_{\odot}$; Miller, Fabian & Miller 2004) with the best IMBH candidate being HLX-1 (Webb

et al. 2012). An alternative scenario suggested stellar-mass black holes whose light was beamed along the line of sight (LOS) of the observer by a thick disc-wind cone (e.g. King et al. 2001; Poutanen et al. 2007). However, the discovery of coherent X-ray pulsations from M82 ULX-2 with NuSTAR provided unambiguous evidence in support of a ULX hosting a neutron star (NS; Bachetti et al. 2014). Other notable examples are NGC 7793 P13 and NGC 5907 ULX-1 with similar properties (Fürst et al. 2016; Israel et al. 2017). NGC 7793 P13, the second discovered pulsating ULX (or pULX), is also the only ULX for which an upper limit to the mass of the compact object was dynamically obtained (15 $M_{\odot}$; Motch et al. 2014). The pulsating source NGC 5907 ULX-1 reaches $L_X \sim 10^{41}$ erg s^{−1} (Fürst et al. 2017), which corresponds to 500 times the Eddington limit of a NS, *de facto* making it the brightest NS known. As of today, only 10 pulsating ULXs (including transient ULXs, see e.g. King et al. 2020 and references therein) are confirmed among the ~ 1800 ULXs known (Walton et al. 2021). However, the fraction of pulsating

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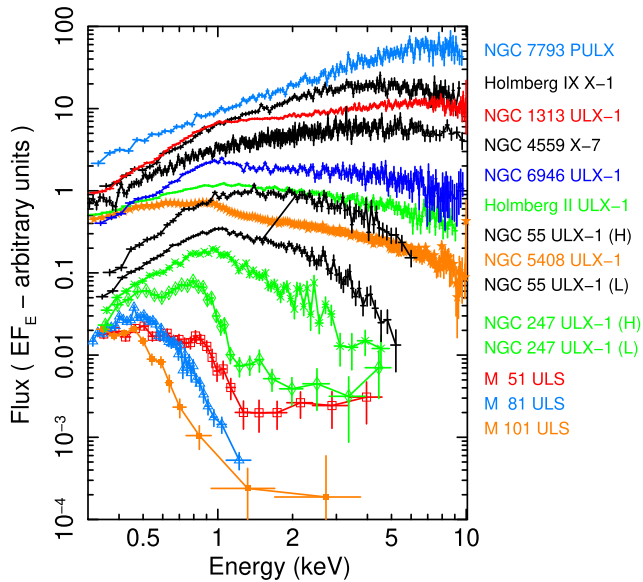


Figure 1. X-ray spectra of some brightest ULXs with the hardness increasing from the bottom to top. Note how the high- and low-flux spectra of NGC 55 ULX-1 link the ULX spectra with soft and intermediate hardness. Adapted from Pinto et al. (2017).

neutron stars might be higher in ULXs as only about 30 ULXs have data with sufficiently good quality to search for pulsations. This suggests that neutron stars might power $\gtrsim 30$ per cent of the nearby, bright, ULXs (see e.g. Rodríguez Castillo et al. 2020).

The so-called *ultraluminous state* (Gladstone, Roberts & Done 2009) is characterized by a strong curvature between 2 and 10 keV (e.g. Walton et al. 2020 and references therein), and often a soft excess below 2 keV (see Fig. 1). Sutton, Roberts & Middleton (2013) classified ULXs into three main regimes according to their spectral slope in the 0.3–10 keV band (soft ultraluminous/SUL for $\Gamma > 2$ or hard ultraluminous/HUL for $\Gamma < 2$). In the latter case, if the X-ray spectrum has a single peak and is dominated by a blackbody-like component in the 2–5 keV band, it is classified as in the broadened disc (BD) regime. ULXs often switch between different spectral regimes (Walton et al. 2020). The presence of the low-energy spectral turnover rules out models of sub-Eddington accretion on to intermediate mass black holes because the temperature of the soft component would require black hole masses of up to $1000 \text{ s } M_{\odot}$ with $\dot{M}$ (accretion rate) $\sim 0.01 \dot{M}_{\text{Edd}}$, which disagree with their soft spectra.

Short time-scales variability from seconds to hours has been observed in several ULXs (Heil, Vaughan & Roberts 2009) rarely associated to quasi-periodic patterns (Alston et al. 2021; Strohmayer & Mushotzky 2003; Strohmayer et al. 2007; Gúrpide et al. 2021) but is generally at a lower level than in sub-Eddington AGN and black hole X-ray binaries. Long-term variability is also observed on time-scales of a few months and could be associated with super-orbital motions due to precession and is most common in the HUL regime and, particularly, in pulsating ULXs (Walton et al. 2016; Fürst et al. 2018; Brightman et al. 2019; Gúrpide et al. 2021). Heil & Vaughan (2010) and De Marco et al. (2013) showed that the soft energy band lagged the hard band in the ULX NGC 5408 ULX-1 at frequencies of $\sim 10 \text{ mHz}$. More recently, very long soft lags of the order of a few ks were found in NGC 55 ULX-1, NGC 1313 ULX-1, and NGC 7456 ULX-1 which show a broad range of spectral hardness (Pinto et al. 2017; Kara et al. 2020; Pintore et al. 2020). The time lags range

between a few seconds to ks and it is not clear whether they are produced by the same mechanism. They could be produced by down scattering of hard X-ray photons through a thick disc wind cone in the LOS. In fact, super-Eddington accretion predicts the launch of powerful, relativistic ($\sim 0.1c$) winds (Takeuchi, Ohsuga & Mineshige 2013).

Evidence in support of winds in ULXs was found through the presence of strong, although unresolved, features at soft X-ray energies ($< 2 \text{ keV}$) in CCD low-resolution spectra (Strohmayer et al. 2007). Their time variability and correlation with the source spectral hardness suggested that they might be produced by the ULX itself in the form of a wind (Middleton et al. 2015b). This scenario was unambiguously confirmed through the first detection and identification of emission and absorption lines in the high-resolution XMM-Newton (here and after XMM)/RGS spectra of NGC 1313 ULX-1 and NGC 5408 ULX-1 (Pinto, Middleton & Fabian 2016). In particular, the line-emitting gas is generally close to rest (see e.g. Kosec et al. 2021) with some exceptions such as NGC 5204 ULX-1 ($v_{\text{LOS}} \sim 0.3c$; Kosec et al. 2018) and in NGC 55 ULX-1 ($0.01\text{--}0.08c$; Pinto et al. 2017). The absorption lines are highly blueshifted ($0.1\text{--}0.3c$). The ionization state increases with the outflow velocity and the source spectral hardness, which indicates a detection of hotter and faster phases coming from the inner region at lower inclinations (Pinto et al. 2020a).

An interesting sub-class of ULXs are ultraluminous supersoft sources (ULSs or SSUL regime). These objects are identified with X-ray spectra dominated by a cool blackbody-like component with $kT \sim 0.1 \text{ keV}$, a $\gtrsim 10^{39} \text{ erg s}^{-1}$ bolometric luminosity, and very little emission above 1 keV. The discovery of similar winds in archetypal, persistent, ULXs (Pinto et al. 2016) and very recently in NGC 247 ULX-ULS 1 (Pinto et al. 2021), and the presence of a variable hard X-ray tail in some ULSs suggested that they are similar super-Eddington accretors but viewed at a different angle with respect to the disc-wind cone. The fainter hard tail and strong variability such as the presence of dips in the light curves of ULSs may be the consequence of a higher inclination angle or a higher accretion rate and a thicker (and variable) wind in the LOS (see e.g. Urquhart & Soria 2016; Pinto et al. 2017; Alston et al. 2021; D’Ái et al. 2021).

