ESO 243-49 HLX-1: scaling of X-ray spectral properties and black hole mass determination

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**ABSTRACT**

We report the results of *Swift*/XRT observations (2008–2015) of a hyper-luminous X-ray source, ESO 243-49 HLX-1. We found a strong observational evidence that ESO 243-49 HLX-1 underwent spectral transitions from the low/hard state to the high/soft state during these observations. The spectra of ESO 243-49 HLX-1 are well fitted by the so-called bulk motion Comptonization model for all spectral states. We have established the photon index (\(\Gamma\)) saturation level, \(\Gamma_{\text{sat}}=3.0\pm0.1\), in the correlation of \(\Gamma\) versus mass accretion rate (\(\dot{M}\)). This \(\Gamma - \dot{M}\) correlation allows us to estimate the black hole (BH) mass in ESO 243-49 HLX-1 to be \(M_{\text{BH}} \sim 7 \times 10^4 M_{\odot}\), assuming the distance to ESO 243-49 of 95 Mpc. For the BH mass estimate we used the scaling method, taking Galactic BHs XTE J1550-564, H 1743-322 and 4U 1630-472, and an extragalactic BH source, M101 ULX-1 as reference sources. The \(\Gamma - \dot{M}\) correlation revealed in ESO 243-49 HLX-1 is similar to those in a number of Galactic and extragalactic BHs and it clearly shows the correlation along with the strong \(\Gamma\) saturation at \(\approx 3\). This is a reliable observational evidence of a BH in ESO 243-49 HLX-1. We also found that the seed (disk) photon temperatures are quite low, of order of \(50-140\) eV which are consistent with a high BH mass in ESO 243-49 HLX-1.

*Subject headings:* accretion, accretion disks—accretion disks—black hole physics—stars: individual (ESO 243-49 HLX-1)—radiation mechanisms

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1. Introduction

The prominent edge-on galaxy ESO 243-49, located at 95 Mpc away in the constellation Phoenix (see Afonso et al. 2005), hosts a hyper-luminous X-ray source commonly known as HLX-1, which is possibly an intermediate-mass black hole (IMBH). This black hole candidate (BHC) was first observed in 2004 as a source emitting X-rays in the vicinity of the spiral galaxy ESO 243-49 and it was catalogued as 2XMM J011028.1-460421. Later, in 2008 the field of this X-ray source was deeply re-imaged by a team led by Natalie Webb (the Institut de Recherche en Astrophysique et Planetologie in Toulouse, France).

Farrell et al. 2009 suggested that HLX-1 is an intermediate-mass black hole candidate with mass of $\sim 10^4 M_\odot$ because of very high X-ray luminosity of HLX-1 ($\sim 10^{42}$ erg/s in the 0.2 – 10 keV range) and because its disk Blackbody spectrum peaked at $kT_{in} \sim 2$ keV along with its X-ray spectral variability. X-ray spectral analysis (see Godet et al. 2009, 2012; Servillat et al. 2011; Lasota et al. 2011; Farrell et al. 2009; Davis et al. 2011), optical observations (see Farrell et al. 2012; Wiersema et al. 2010; Soria et al. 2010) and radio observations (see Webb et al. 2012) support the presence of an intermediate-mass BH in ESO 243-49 HLX-1.

Long-term monitoring with the Swift/XRT has shown that X-ray luminosity of HLX-1 changes by a factor of $\sim 50$ (Godet et al. 2009; Yan et al. 2015), and its spectral variability is reminiscent of that seen in Galactic stellar-mass BHs (see Servillat et al. 2011). Specifically, the X-ray light curve demonstrates a recurrent fast rise-exponential decay” (FRED) type of pattern in the range of $\sim 370 – 460$ days. This recurrency has been interpreted as an orbital period of the companion star (see Lasota et al. 2011 and Soria 2013). However, the last 2 outbursts have been too late to be consistent with that explanation. The interval between the last two outbursts is almost 3 months longer than the interval between the first two [Soria (2015), a private communication].