Despite two decades of dedicated studies several open questions remain unanswered. *Are ULX spectral transitions driven by stochastic changes in the wind or variations in the accretion rate/geometry? What is the fraction of matter lost into the wind and therefore the net accretion rate on to the compact object? What is the fraction of NS-powered ULXs? ULXs which exhibit strong spectral variability are the ideal targets to tackle them.*

1.1 NGC 55 ULX-1

ULX-1 is the brightest X-ray source in the NGC 55 galaxy (see Fig. 2). At a distance of 1.94 Mpc ,¹ this source has an X-ray luminosity peak of about $4 \times 10^{39} \text{ erg s}^{-1}$ (see e.g. Gúrpide et al. 2021). The X-ray light curve exhibits sharp drops and 100 s-long dips, during which the source flux is quenched in the 2.0–4.5 keV band (Stobbart, Roberts & Warwick 2004). The spectrum is very soft (if modelled with a power law it yields a slope $\Gamma = 4$; Pinto et al. 2017) and similar to the brightest ULSs, but with a stronger hard tail above 1 keV. It is possible to see from Fig. 1 that the X-ray spectrum of NGC 55 ULX-1 fits just in between the spectra of bright ULSs and the soft-intermediate spectra of ULXs and therefore the source can

¹<https://ned.ipac.caltech.edu>

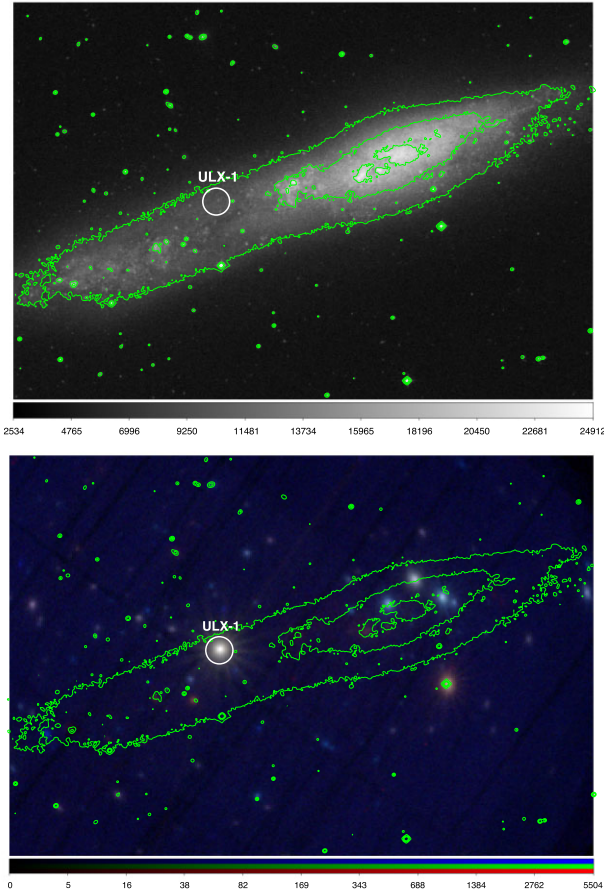


Figure 2. Upper panel: Optical image of NGC 55 obtained from the Digitized Sky Survey. Lower panel: False-colour RGB X-ray image obtained by extracting images in three energy bands (red 0.3–1 keV, green 1–2 keV, blue 2–10 keV) and stacking over all observations. The contours of the optical image are overlaid to show the ULX position in the galaxy.

be considered as a link between these subclasses of ULXs. NGC 55 ULX-1 is the ideal target for our study as it is very bright, has a spectral curvature above 1 keV similar to (although less severe than) ULXs and both broadband and wind properties are halfway between ULXs and soft-intermediate ULXs (see Pinto et al. 2020a). Moreover, its X-ray luminosity often crosses the 10^{39} erg s $^{-1}$ threshold, giving an opportunity to test disc structural changes around the Eddington limit, assuming the accretor is a stellar mass BH or a NS. Finally, its flux and spectral variability provide the workbench necessary to fit luminosity–temperature (L–T) trends and break model degeneracies.

In order to study the spectral variability of NGC 55 ULX-1 and the wind response to changes in the broadband flux, our team has requested and has been awarded with three full XMM orbits in different AOs (about 390 ks, PI: Pinto). The first observation occurred in 2018 and caught the source in a low state, while the two latter ones were triggered in 2020 and 2021 in order to obtain well-exposed RGS spectra during intermediate-high states. More detail on the triggering and the RGS analysis will be provided in a forthcoming paper.

This paper is the first in a series and will focus on the broadband spectral variability. This paper is organized as follows. In Section 2 we report the details on the observations, the spectral modeling in Section 3. In Section 4 we discuss our results and provide our conclusions in Section 5. All uncertainties are at 1σ (68 per cent level).

Table 1. Table of observations of the source NGC 55 ULX-1.

Obs. ID	Date	t_{tot} [s]	$t_{\text{net, EPIC-PN}}$ [s]	CR _{EPIC-PN} [c/s]
00287402012001-11-14		33 619	27 223	1.197 ± 0.007
00287401012001-11-15		31 518	24 718	0.578 ± 0.005
06550501012010-05-24		127 437	95 295	0.772 ± 0.003
08245701012018-11-17		139 800	90 733	0.513 ± 0.002
08526101012019-11-27		11 000	4079	1.10 ± 0.02
08526102012019-12-27		8000	4055	1.09 ± 0.02
08526103012020-05-11		9000	4909	0.422 ± 0.009
08526104012020-05-19		8000	3969	0.152 ± 0.006
08648101012020-05-24		132 800	102 158	0.707 ± 0.003
08839601012021-12-12		130 200	92 294	0.872 ± 0.003

t_{net} is the exposure time after the removal of periods with high solar flares and CR_{EPIC-PN} is the net source count rate.

2 OBSERVATIONS AND DATA REDUCTION

XMM-Newton observed NGC 55 ULX-1 ten times over a period of 20 yr. As we can see from Table 1, XMM-Newton observed NGC 55 ULX-1 six times with reasonably long (>30 ks) observations, which enabled us to study the evolution of the spectra over two decades. Four additional short (<10 ks net) observations were taken in the recent years. This permits us to probe both short-term (hours-days) and long-term (months-years) variability time scales.

The data were reduced with the SCIENCE ANALYSIS SYSTEM (SAS) version 18.0.0.² The raw data were obtained from the XMM-Newton Science Archive (XSA).³ We used recent calibration files (February 2021). We ran the *epproc* and *emproc* tasks to build the EPIC-PN and EPIC-MOS 1,2 event files, respectively. These are subsequently filtered for the flaring particle background. We chose the recommended cutting threshold in the light curves above 10 keV (count rate < 0.5 c/s for EPIC-PN and < 0.35 c/s for EPIC-MOS 1 and 2).

We extracted EPIC MOS 1-2 and PN images in three energy bands to create a false-colour RGB image (red 0.3–1 keV, green 1–2 keV, blue 2–10 keV).⁴ The images from the same energy band and different observations were stacked to increase the statistics. The final RGB mosaic is shown in Fig. 2 (bottom panel). ULX-1 is the yellow-white, brightest object, in the central-left region. Some fainter and harder (blue) X-ray binaries are present near the galaxy centre. The soft (red) source outside the galaxy contours is a field star in our Galaxy. Overlaid are the contours of surface brightness of the optical image obtained from the Digitized Sky Survey (DSS; top panel).⁵

We also extracted background-corrected light curves for ULX-1 and each individual observation after carefully selecting the source and the background regions using the *epiclccorr* task. For the source we selected a circular region of 0.5 arcmin radius centered on the *Chandra* X-ray estimated position (RA: $00^{\text{h}} 15^{\text{m}} 28.89^{\text{s}}$ DEC: $-39^{\circ} 13' 18.8''$), while for the background we chose a larger circular region a few arc minutes away from the source and avoiding contamination from the copper ring (wherever it was possible) in the same chip of the source region and away from of chip gaps. There might be a very small loss of counts in the observations, especially for Obs. ID: 0028740101, with the ULX-1 off-axis but this should be marginal given the softness of its spectra. Indeed, despite the larger