Recently, Webb et al. (2012), hereafter W12, reported a detection of transient radio emission at the location of HLX-1, which agrees with a discrete jet ejection event. These observations also allowed W12 to re-estimate the BH mass to be between $\sim 9 \times 10^3 M_\odot$ and $\sim 9 \times 10^4 M_\odot$. In contrast, King & Lasota (2014) suggested that HLX-1 may be a stellar mass binary like SS 433 (see also Lasota et al. 2015), in which the X-ray emission possibly comes from the beamed jet.

HLX-1 is projected in the sky at $\sim 0.8$ kpc out of the plane and $\sim 3.3$ kpc ($\approx 8 "$) of the nucleus of the S0/a galaxy ESO 243-49 (the luminosity distance $\sim 96$ Mpc). Galaxy ESO 243-49 is a member of the cluster Abell 2877 (e.g. Malumuth et al. 1992). The association of HLX-1 with ESO 243-49 is confirmed by the redshift measurements of the observed H{$\alpha$}
emission line of the counterpart (Soria et al. 2013, hereafter SHP13; Wiersema et al. 2010), although the velocity offset between this and the bulge of ESO 243-49 is $\sim 430$ km/s, close to the escape velocity from the S0 galaxy (SHP13). This allows to suggest that HLX-1 might be in a dwarf satellite galaxy or a star cluster near ESO 243-49 are not than in the galaxy itself (SHP13). The HII region in which the HLX is located could be the remnant of a dwarf satellite galaxy that has been accreted (Farrell et al. 2012). The optical counterpart of HLX-1 was detected in various bands, from near-infrared to far-ultraviolet (FUV, Wiersema et al. 2010; Soria et al. 2010, 2012; Farrell et al. 2012), but its nature remains puzzling.

Cseh et al. (2015) used radio observations of ESO 243-49 HLX-1 in 2012 based on the Australia Telescope Compact Array (ATCA) and Karl G. Jansky Very Large Array (VLA). They estimated the BH mass as $2.8^{+7.5}_{-2.1} \times 10^6$ M$_\odot$. Yan et al. (2015) have analyzed Swift monitoring observations of ESO 243-49 HLX-1 and compared the HLX-1 outburst properties with those of bright Galactic low-mass X-ray binary transients (LMXBTs). Furthermore, they stated that HLX-1 spends progressively less time in the succeeding outburst state and much more time in quiescence, but its peak luminosity remains approximately constant. The spectral analysis by Yan et al. strengthened the similarity between the state transitions in HLX-1 and those in Galactic LMXBTs.

A very high luminosity of ESO 243-49 HLX-1 is considered as evidence for the existence of IMBH in HLX-1 (Farrell et al. 2009). However, luminosities up to $\sim 10^{41}$ erg/s can be explained by stellar-mass BHs undergoing super-Eddington accretion (see Begelman 2002) that is followed. As a result, the apparent luminosity can exceed the Eddington limit estimated for isotropic radiation (King 2008; Freeland et al. 2006). Highly collimated sources are not expected to have a disk-blackbody or thermal-dominant spectrum, like we see in HLX-1 in the high/soft state. Therefore HLX-1 may not be a strongly beamed source.

Consequently, luminosity above $\sim 10^{41}$ erg/s is difficult to explain without considering a massive BH source. Generally, two scenarios for an interpretation of HLX/ULX phenomena have been proposed. First, these sources can be stellar-mass BHs ($<100$ M$_\odot$) radiating at Eddington or super-Eddington rates [see e.g. Mukai et al. (2005)]. Alternatively, they can be intermediate-mass BHs ($>100$ M$_\odot$) whose luminosities are essentially sub-Eddington. The exact origin of such objects still remains uncertain, and there is still no general consensus on the causes of the powerful outbursts. Recently, Bachetti et al. (2014) discussed another scenario for ULX.

Using the NuSTAR mission (Harrison et al. 2013), Bachetti and collaborators detected pulsations of X-ray emission with an average period 1.37 s modulated by a 2.5-day cycle from ULX-4 located in the nuclear region of the galaxy M82. Bachetti et al. also argued that these pulsations are results of the rotation of a magnetized neutron star, while the modulation
arises from its binary orbital motion. We note that the X-ray luminosity of M82 ULX-4 is about $L_X \sim 2 \times 10^{40} \text{ erg s}^{-1}$ in 0.3 – 10 keV energy range, which suggests a luminosity $\sim 100 \times L_{\text{Edd}}$ for a 1.4 $M_\odot$ neutron star (NS). Such a source is ten times brighter than any known accreting pulsar. The discovery of M82 ULX-4 and its possible interpretation as a NS can expand possible scenarios for ULXs.

It is desirable for ESO 243-49 HLX-1 to independently identify the BH for its central object and also determine the mass of its BH as an alternative to previously employed methods (based on luminosity estimates alone). A new method for determining the BH mass was developed by Shaposhnikov & Titarchuk (2009), hereafter ST09, who used a correlation scaling between X-ray spectral and timing (or mass accretion rate) properties observed from many Galactic BH binaries during the spectral state transitions. This method has also been applied to study of another class of X-ray sources, ULXs sources, NGC 5408 X-1 (Strohmayer & Mushotzky (2009) and M101 ULX-1 (Titarchuk & Seifina, 2015). We note, this method is commonly used for a BH mass determination of supermassive BHs, such as NGC 3227, NGC 5548 NGC 5506 and NGC 3516 (Papadakis et al. 2009; Sobolewska & Papadakis, 2009) and NLS1 galaxy Mrk 766 (Giacche et al. 2014), using a sample of Galactic BHC binaries as reference sources. This scaling method can also be applied for BH mass estimates when the conventional dynamical method cannot be used.

We applied the ST09 method to Swift/XRT data of ESO 243-49 HLX-1. Previously, many properties of HLX-1 were analyzed using Swift/XRT observations (e.g., Soria et al. 2010; Farrell et al. 2013; Webb et al. 2014; Yan et al. 2015). In particular, Soria et al. (2010) assessed Swift (2008 – 2009) observations by fitting their X-ray spectra. They used a few models, in particular, an additive model of the blackbody/diskbb plus power-law. They found that in these X-ray spectra the photon index changes from 1.8 to 2.95 but they were unable to present any argument that this source to be intermediate-mass BH or foreground NS.

Farinelli & Titarchuk (2011), Seifina et al. (2015), Seifina et al. (2013), Seifina & Titarchuk (2012), Seifina & Titarchuk (2011), hereafter ST11, have shown that BH and NS sources can be distinguished using $\Gamma$-$\dot{M}$ correlation. ST11 predicted a BH source in ESO 243-49 HLX-1 and ruled out a quiescent neutron star in this source. Only in BH sources the photon index $\Gamma$ can increase from $\Gamma \sim 1.6$ to $\Gamma \sim 3$ with mass accretion rate, in contrast to neutron stars, for which we usually find the constant photon index around $\Gamma \sim 2$ (see e.g. ST11). Furthermore, Wiersema et al. (2010) measured a redshift of $z=0.0223$ for HLX-1, which clearly indicates that HLX-1 cannot be a neutron star (NS) source because its luminosity is too high for a NS.

In this paper we present an analysis of available Swift observations of ESO 243-49 HLX-1
made during 2008 – 2015 to re-examine our previous conclusions on a BH nature of HLX-1 and to find further indications on intermediate-mass BH in HLX-1. In Sect. 2 we present the list of observations used in our data analysis, while in Sect. 3 we provide details of the X-ray spectral analysis. We discuss the evolution of the X-ray spectral properties during the high-low state transitions and present the results of the scaling analysis to estimate the BH mass of ESO 243-49 HLX-1 in Sect. 4. We conclude on our results in Sect. 5.