²<https://www.cosmos.esa.int/web/XMM-Newton>

³<https://www.cosmos.esa.int/web/XMM-Newton/xsa>

⁴<https://sites.google.com/cfa.harvard.edu/saomageds9>

⁵DSS, <https://irsa.ipac.caltech.edu/data/DSS/>

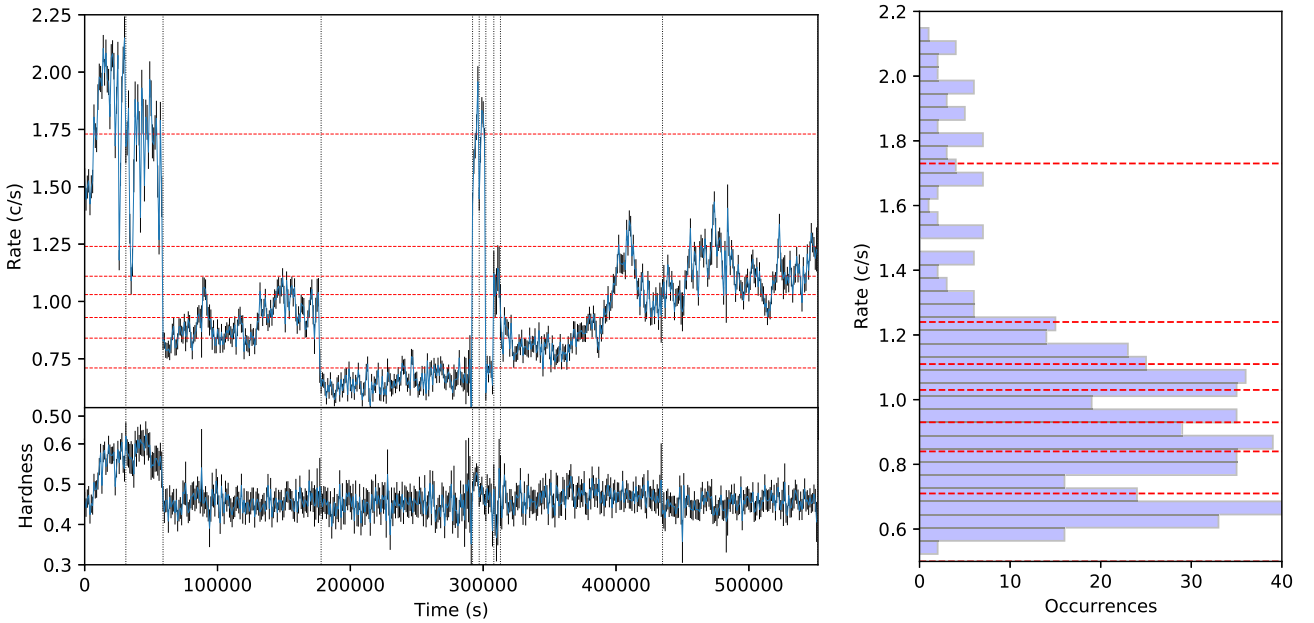


Figure 3. Left-hand panel: XMM EPIC-PN light curves (top left) of NGC 55 ULX-1 and hardness ratio (bottom left, defined as the 1–10 keV/0.3–10 keV counts ratio) from 2001 to 2021 with time bins of 1 ks. Vertical dotted lines separate the individual XMM observations, which have been attached for displaying purposes. Right-hand panel: Count-rate histogram. The horizontal red lines indicate the levels chosen to extract eight count-rate resolved spectra.

off-axis angle, its spectrum appears as the brightest and hardest (see Section 3.2).

The 0.3–10 keV EPIC-PN light curves of the individual observations were joined with PYTHON and shown in Fig. 3 (top left-hand panel). The XMM light curves confirm that the source flux changed dramatically as anticipated in Section 1. In the early XMM observations – when the source was brighter – the light curve exhibited flux dips lasting hundreds of seconds where its flux dropped by a factor of 2. In the top right-hand panel we also show the histogram of the count rate for the all-time light curve. In particular, defining the hardness ratio (HR) as the ratio between the counts in the 1–10 keV and the 0.3–10 keV energy band, respectively, we show that the HR is generally higher when the source is brighter and that decreases in proximity of the dips (Fig. 3 bottom left-hand panel).

We extracted EPIC PN and MOS spectra for each observation using the same source and background regions chosen for the light curves extraction. The *rmfgen* and *arfgen* tasks were used to generate response matrices and effective area files. The EPIC-PN spectra of all the observations are shown in Fig. 4.

The individual observations have exposure times which differ by up to an order of magnitude and do not show dramatic changes in the spectral hardness despite their substantial flux variability in agreement with the light curve. The spectra extracted for some observations are also nearly superimposable (see Fig. 4). In order to compare spectra with similar statistics, we also extracted spectra in ranges of count rate selected *ad hoc* according to the count rate histogram (see also Pinto et al. 2017). We split the XMM all-time light curve in eight regimes of count rate as shown in Fig. 3. These regimes were chosen in order to balance the total counts for each level (see Table 2 for more detail) and some spikes appearing in the count-rate histogram (Fig. 3, top right-hand panel). The count-rate selected spectra were then stacked among the different observations in order to obtain eight time-averaged flux-resolved spectra (one per EPIC camera). This selection criterion allows us to probe variability

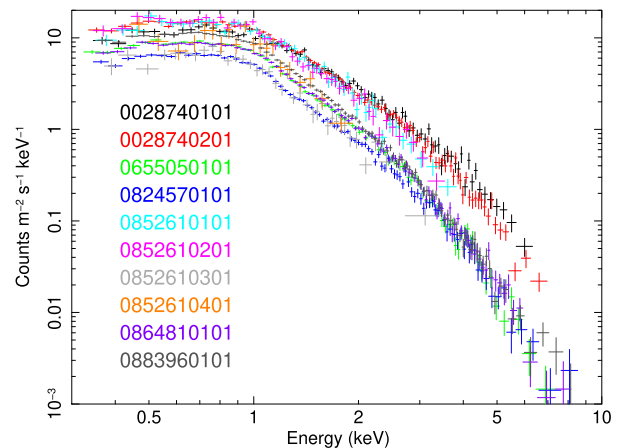


Figure 4. EPIC-PN spectra for all observations.

Table 2. Total counts and net exposure times of EPIC flux-selected spectra.

Range [c/s]	EPIC-PN Cnts	MOS1 Cnts	MOS2 Cnts	EPIC-PN Exp. [s]	MOS1 Exp. [s]	MOS2 Exp. [s]
0.50-0.71	38392	13274	13121	76795	95051	95322
0.71-0.84	43729	13977	14160	72282	84108	84206
0.84-0.93	43845	14728	14699	64371	79211	78945
0.93-1.03	41879	14215	13847	55327	66468	66286
1.03-1.11	42008	13816	13925	50550	61191	60917
1.11-1.24	40366	12964	13021	44413	53436	53513
1.24-1.73	31926	10640	10737	36211	42301	42391
1.73-2.25	29716	10735	10657	28954	32309	32332

mechanisms at different time scales. The flux-selected EPIC-PN spectra are plotted in Fig. 5.

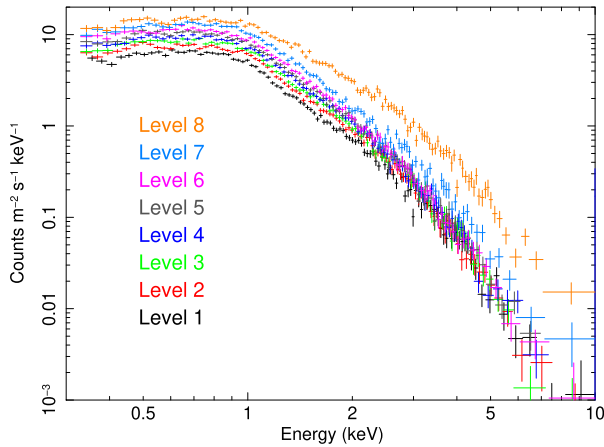


Figure 5. EPIC-PN spectra extracted for the eight flux-resolved interval.

3 SPECTRAL MODELLING

The spectra were modelled with the SPEX fitting package v3.06 (Kaastra, Mewe & Nieuwenhuijzen 1996). In order to use χ^2 statistics, we rebinned the EPIC PN and MOS 1,2 spectra with bins of at least 1/3 of the spectral resolution and with at least 25 counts using the SAS task *specgroup*. All emission components were corrected for absorption from the circumstellar and interstellar medium with the *hot* model (freezing the temperature of the gas to 10^{-4} keV, which provides a neutral gas in SPEX). For all emitting and absorbing plasma components we adopted the recommended Solar abundances of Lodders & Palme (2009) which are the default abundances in SPEX. The spectral models accounted for the source redshift as well ($z = 0.00043$).⁶ Each spectral model is fitted simultaneously to the EPIC MOS 1,2 and PN spectra as they overlap in the 0.3–10 keV energy band.

3.1 Testing different spectral models for Obs. ID 0655050101

It is common to use multiple thermal models (e.g. blackbody emission components) to reproduce ULX spectra (see e.g. Stobbart, Roberts & Warwick 2006; Pintore et al. 2015; Walton et al. 2018; Gúrpide et al. 2021). At first, we tested several models with the spectra from the observation 0655050101. On the one hand we wanted to compare the new SPEX code used for this spectral modelling with the previous versions and other codes, e.g. XSPEC or other SPEX versions, used in the recent years for the same source (see e.g. Pinto et al. 2017, Pintore et al. 2015). On the other hand, the comparison of the χ^2 values (and degrees of freedom or d.o.f.) from different spectral models constrains the best-fitting continuum model. Finally, we aimed at understanding the systematic effects when we have not modelled the features.