2. Observations and data reduction

We used Swift data (Gehrels et al. 2004) of ESO 243-49 HLX-1 carried out from 2008 to 2015. In Table 1 we show the summary of the Swift/XRT (Burrows et al. 2005) observations. In the Swift observations, HLX-1 has been detected, at least, at $\sim 2$-$\sigma$ significance (see, Evans et al. 2009). The Swift-XRT/PC data (ObsIDs, indicated in the first column of Table 1) were processed using the HEA-SOFT v6.14, the tool XRTPPIPELINE v0.12.84 and the calibration files (latest CALDB version is 20150721 1). The ancillary response files were created using XRTMKARF v0.6.0 and exposure maps were generated by XRTEXPOMAP v0.2.7. We fitted the spectrum using the response file SWXPC0TO12S6–20010101v012.RMF. We also applied the online XRT data product generator 2 for an independent check of light curves and spectra (including background and ancillary response files, see Evans et al. 2007, 2009). We also identified the state using the hardness (color) ratio (HR) (see Sect. 3.2) and the Bayesian method developed by Park et al. (2006). Moreover, we applied an effective area option of the Park’s code which includes the count-rate correction factors in their calculations. Our results, obtained by adapting this technique, indicate a continuous distribution of the HR with source intensity from a high hardness ratio at lower count-rate to a low hardness ratio at higher count events (see Figure 1). Furthermore, the hardness–intensity diagram shows a smooth track. Therefore, we grouped the Swift spectra into seven bands according to count rates (see Sect. 3.1) and fitted the combined spectra of each band using the XSPEC 3 package [version 12.8.14, see Arnaud (1996)]. In addition, all groups of the Swift spectra were binned to a minimum of 20 counts per bin in order to use $\chi^2$ statistics for our spectral fitting.

We also employed Chandra data for more deep image analysis. Specifically, we investigated an observation of HLX-1 for which the HRC-I camera was operated on the board of

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1http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/
2http://www.swift.ac.uk/user_objects/
3http://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/manual.html
Chandra with the CIAO v4.1.1 task WAVDETECT.

3. Results

3.1. Images

We visually inspected the source field-of-view (FOV) image to exclude a possible contamination from nearby sources. To do this, we implemented the Chandra image which has a better resolution than the Swift image. In Figure 2 we show the adaptively smoothed Chandra/HRC-I (0.1 – 10 keV) image of the ESO 243-49 HLX-1 field, obtained on 2009 July 4 with an exposure of 1175 s (ObsID: 10919) when ESO 243–49 HLX–1 was in quiescence (see also blue dashed vertical line in Figure 3 which indicates the Chandra/HRC-I observational MJD point in the lightcurve). Two sources were detected in the FOV near HLX–1 position: 2XMM J011050.4-460013 and 2XMM J010953.9-455538. A source related to the position of HLX-1 (Webb et al. 2010) is 2XMM J010953.9-455538, identified as ESO 243-49 HLX-1 (α = 01h10m28s.30, δ = −46°04′22′′.3, J2000.0 and indicated by yellow circle in Figure 2). To separate X-ray emissions from these two sources and minimize contamination of ESO 243–49 HLX–1 by the nearby source we additionally used specific Swift pointing (see dashed circle in Figure 2), within which only HLX–1 is detected. In Figure 2 the large circles (labeled nominal and offset) show the two pointing positions used to extract HLX–1 data for the Swift observations. In this way, we compared the relative contributions of these two sources throughout all Swift observations. For the observations made at the offset pointing positions, the count rates are almost the same as that made at the nominal pointing position. Thus, we conclude that during Swift observations this nearby source remains faint in comparison with the variable HLX–1.

3.2. Hardness-intensity diagrams and light curves

Before we proceed with details of the spectral fitting we study the hardness ratio (HR). In application to the Swift data we considered the HR is a ratio of the hard and soft counts in the 1.5 – 10 keV and 0.3 – 1.5 keV bands, respectively. The HR is evaluated by calculating the background counting. In Figure 1 we show the hardness-intensity diagram (HID) and thus, we show that the different count-rate observations are associated with different color regimes: the higher HR values correspond to harder spectra. A Bayesian approach was used
to estimate the HR values and their errors \cite{Park et al. 2006}.