The spectral models that we tested were based on different combinations of the following continuum components: blackbody emission (*bb* model in SPEX), blackbody modified by coherent⁷ Compton scattering (*mbb*), multitemperature disc blackbody (*dbb*), and Comptonization of soft photons in a hot plasma (*comt*). The components used to fit emission and absorption lines are: Gaussian line (*gaus*), collisional-ionization equilibrium emission (*cie*), and

photoionization-equilibrium absorption (*xabs*; see SPEX manual for more details).

Here there is a summary of the models tested.

- RHB: simple blackbody emission (B) corrected for redshift (R) and neutral interstellar absorption (H).
- RHBB: two blackbody components are used to account for a different structure in the inner and outer regions of the accretion disc.
- RHBD: a cool blackbody describes the outer disc and a disc blackbody (D) reproduces the inner disc.
- RHBM: a modified blackbody model (M) describes the inner disc.
- RHBCom: a Comptonization emission is added to the RHB model.
- RHBMC: a *cie* emission model (C) is added to the RHBM model.
- RHBMCX: The *xabs* absorption model is added to the RHBMC.
- RHBMC(G): One or more Gaussian lines (G) are used to fit emission and absorption lines.

The first five models were primarily used to reproduce the broadband shape and continuum spectrum of the source. All the continuum models leave strong residuals around 1 keV (positive) and 0.7–0.8 keV and 1.2–1.3 keV (negative), see e.g. Fig. 6. These were resolved in groups of narrow lines with the high-resolution RGS spectrometers (Pinto et al. 2017, 2021).

The other 4 models mentioned above were therefore used to account for any wind features. The *cie* emission model was used mainly to describe the broad emission feature at around 1 keV, which is the most intense. CCD detectors cannot resolve the small velocity shift of the emission lines and we therefore considered the *cie* to be at rest. The dominant absorption component of the wind was found to be outflowing at $0.2c$ (Pinto et al. 2017) which is a shift large enough to be detected even with the EPIC detectors. However, we chose to fix the outflow velocity for the *xabs* absorption component to this value, in order to avoid model degeneracies with the ionization parameter ξ . Both absorption and emission lines were found to be narrow ($\sigma_v \lesssim 1000$ km s^{−1}) in RGS, which cannot be resolved by EPIC and therefore we adopted the default velocity dispersion of 100 km s^{−1} for the *cie* and *xabs* components (EPIC resolution $\gg 1000$ km s^{−1} around 1 keV). The Gaussian model provided an alternative phenomenological approach to measure the strength of the dominant spectral emission feature around 1 keV and the absorption features around 0.75 and 1.25 keV.

In Fig. 6 we show three representative examples of our fits for Obs. ID 0655050101 showing a single *bb* component continuum model (top panel), a *bb+mbb* model (middle panel) and a model which also accounts for wind emission lines (*bb+mbb+cie*, bottom panel). As expected, a single thermal component provided a very poor description of the spectral continuum. Two thermal models were able to fit the broadband shape, while the inclusion of the *cie* accounts for the dominant wind emission feature at 1 keV.

In Table 3 we report the results from our fits of Obs. ID 0655050101. Among all pure-continuum models the best-fitting one turned out to be the RHBM model, composed of a cool (~ 0.16 keV) blackbody and a hot (~ 0.7 keV) blackbody modified by coherent Compton scattering (see SPEX manual for more details), although comparable results were achieved by a hot disc-blackbody or Comptonization component. The results obtained with the RHBM model on the observation 0655050101 were fully consistent with Pinto et al. (2017). We therefore decided to keep such model as the baseline continuum model for the rest of the analysis.

The total column density of cold gas in the LOS towards the source, N_H , was about 2.5×10^{21} cm^{−2}, a few times larger than the

⁶<https://ned.ipac.caltech.edu>

⁷SPEX manual for more detail at <https://personal.sron.nl/jellep/speX/manual.pdf>

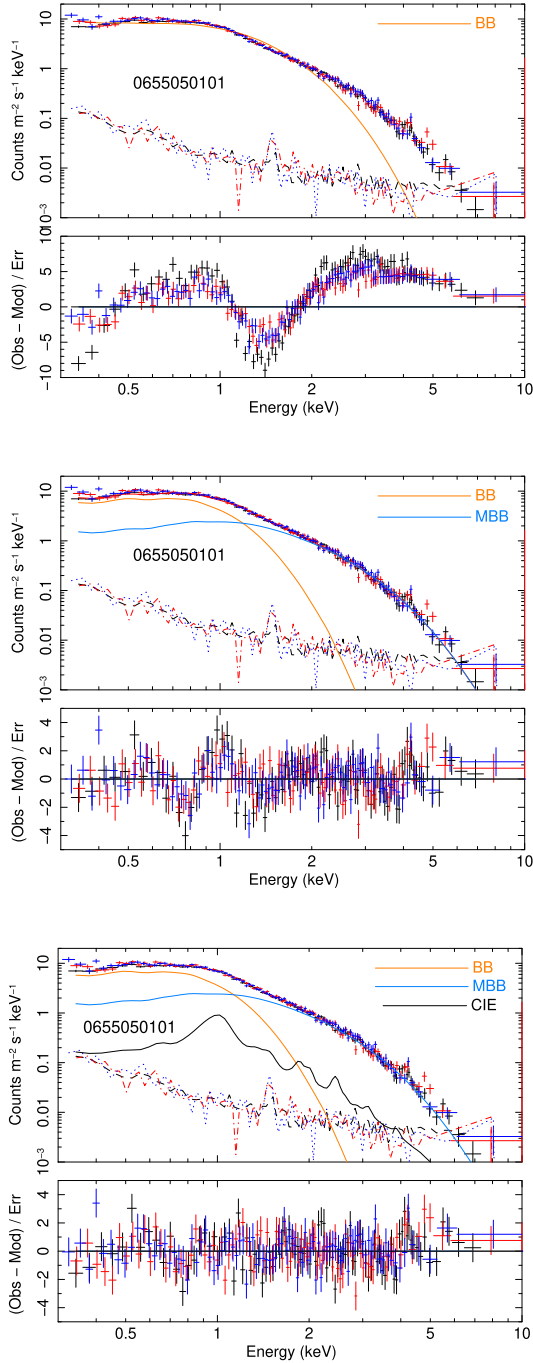


Figure 6. NGC 55 ULX-1 EPIC MOS and PN spectral fits performed using the RHB model (top panel), RHB model (middle panel) and the RHBMC model (bottom panel) for the Obs. ID: 06555050101. The dashed-dotted lines represent the background spectra.

Galactic value ($7 \times 10^{20} \text{ cm}^{-2}$).⁸ This suggested that a substantial amount of gas found along the LOS is located in the circumstellar medium around the ULX or in the host galaxy.

The inclusion of the wind (both emission and absorption models) significantly improved the overall quality of the fits. The addition of the wind emission corresponded to a decrease in the overall χ^2 of 73 for two additional d.o.f. (normalization and temperature of

the *cie*) which flattened most residuals around 1 keV (see Fig. 6). The addition of the wind absorption yields a further $\Delta\chi^2 = 18$ for two more d.o.f. (column density and ionization parameter of the *xabs*). However, it is important to notice that these additional line components did not strongly affect the continuum parameters nor the total bolometric luminosity as previously found by Pinto et al. (2020b) and Walton et al. (2020).

3.2 Spectral modelling of individual observations

In Fig. 4 we show the EPIC-PN spectra of the 10 XMM observations (the other two EPIC MOS 1,2 cameras are not shown here for clarity). We fitted the EPIC PN and MOS 1,2 from all observations using only continuum models because in some observations the residuals were too weak to constrain the parameters of the wind model. Besides the inclusion of the wind does not alter the continuum parameters even for the high quality spectra.

As for observation 06555050101, the spectral modelling was performed again simultaneously to the EPIC-PN, MOS1,2 spectra for each observation and testing all models mentioned before (blackbody, modified blackbody, powerlaw, and Comptonization). However, for clarity purposes and means of comparison with previous work, we focused on the results obtained with a double thermal model. A warm ($kT_{\text{bb}} \sim 0.2 \text{ keV}$) blackbody component reproduces the soft X-ray emission, presumably from the outer disc and the wind photosphere. A hot ($kT_{\text{mbb}} \sim 0.7 \text{ keV}$) blackbody component modified by coherent Compton scattering, accounts for the inner disc emission. The results are shown in detail in Table 4 and the plots for the four observations with longest ($\gtrsim 90 \text{ ks}$ net) exposure and therefore the spectral fits are shown in Fig. 6 (middle panel) and Fig. 7.