Figure 1 indicates that the HR monotonically reduces with the total count rate (0.3 – 10 keV). This particular sample is similar to those of most of outbursts of Galactic X-ray binary transients (see Belloni et al. 2006; Homan et al. 2001; Shaposhnikov & Titarchuk, 2006; ST09; TS09; Shrader et al. 2010; Muñoz-Darias et al. 2014).

Six recurring outbursts occurred in HLX-1 during the \textit{Swift} monitoring (from 2008 up to now). These outbursts were approximately separated by one year apart. We show the \textit{Swift}/XRT light curve of ESO 243-49 HLX-1 during 2008 – 2015 for the 0.3 – 10 keV band in Figure 3. Red points indicate the source signal and green points correspond to the background level. We found six outbursts of ESO 243-49 HLX-1 peaked at MJD=55060, 55446, 55791, 56178, 56586 and 57060 with a FRED profile and rough duration from 70 to 200 days. For the remaining \textit{Swift} observations the source were in the low state. Unfortunately, individual \textit{Swift}/XRT observations of ESO 243-49 HLX-1 in photon counting (PC) mode do not have enough counts in order to make statistically significant spectral fits.

We studied the \textit{Swift}/XRT HID (see Figure 1) and grouped the observations into seven bands: very low (A, HR>1; B, 0.5<HR<1), low (C, 0.25< HR <0.6), intermediate (D, 0.13< HR <0.25), high (E, 0.07< HR <0.13; F, 0.03< HR <0.07) and very high (G, HR<0.03) count rates to resolve this difficult problem. To do this, we have combined the spectra in each related band, regrouping them with the task grppha and then fitted them using the 0.3 – 10 keV range.

\subsection{3.3. Spectral Analysis}

Different spectral models were used in order to test them for all available data for ESO 243-49 HLX-1. We wish to establish the low/hard and high/soft state evolution using these spectral models. We investigated the combined \textit{Swift} spectra to test the following spectral models: powerlaw, blackbody, BMC and their possible combinations modified by an absorption model. To fit all of these spectra, we used a neutral column, which was obtained by the best-fit column $N_H$ of $5 \times 10^{20}$ cm$^{-2}$ (see also Yan et al. 2015; Farrell et al. 2009; Webb et al. 2010, 2012).

\footnote{A Fortran and C-based program which calculates the ratios using the methods described by Park et al. 2006 (see \url{http://hea-www.harvard.edu/AstroStat/BEHR/}).}
3.3.1. Choice of the Spectral Model

The phabs*power-law model fits the low state data well [e.g., for band-A spectrum, $\chi^2_{\text{red}} = 1.15$ (138 d.o.f.), see the top of Table 2]. As we established this power-law model indicates to very large photon indices (greater than 3, particularly for band-G spectrum, see Figure 1) and moreover, this model has unacceptable fit quality, $\chi^2$ for all D, E, F and G-spectra of Swift data. For the high-state data, the thermal model (blackbody) provides better fits than the power-law model. However, the intermediate state spectra (D-spectra) cannot be fitted by any single-component model. A simple power-law model produces a soft excess. These significant positive residuals at low energies, lower than 1 keV, suggest the presence of additional emission components in the spectrum. As a result we also tested a sum of blackbody and power-law component model. The model parameters are $N_H = 5 \times 10^{20}$ cm$^{-2}$; $kT_{bb} = 90 - 300$ eV and $\Gamma = 1.3 - 2.9$ (see more in Table 2). The best fits of the Swift spectra has been found using of the bulk motion Comptonization model [BMC XSPEC model, Titarchuk et al. (1997)], for which $\Gamma$ ranges from 1.6 to 3.0 for all observations (see Table 2 and Figures 4-6). We emphasize that all these best-fit results are found using the same model for the high and low states.

3.3.2. Spectral modelling for ESO 243-49 HLX-1

Now, we briefly recall the physical picture described by the BMC model, its key assumptions and parameters. The BMC Comptonization spectrum is a sum of a part of the blackbody (BB) directly visible by the Earth observer [a fraction of $1/(1 + A)$] and a fraction of the BB, $f = A/1 + A$, convolved with the Comptonization Green function which is, in the BMC approximation, a broken power-law. It is worthwhile to emphasize that this Comptonization Green function is characterized by only one parameter, the spectral index $\alpha = \Gamma - 1$. Thus, as one can see that the BMC model has the main parameters, $\alpha$, $A$, the seed blackbody temperature $T_s$ and the BB normalization which is proportional to the seed blackbody luminosity and inverse proportional to $d^2$ where $d$ is a distance to the source (see Figure 5).

The spectral evolution for the low/hard state-high/soft state (LHS–HSS) transition is evident in Figure 1. Seven $EF_{E}$ spectral diagrams related to different spectral states in HLX–1 are presented there (see also Sect 3.2 and Figure 1).

Thus, the BMC model successfully fits the ESO 243-49 HLX-1 spectra for all spectral states. In particular, the Swift/XRT spectra for band A (red) and band G (blue) fitted using the BMC model are shown in Figure 6. In Table 2 (at the bottom), we present the
results of spectral fitting *Swift/XRT* data of ESO 243-49 HLX-1 using our main spectral model. phabs*bmc. In particular, the LHS–HS transition is related to the photon index, \( \Gamma \) changes from 1.6 to 3.0 when the relatively low seed photon temperature \( kT_s \) changes from 50 eV to 140 eV. The BMC normalization, \( N_{bmc} \) varies by a factor of fifteen, in the range of \( 0.3 < N_{BMC} < 5.2 \times L_{33}/d_{10}^2 \text{ erg s}^{-1} \text{ kpc}^{-2} \), while the Comptonized (illumination) fraction varies in a wide range \( (-1.2 < \log A < 1.1 \text{ or } f \sim 0.1 - 1) \).

In Figure 6 we also plot the spectral evolution of ESO 243-49 HLX-1 in \( E^*F(E) \) units (top) along with \( \Delta \chi \) (bottom). Data are taken from *Swift/XRT* observations with HR=1.1±0.1 [red, LHS; \( \Gamma = 1.6 \pm 0.2, T_s = 54 \pm 9 \text{ eV}, \chi^2_{red} = 0.86 \text{ (136 d.o.f.)} \)] and HR=0.02±0.01 [blue, HSS; \( \Gamma = 3.0 \pm 0.1, T_s = 130 \pm 10 \text{ eV}, \chi^2_{red} = 1.04 \text{ (217 d.o.f.)}, \text{ see also Table 2 for details}\].

In the fit of the HSS spectrum shown in the third panel of Fig. 6 the BMC model appears to be systematically over-predicting the strength of the thermal emission below 1 keV. This energy range is related to the oxygen and iron line region where absorption features occur at 0.6 keV and 0.9 keV, most likely associated with O VIII Ly\( \alpha \) and Fe XVIII – Fe XIX. However, this possible complexity of the model is not well constrained by our data.

As we have already discussed above, the spectral evolution of ESO 243-49 HLX-1 was previously investigated using the *Swift* data by many authors. In particular, Soria et al. (2010) and Yan et al. (2015) studied the 2008 – 2009 and 2009 – 2015 *Swift*-data sets (see also Table 1) using an additive diskbb plus power-law model and a simple power-law model. These qualitative models describe an evolution of these spectral model parameters throughout state transitions during the outbursts.

We have also found a similar spectral behavior using our model and the full set of the *Swift* observations. In particular, as Soria’s and Yan’s et al., we also found that the photon index \( \Gamma \) of HLX-1 grows monotonically during the LHS – HSS transition from \( \sim 1.6 \) to 3. In addition, we found that \( \Gamma \) tends to saturate at 3 at high values of \( N_{bmc} \). In other words we found that \( \Gamma \) saturates at high values of mass accretion rate.