This model provided a good description of the data except for the usual strong, narrow, residuals around 1 keV due to the well-known winds. Indeed, by adding a wind photoionization absorption or collisionally ionized components – as previously found with the high-resolution RGS detectors – we could get rid of most spectral residuals (see observation 06555050101 as an example in Fig. 6 bottom panel and Table 3). Our results are fully consistent with previous work and, in particular, seem to indicate that both thermal components become increasingly hotter (i.e. with a higher kT) at higher luminosities (Pintore et al. 2015; Pinto et al. 2017). For a comparison with results from the literature see Section 4.

The neutral column density was consistent among all high-quality, deep ($\gtrsim 100 \text{ ks}$) exposures. The shortest ($\lesssim 30 \text{ ks}$) exposures did not have sufficient signal-to-noise ratio to constrain both the spectral shape and the neutral ISM absorption. In particular, testing several models from single to multiple components model (RHB, RHBB, RHBMC, etc.), we obtained values ranging from $(2 - 3) \times 10^{21} \text{ cm}^{-2}$. This was likely due to degeneracy produced by the lower statistics. Therefore, whilst fitting the spectra of these six short exposures we preferred to fix the N_H to the average value obtained in the latter observations as previously done in e.g. Robba et al. (2021) for NGC 1313 ULX-2.

3.3 Spectral modelling of different flux levels

In order to confirm and corroborate any trends between spectral hardness and source flux we fit the eight flux-resolved spectra shown in Section 2 with the RHBMC model as done before for the individual observations. The results of the spectral fits, fixing the column density N_H to the average value obtained in the previous results ($2.5 \times 10^{21} \text{ cm}^{-2}$), are shown in Table 5. At higher luminosities, the

⁸<https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl>

Table 3. Results from the modeling of the XMM-Newton spectrum of NGC 55 ULX-1 with the data of the observation 0655050101.

Parameter / component	RHB Model	RHBB Model	RHBD Model	RHBM Model	RHBCom Model	RHBMC Model	RHBMCX Model	RHBMG Model	RHBMG Model
$L_{X\,bb1}$	0.72 ± 0.01	0.98 ± 0.09	0.9 ± 0.1	0.93 ± 0.02	0.8 ± 0.1	0.8 ± 0.1	1.0 ± 0.3	0.8 ± 0.1	1.3 ± 0.3
$L_{X\,bb2}$	—	0.36 ± 0.02	—	—	—	—	—	—	—
$L_{X\,mbb}$	—	—	—	0.57 ± 0.02	—	0.56 ± 0.03	0.6 ± 0.1	0.61 ± 0.03	0.63 ± 0.03
$L_{X\,dbb}$	—	—	0.58 ± 0.04	—	—	—	—	—	—
$L_{X\,comt}$	—	—	—	—	0.7 ± 0.1	—	—	—	—
$L_{X\,CIE}$	—	—	—	—	—	0.07 ± 0.01	0.08 ± 0.02	—	—
$L_{X\,gauss}$	—	—	—	—	—	—	—	0.025 ± 0.004	0.008 ± 0.003
kT_{bb1}	0.287 ± 0.001	0.179 ± 0.002	0.164 ± 0.002	0.164 ± 0.001	0.158 ± 0.005	0.159 ± 0.003	0.164 ± 0.004	0.159 ± 0.003	0.147 ± 0.003
kT_{bb2}	—	0.482 ± 0.005	—	—	—	—	—	—	—
kT_{mbb}	—	—	—	0.680 ± 0.007	—	0.668 ± 0.008	0.673 ± 0.008	0.663 ± 0.008	0.654 ± 0.008
kT_{dbb}	—	—	1.2 ± 0.1	—	—	—	—	—	—
kT_{seed}	—	—	—	—	0.158 (coupled)	—	—	—	—
kT_e	—	—	—	—	0.58 ± 0.02	—	—	—	—
τ	—	—	—	—	12 ± 2	—	—	—	—
kT_{CIE}	—	—	—	—	—	1.11 ± 0.05	1.10 ± 0.05	—	—
N_H	0.733 ± 0.001	2.23 ± 0.07	2.52 ± 0.07	2.53 ± 0.07	2.5 ± 0.1	2.44 ± 0.09	2.3 ± 0.1	2.40 ± 0.09	3.0 ± 0.2
N_{HXabs}	—	—	—	—	—	—	$0.14^{+0.26}_{-0.10}$	—	—
$\log \xi$	—	—	—	—	—	—	3.7 ± 0.1	—	—
E_0^1	—	—	—	—	—	—	—	0.98 ± 0.01	1.01 ± 0.02
E_0^2	—	—	—	—	—	—	—	—	0.76 ± 0.01
FWHM	—	—	—	—	—	—	—	0.22 ± 0.03	0.12 ± 0.03
Norm ₁	—	—	—	—	—	—	—	1.6 ± 0.3	0.5 ± 0.2
Norm ₂	—	—	—	—	—	—	—	—	$-2.7^{+0.7}_{-1.0}$
$\chi^2/\text{d.o.f}$	4537/287	463/285	437/285	428/285	438/284	360/283	342/281	346/282	325/279
χ^2_P	2368	214	204	202	206	145	133	132	120
χ^2_{MOS1}	1064	141	125	122	122	118	117	123	112
χ^2_{MOS2}	1104	108	108	109	110	96	91	91	92

Parameter units: E_0^1 and E_0^2 (in keV unit) refer to the centroids of the first and second Gaussian, respectively. Norm₁ and Norm₂ (in 10^{46} ph/s units) refer to the normalizations of the first and second Gaussian, respectively. The temperatures kT (for each model) and FWHM are expressed in keV unit. The X-ray and bolometric luminosities L_X and L_{bol} (always intrinsic or unabsorbed) are calculated, respectively, between the 0.3–10 keV and 0.001–1000 keV bands, and are expressed in 10^{39} erg s⁻¹ unit. The ionization parameter $\log \xi$ is in erg s⁻¹ cm. The column density of the cold gas N_H is in 10^{21} /cm² unit, while N_{HXabs} is in 10^{24} /cm² unit. τ is the optical depth of the Comptonization component.

Table 4. Results from the spectral modeling for the individual observations (RHBM model).

Parameter / component	0028740201 Obs	0028740101 Obs	0655050101 Obs	0824570101 Obs	0852610101 Obs	0852610201 Obs	0852610301 Obs	0852610401 Obs	0864810101 Obs	0883960101 Obs
$L_{X\,bb}$	1.50 ± 0.06	1.12 ± 0.08	0.93 ± 0.02	0.71 ± 0.02	1.5 ± 0.2	1.6 ± 0.2	0.7 ± 0.1	1.1 ± 0.2	0.91 ± 0.02	1.15 ± 0.03
$L_{X\,mbb}$	1.37 ± 0.06	1.48 ± 0.08	0.57 ± 0.02	0.38 ± 0.01	1.2 ± 0.2	1.2 ± 0.2	0.46 ± 0.03	0.6 ± 0.2	0.58 ± 0.02	0.67 ± 0.02
kT_{bb}	0.172 ± 0.002	0.174 ± 0.003	0.164 ± 0.001	0.162 ± 0.001	0.168 ± 0.004	0.162 ± 0.004	0.153 ± 0.005	0.163 ± 0.006	0.167 ± 0.001	0.166 ± 0.001
kT_{mbb}	0.82 ± 0.01	0.90 ± 0.02	0.680 ± 0.007	0.755 ± 0.008	0.71 ± 0.03	0.69 ± 0.03	0.67 ± 0.04	0.68 ± 0.05	0.713 ± 0.007	0.680 ± 0.006
N_H	2.5	2.5	2.53 ± 0.07	2.57 ± 0.09	2.5	2.5	2.5	2.5	2.52 ± 0.07	2.5
$\chi^2/\text{d.o.f}$	334/275	294/240	428/285	413/279	192/153	139/137	135/97	87/87	463/285	378/294
L_{bol}	3.19	2.85	1.71	1.26	3.15	3.17	1.32	2.01	1.69	2.08

Units are the same as in the Table 3.

temperature of the hot modified blackbody component increased from 0.70 to 0.86 keV while the one for the cooler component increased by just 0.01 keV. An exception was the lowest flux level 1, which was largely dominated by Obs. ID: 0824570101, where there seemed to be an increase in the mbb temperature. An interesting result is the consistency between the parameters of the cool bb component between the highest level 8 and the bright, dipping, level 7. At odds, there was instead a clear drop in the luminosity and temperature of the hot mbb component during level 7. The results from these spectral fits are discussed later on in Section 4.

In Section 3.4 we show how Gaussian lines can describe the spectral residuals in these high-quality flux-resolved spectra, discuss their variability and how they may provide insights on the overall disc evolution and structure.

3.4 Variability of the wind features

In order to study the strength of the spectral features and their variability in NGC 55 ULX-1, we performed a quick fit of the flux resolved spectra modifying our baseline $bb + mbb$ model by adding three Gaussian lines (RHBMG model). Following Pinto et al. (2021), we fixed the line width to 1 eV for all three Gaussian lines since EPIC spectra lack the necessary spectral resolution around 1 keV. The energy centroids were free to vary however they agreed within the error bars with 0.8 and 1.2 keV for the absorption lines and 1.0 keV for the emission line.

The normalizations of the Gaussian lines for the eight spectra are shown in Fig. 8. They do not show strong trends with the flux, possibly due to fairly large uncertainties, with the exception of the lowest-energy line at 0.8 keV, which seems to get stronger at high

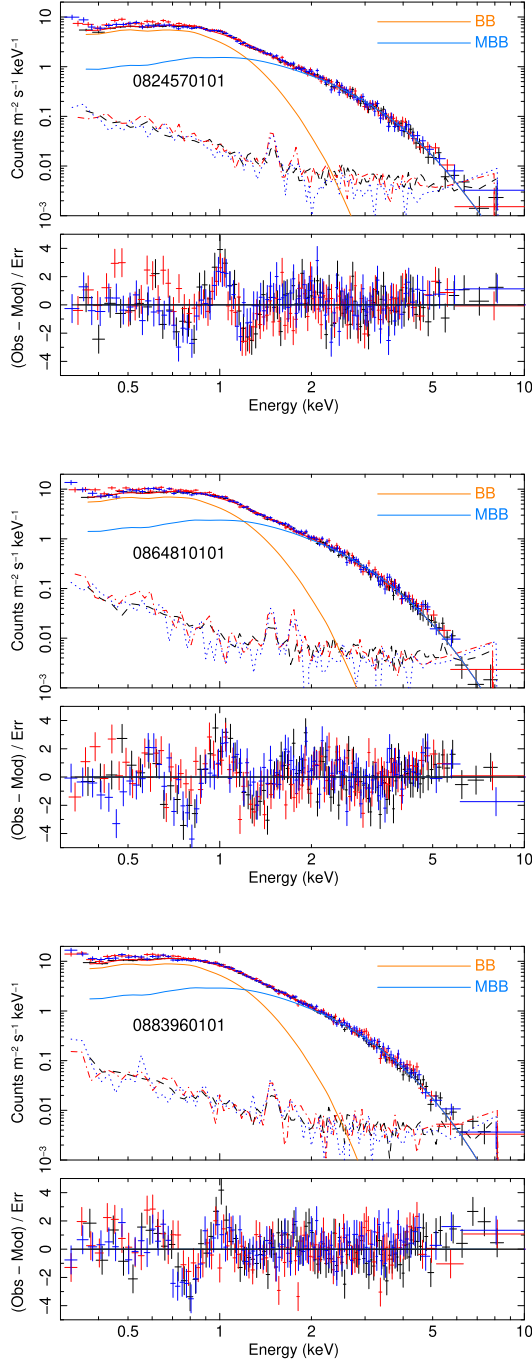


Figure 7. Spectral fits for the other three long ($\gtrsim 90$ ks net) observations of NGC 55 ULX-1 using the RHB model (blackbody + modified blackbody).

fluxes in agreement with NGC 1313 ULX-1 (Pinto et al. 2020b) and NGC 247 ULX-1 (Pinto et al. 2021). These trends were also attributed to an increasing $\dot{M}$.

4 DISCUSSION

The aim of this work is to investigate the processes that trigger the spectral transitions in ULXs, particularly between the soft and intermediate hardness regimes. The main question is whether they are driven by stochastic variability in the wind (e.g. Kobayashi et al. 2018) or variations in the accretion rate, which in turn produce

variability in the wind and in the obscuration of the innermost, hottest, regions (e.g. Urquhart & Soria 2016). Geometrical effects may also play a relevant role in systems where the accretion disc precesses (e.g. Middleton et al. 2015a).

According to radiation-magnetohydrodynamic (r-MHD) simulations of super-Eddington accretion discs (e.g. Takeuchi et al. 2013), the winds are expected to become optically thick enough to block and reprocess a fraction of the disc X-ray photons, making the source appear as a soft thermal emitter or ultraluminous (super)soft X-ray source (e.g. Guo et al. 2019) at moderately high inclination angles. A comprehensive study would require to measure the properties of the winds and compare them to the characteristics of the spectral continuum (similarly to the Pinto et al. 2020b for the intermediate-to-hard source NGC 1313 ULX-1). In order to do this, we used the XMM-Newton observations of one of the most variable and brightest (in flux) nearby source NGC 55 ULX-1. The X-ray spectra of this ULX fit in just between the softest and intermediate ULX spectra (see Fig. 1). Indeed, the temperatures of the *bb* fits are among the lowest in ULXs (e.g. Sutton et al. 2013). Moreover, we benefited from three new deep observations that enabled us to achieve more statistics in the low-flux regime and four new short observations which fill the gaps between the high- and low-flux regimes. In this work we focused on the evolution of the spectral continuum throughout the different epochs. A follow-up work will focus on the study of the high-resolution X-ray spectra which are however available only for the low-intermediate flux on-axis observations and the evolution of the wind in detail.

4.1 X-ray broadband properties

The XMM-Newton/EPIC light curves showed evidence for strong variability by up to a factor 4 in flux over time-scales of a few days (see Fig. 3, top panel) along with dips lasting a few 100s to a few ks, which have been interpreted as due to wind clumps that temporarily obscured the central object (see e.g. Stobbart et al. 2004; Pintore et al. 2015). In fact, during the dips the spectral hardness decreased and reached levels comparable to the low-flux observations although the dip flux was 2–3 times higher than that of the low-flux observations (Fig. 3, bottom panel). The dips appear mainly when the source is bright indicating that the accretion rate increases thereby launching optically thick wind clouds into the LOS. This suggests the presence of at least two different ongoing variability processes (see also below). *Swift*/XRT long-term light curves taken between 2013 and 2021 confirm the general source behaviour with flux variations by a factor of up to 6 with the spectrum of the source appearing harder when brighter (Jithesh 2022).

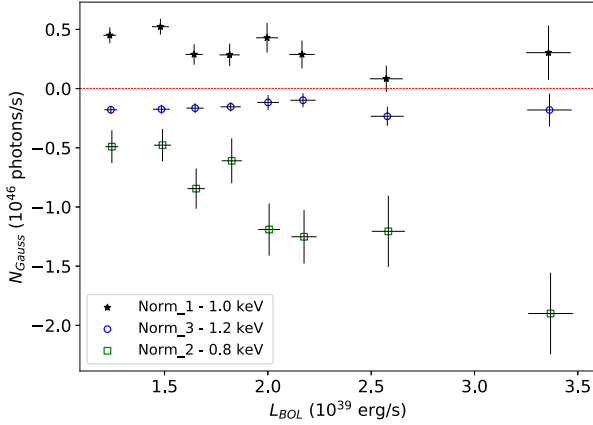
We extracted spectra for individual observations to probe variations on time-scales of a few days to years as well as flux-resolved spectra to probe the nature of on different time-scales variability (see Figs 4 and 5). Flux level 1 mainly sampled the lowest flux observation (Obs. ID: 082457), while flux levels 7 and 8 described the dip and no-dip time intervals in the bright epochs (Obs. ID: 002874–0201, from 2001, see Fig. 3). The other levels (2–6) traced the intermediate-flux epochs (Obs. ID: 065505, 086481). All spectra peaked around 1 keV with the peak slightly shifting towards higher energies at higher fluxes. Interestingly, the lowest-flux spectrum appeared harder than the intermediate-flux ones in contradiction with the trend seen at higher fluxes.