Seed photons with the lower \( kT_s \), related to a lower mass accretion rate, are Comptonized more efficiently in the LHS because, we revealed that the illumination fraction \( f \) [or \( \log(A) \)] is quite high in this state. In contrast, in the HSS, these parameters, \( kT_s \) and \( \log(A) \) show an opposite behavior, namely \( \log(A) \) is lower for higher \( kT_s \). This means that a relatively small fraction of the seed photons, whose temperature is higher because of the higher mass accretion rate in the HSS than that in the LHS, is Comptonized.

Our spectral model performs very well throughout all data sets. In Table 2 we list a good performance of the BMC model when it is applied to the *Swift* data \( (0.79 < \chi^2_{red} < 1.14) \).
The reduced $\chi^2_{\text{red}} = \chi^2/N_{\text{dof}}$ (where $N_{\text{dof}}$ is the number of degree of freedom) is lower than or around 1 for all observations.

We also estimate the radius of the blackbody emission region. We found the blackbody radius $R_{BB}$ derived using a relation $L_{BB} = 4\pi R_{BB}^2\sigma T_{BB}^4$, where $L_{BB}$ is the seed blackbody luminosity and $\sigma$ is the Stefan-Boltzmann constant. With a distance $D$ to the source of 95 Mpc, we obtain that the region associated with the blackbody has a radius of $R_{BB} \sim 5 \times 10^6$ km. Such a large BB region is only around the IMBH which means that ESO 243-49 HLX-1 probably is the IMBH source. Taking into account that the BMC normalization varies by a factor of 15 and the blackbody (seed) temperature $T_s$ changes by a factor of 2 (see Table 2) we find that the blackbody radius is almost constant. We note that $R_{BB}$ is of order of $10 - 30$ km for a Galactic BH with a mass of around 10 solar masses (see STS14).

We have also found that the emergent spectra of ESO 243-49 HLX-1 undergo an evolution from the low/hard state to the high/soft state (see Figs. 1 and 4). In Table 2 we present the change in the seed photon temperature $kT_s$, the BMC normalization and the photon index $\Gamma$ during 2008–2015 outburst transitions observed with Swift/XRT.

In particular, we detected a high value of the seed photon temperature $kT_s = 130$ eV in the high/soft state (see Table 2, band-G). On the other hand, the low/hard state of ESO 243-49 HLX-1 is associated with the low $kT_s \sim 54$ eV (see Table 2, band-A).

We also establish that the photon index $\Gamma$ correlates with the BMC normalization, $N_{BMC}$ (proportional to mass accretion rate $\dot{M}$) and finally saturates at high values of $\dot{M}$ (see Figure 7). The index $\Gamma$ monotonically grows from 1.3 to 2.8 with $\dot{M}$ and then finally saturates at $\Gamma_{\text{sat}} = 3.0 \pm 0.1$ for high values of $\dot{M}$.

4. Discussion

4.1. Saturation of the index as a signature of a BH

After applying our analysis of the evolution of the photon index $\Gamma$ in ESO 243-49 HLX-1 we probably find the photon index, $\Gamma$ saturation with mass accretion rate, $\dot{M}$. ST09 have reported that this index saturation is a first indication of the converging flow into a BH.

Titarchuk et al. (1998) have reported using the equation of motion that the innermost part of the accretion flow (TL) shrinks when $\dot{M}$ grows. It is worthwhile to emphasize that for a BH the photon index $\Gamma$ grows and saturates for high $\dot{M}$. Titarchuk & Zannias (1998), hereafter TZ98, semi-analytically discovered the saturation effect and later Laurent & Titarchuk (1999), (2011), hereafter LT99 and LT11, confirmed this effect making Monte Carlo simula-
tions.

Observations of many Galactic BHs (GBHs) and their X-ray spectral analysis [see ST09, Titarchuk & Seifina (2009), Seifina & Titarchuk (2010) and STS14] have confirmed this prediction of TZ98. For our particular source HLX-1, we also found that $\Gamma$ monotonically increased from 1.6 and then they finally saturated at a value of 3.0 (see Figure 7).