Our analysis confirmed that the spectrum requires at least two components with a blackbody-like shape. A double blackbody model could indeed reproduce the overall spectral shape with the hotter component being broader and likely modified by Compton scattering

Table 5. Results from the modeling with the RHB model of the eight flux-resolved spectra.

Parameter / component	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
$L_{X\,bb}$	0.70 ± 0.02	0.81 ± 0.03	0.90 ± 0.03	1.00 ± 0.03	1.11 ± 0.03	1.20 ± 0.04	1.39 ± 0.05	1.40 ± 0.07
$L_{X\,mbb}$	0.38 ± 0.02	0.50 ± 0.02	0.55 ± 0.03	0.60 ± 0.03	0.65 ± 0.03	0.70 ± 0.04	0.89 ± 0.05	1.65 ± 0.07
kT_{bb}	0.162 ± 0.001	0.162 ± 0.001	0.165 ± 0.001	0.166 ± 0.001	0.166 ± 0.001	0.167 ± 0.001	0.170 ± 0.001	0.175 ± 0.002
kT_{mbb}	0.75 ± 0.01	0.704 ± 0.008	0.705 ± 0.009	0.694 ± 0.009	0.692 ± 0.009	0.669 ± 0.009	0.74 ± 0.01	0.89 ± 0.01
N_H	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
$\chi^2/\text{d.o.f}$	452/282	431/276	390/279	350/274	366/271	295/262	324/270	390/295
L_{bol}	1.24	1.49	1.65	1.82	2.00	2.17	2.58	3.36

Units are the same as in the Table 3.

**Figure 8.** Normalization of the Gaussian lines versus Bolometric luminosity for the three-Gaussian model fits of the flux resolved spectra. The negative normalizations refer to absorption lines.

in the wind (see Fig. 6 and Table 3). This agrees with the general picture and the typical properties of soft ULXs (see e.g. Sutton et al. 2013). The inclusion of wind features in the model in the form of Gaussian lines or physical components produced significant improvements to the spectral fits in terms of $\Delta\chi^2$ but did not affect the continuum parameters albeit slightly increasing the uncertainties (see Table 3).

The spectral fits of both the individual observations and the eight flux levels showed that both the soft and hard components became hotter (i.e. with a higher kT) at higher luminosities (see Tables 4 and 5), which indicates that either the accretion rate is increasing or that we are progressively having a clearer view of the inner accretion flow through a less dense wind photosphere. However, the results on the wind features (e.g. the more intense 0.8 keV line at high fluxes) would favour an increase in the $\dot{M}$ (see Section 3.4). This agrees with a scenario in which variations in the local accretion rate are driving the transition from soft/fainter to hard/brighter spectra. The brightest ones are associated to epochs in which a surplus of matter may launch optically thick clouds that obscure the innermost region thereby producing the flux dips.

4.2 Comparison with disc models

The nature of the compact object powering NGC 55 ULX-1 is not yet known and therefore the accretion in Eddington units is uncertain. Although the best-fitting values of temperatures might not exactly correspond to gas temperatures due to the unknown structure of the emitting regions (because we have modelled a thick disk with a thin disk template), it is still very useful to compare them with the

bolometric luminosities of the blackbody components. This is indeed a commonly adopted procedure to understand the behaviour of the thermal components and, in particular, to place some constraints on the disc structure and accretion regime, possibly providing some information on the nature of the compact object, especially for not too high accretion rates or luminosities ($L_{BOL} \sim 10^{39}$ erg s $^{-1}$; e.g. Urquhart & Soria 2016; Earnshaw & Roberts 2017; Walton et al. 2020; D’Aí et al. 2021; Gúrpide et al. 2021; Robba et al. 2021).

It is useful to compare the L – T trends measured for NGC 55 ULX-1 with those expected from theoretical models such as the thin disc in a sub-Eddington regime ($L \propto T^4$) with a constant emitting area (SS73; Shakura & Sunyaev 1973) and the advection-dominated disc model with $L \propto T^2$ (Watarai & Mineshige 2001). In Fig. 9 (top panel) we show the trends between the temperature and the bolometric luminosity for both the cool (blue points) and warm (orange points) blackbody components from the spectral fits of the ten individual XMM observations. Overlaid are the best-fitting least-squares regression line (solid blue, $L \propto T^\alpha$), the $L \propto T^4$ (dashed red) and the $L \propto T^2$ (dotted black) trends. In Fig. 9 (bottom panel) we show the same results obtained with the eight spectra extracted in the count rate ranges of the XMM light curve (see Fig. 3). The bolometric (or total) luminosities of the cool blackbody and warm modified blackbody components are computed between 0.001 and 1000 keV by extrapolation, although most of the flux is emitted in the 0.1–10 keV range. Both plots show that the measured L – T relationship is in broad agreement with the thin SS73 disc. From the regression lines we obtain a power index, with the time resolved spectroscopy $\alpha_{cool} = 4.2 \pm 1.9$ and $\alpha_{hot} = 6.1 \pm 2.3$, for the cool and hot components, respectively. Instead, with the flux resolved spectroscopy, the power indices are $\alpha_{cool} = 5.4 \pm 1.7$ and $\alpha_{hot} = 5.4 \pm 1.8$. The possible correlation of the points in the L – T plot, for the cool and hot components, can be established with the Pearsons and Sperman correlation coefficients. These are reported in the Table 6 by using *scipy.stats.pearsonsr* and *scipy.stats.spearmanr* routine in PYTHON. They do not show always strong correlations.

Locally there are small deviations in Fig. 9 from the tight correlations. In particular, at high luminosities the temperature of the cool component is lower than the predictions from the $L \propto T^4$ model or the regression line, which suggests that the disc is expanding and, perhaps, that the wind starts to contribute to the emission or the radius of the thermal component is not constant. The lowest-flux observation also shows a notable deviation, especially for the warm disc component, with a temperature higher than as predicted from the L – T trends. This could be a hint of low/hard–high/soft behaviour seen in Galactic X-ray binaries and might indicate a spectral transition below 10^{39} erg s $^{-1}$, although the spectra of NGC 55 ULX-1 never get as hard as the Galactic X-Ray Binaries (XRBs) likely due to its persistently high accretion rate (Koljonen et al. 2010).

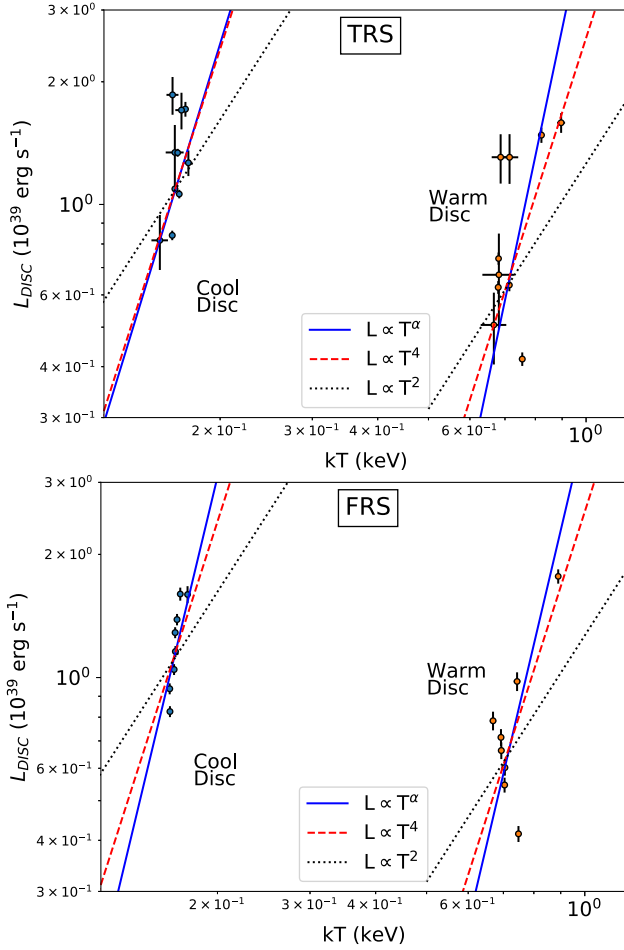


Figure 9. Bolometric luminosity estimated in the 0.001–1000 keV energy band versus temperature for the cool blackbody (in blue) and hot modified blackbody (in orange) components. Top panel: Luminosity–temperature plot for the time resolved spectra (TRS). Bottom panel: Luminosity–temperature plot for the flux resolved spectra (FRS). The blue solid line, the black-dotted and the red dashed lines represent the regression line and the two theoretical models of the slim disc and Shakura–Sunyaev models, respectively.

Table 6. Pearsons and Spearman coefficients for the L – T trends, for both cool and hot components, by using the best-fitting values of the RHBM model.

Correlation coefficient	TRS		FRS	
	$(L-T)_{\text{cool}}$	$(L-T)_{\text{hot}}$	$(L-T)_{\text{cool}}$	$(L-T)_{\text{hot}}$
Pearsons	0.48	0.65	0.90	0.83
Spearman	0.39	0.55	0.93	0.05

TRS and FRS acronyms stand for time-resolved spectroscopy and flux-resolved spectroscopy, respectively.

Fig. 9 shows that there are deviations for the luminosity and temperatures from the best-fitting regression line, approximately for total luminosity greater than $2 \times 10^{39} \text{ erg s}^{-1}$. This fact can be used to give a rough estimate of the mass of the compact object. For instance, if we assume that the deviation is due to the total luminosity reaching the Eddington limit ($L_{\text{tot}} \sim L_{\text{Edd}}$) and that the apparent luminosity is comparable to the intrinsic luminosity, using the definition $L_{\text{Edd}} = 1.4 \times 10^{38} \frac{M}{M_{\odot}} \text{ erg s}^{-1}$, we estimate that the mass of the compact object is about $14 M_{\odot}$. Instead, if we assume that the deviation is due to the disc becoming supercritical ($L_{\text{tot}} \sim L_{\text{critical}} = 9/4 L_{\text{Edd}}$, Poutanen et al. 2007), then we obtain a value for

the mass of the compact object of about $6 M_{\odot}$. Of course, should the intrinsic luminosity be greater than the apparent luminosity, which is possible given the weakness of the hard component, then the mass of the compact object would be larger. Bright ULXs with hard spectra typically have $L_{\text{Bol}} = (0.5-1) \times 10^{40} \text{ erg s}^{-1}$, which would result in $10-30 M_{\odot}$ for NGC 55 ULX-1. Therefore, the mass range obtained would suggest that the compact object is a black hole. This agrees with the results obtained by Fiacconi et al. (2017) using wind arguments. Interestingly, some deviations are also seen in Galactic XRBs above $0.3 L_{\text{Edd}}$ (e.g. Steiner et al. 2009). If the deviations that we see refer to such threshold, then a larger mass of the compact object, i.e. a heavier BH, is forecast.

The radius of the cool component has a value of the order of 3000 km; instead the radius of the hot component is of the order of 100 km, (estimated with the relations between luminosity and temperature and blackbody definition). These correspond to, respectively, $200 R_G$ and $10 R_G$, assuming a black hole of $10 M_{\odot}$. The radii of both components from the first to the eighth flux level do not vary significantly possibly due to the much larger uncertainties with respect to the temperature. Such results show a slight tension with Jithesh (2022) in which a tentative anticorrelation between the radius and the temperature of the cool component was found albeit at large uncertainties. This is probably due to the fact that we fixed the column density N_H since we do not expect a strong variation of the neutral gas within a few hours, which are the times-scale of the dips and the separation between consecutive observations.

By considering that the spherization radius is $R_{\text{sph}} = 27/4 \dot{m} R_G$ and assuming that $\dot{m} \sim \dot{m}_{\text{Edd}}$, the radius of the hot blackbody component is comparable to the spherization radius ($R_{\text{sph}} \sim 7 R_G$) (Poutanen et al. 2007), instead the radius of the cool component is significantly larger than R_{sph} identifying the outer disc. However, these results are correct if the intrinsic luminosity is comparable with the observed one or if there are not large losses due to the occultation of the inner portion of the disc by the wind. Jithesh (2022) also used *NuSTAR* data to better constrain the hard band; we do not think the use of these data might alter our conclusions, since there is only marginal flux in the *NuSTAR* band which is not covered by the EPIC-PN. Besides, there are only a few simultaneous XMM/*NuSTAR* observations.

4.3 Comparison with other ULXs

In the brighter (L_X up to $10^{40} \text{ erg s}^{-1}$) and pulsating source NGC 1313 ULX-2 there is a clear anticorrelation between the bolometric luminosity and the temperature of the cool blackbody-like component (Robba et al. 2021). In that source the trend is in agreement with the $L \propto T^{-4}$ relationship predicted by X-ray emission from a wind photosphere rather than a disc (e.g. Kajava & Poutanen 2009; King 2009; Qiu & Feng 2021), and is likely due to the higher observed luminosity and possibly higher accretion rate for the pulsating neutron star. In the even brighter source in same galaxy, NGC 1313 ULX-1, Walton et al. (2020) found a deviation in the L – T relationship for the warm disc-like component which has been attributed to an intervening wind or a higher disc scale height. The cool component seems fairly constant in luminosity in NGC 1313 ULX-1. The debate on the nature of the different L – T trends is still open.

The light curve of NGC 55 ULX-1 shows a dipping behaviour during the high-flux epochs which is very similar to that one shown by supersoft ULXs such as NGC 247 ULX-1 (Feng et al. 2016). There are much more data available for NGC 247 ULX-1 thanks to a recent deep XMM-Newton campaign (PI: Pinto). The results

from the broadband analysis were shown by D’Aí et al. (2021) who reported on a complex hardness-intensity diagram characterized by two main branches; here at high luminosities the source enters the dipping branch in which the spectrum becomes progressively softer. It is possible that the deviation of the temperature of the cool component shown by NGC 55 ULX-1 at high luminosities (see above and Fig. 9) is the first stage of the dipping behaviour seen in NGC 247 ULX-1 but with the wind not optically thick enough to completely obscure the emission above 1 keV. This could be due to either a lower accretion rate or inclination angle in NGC 55 ULX-1. Given the lower luminosity and harder spectrum of NGC 55 ULX-1 as compared with the NGC 247 ULX-1 (see e.g. Pinto et al. 2021), it is reasonable to speculate that the former is at a lower accretion rate with a thinner wind in the line of sight. Indeed, the dominant emission line blend at 1 keV from the wind is much stronger in NGC 247 ULX-1. More precisely, when modelled it with a *cie* component we obtained $L_{X[0.3-10\text{ keV}]} \sim 0.7 \times 10^{38} \text{ erg s}^{-1}$ in NGC 55 ULX-1 (see Table 3), while for NGC 247 ULX-1 it was $\sim 1.4 \times 10^{38} \text{ erg s}^{-1}$ (Pinto et al. 2021), i.e. twice as strong. A more powerful wind in NGC 247 ULX-1 is likely a consequence of a higher accretion rate.

5 CONCLUSIONS

In this work we have performed a spectral analysis to understand the structure and evolution of the accretion disc in the ultraluminous X-ray source NGC 55 ULX-1. The archival data was enriched with three deep XMM-Newton observations that we obtained in 2018, 2020, and 2021. This enabled to follow up the continuum changes and their relation with the source luminosity. As for most ULXs, it is necessary to use at least two spectral components to reproduce the spectral shape. The spectrum can be well fit with a two-blackbody model composed of a cool blackbody component, that describes the softer X-ray emission coming from the outer and cool part of the accretion disc and the wind photosphere, and a hotter blackbody modified by Compton scattering, that instead accounts for the emission from the hot inner disc. Both components become hotter at higher luminosities, indicating either a better and clearer view of the inner disc, due to e.g. a reduction of the wind photosphere density, or to an increase in the accretion rate. The variability of the wind features would favour the latter case. The trends between the bolometric luminosity and temperature of each component broadly agree with the $L \propto T^4$ relationship expected from constant area such as a thin disc. This suggests that the intrinsic luminosity of the source is not extremely high and likely close to the Eddington limit of a $10 M_{\odot}$ black hole. At high luminosities the cool component is cooler than the predictions from the thin-disc model and the best-fitting regression line. This would imply an expansion of the disc and a contribution to the emission from the wind. If the deviation occurs between the Eddington limit and the supercritical accretion rate, a black hole within $6-14 M_{\odot}$ is foreseen.

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DATA AVAILABILITY

All of the data, with the exception of the Obs. ID 0883960101, and software used in this work are publicly available from ESA’s XMM-Newton Science Archive (XSA)⁹ and NASA’s HEASARC archive.¹⁰

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⁹<https://www.cosmos.esa.int/web/XMM-Newton/xsa>

¹⁰<https://heasarc.gsfc.nasa.gov/>

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