Using the index-$\dot{M}$ correlation found in ESO 243-49 HLX-1 we estimate a BH mass in this source by scaling this correlation with those detected in a number of GBHs and M101 ULX-1 (see details below, in Sect. 4.3).

4.2. X-ray spectra of ULXs

As we have pointed out above, there are different scenarios for a ULX central source: stellar mass black hole, intermediate-mass black hole and neutron star. The ULX population may not be homogeneous, and therefore different ULXs may be related to different origins. In particular, Soria & Kong (2016) developed arguments to introduce two subclasses of ULXs: (i) hyperluminous X-ray sources (e.g., ESO 243–49 HLX–1) and supersoft ULXs (e.g., M101 ULX–1), but discussion of this classification is beyond the scope of this paper. However, in spite of these differences and their classifications as ULXs, we can suggest a possible similarity between ESO 243–49 HLX–1 source and M101 ULX–1 and a number of GBHs in terms of their index-mass accretion rate ($\Gamma$-$N_{\text{bmc}}$) correlations.

We note that Yan et al. (2015) did not find any similarity between HLX-1 and GBHBs in terms of the relations of the total radiated energy versus peak luminosity, as well as the total radiated energy vs. e-folding rise/decay timescales (see Figures 8 and 10, respectively there). On the other hand, we compared the $\Gamma$-$N_{\text{bmc}}$ correlations of M101 ULX-1, ESO 243-49 HLX-1 and those found in GBHs, and found they are self-similar. We therefore applied them to estimate BH mass in ESO 243-49 HLX-1 (see Figure 8).

4.3. Estimate of BH mass in ESO 243-49 HLX-1 and comparison with the estimate found in the literature

To estimate BH mass, $M_{\text{BH}}$ of ESO 243–49 HLX–1, we chose three galactic sources [XTE J1550–564, H 1742–322 (see ST09) and 4U 1630-47 (see STS14)] and the extragalactic source M101 ULX-1 (see TS16), whose BH masses and distances have been estimated previously (see Table 4), as the reference sources. In particular, the BH mass for XTE J1550–564 was estimated by dynamical methods. For the BH mass estimate of ESO 243–49 HLX–1
we also used the BMC normalizations, $N_{BMC}$ of these reference sources. Thus, we scaled the index vs $N_{BMC}$ correlations for these reference sources with that of the target source ESO 243-49 HLX-1 (see Figure 8). The value of the index saturation is almost the same, $\Gamma \sim 3$ for all these target and reference sources. We applied the correlations found in these four reference sources to comprehensively cross-check of a BH mass estimate for ESO 243-49 HLX-1.

Figure 8 shows the correlations of the target source (ESO 243-49 HLX-1) and the reference sources have similar shapes and index saturation levels. This allows us to make a reliable scaling of these correlations with that of ESO 243-49 HLX-1. To implement the scaling technique, we introduce an analytical approximation of the $\Gamma - N_{BMC}$ correlation, fitted by a function (see also ST09)

$$F(x) = A - (D \cdot B) \ln \{\exp[(1.0 - (x/x_{tr})^\beta)/D] + 1\}. \quad (1)$$

with $x = N_{bmc}$.

As a result of fitting the observed correlation by this function $F(x)$ we obtained a set of the best-fit parameters $A$, $B$, $D$, $N_{tr}$, and $\beta$. The meaning of these parameters is described in details in our previous paper [Titarchuk & Seifina (2016), hereafter TS16]. This function $F(x)$ is widely used for a description of the correlation of $\Gamma$ versus $N_{bmc}$ [Sobolewska & Papadakis (2009), ST09, Seifina & Titarchuk (2010), Shrader et al. (2010), STS14, Giacche et al. (2014) and TS16].

To implement this BH mass estimate for the target source, we relied on the same shape of the $\Gamma - N_{bmc}$ correlations for the target source and those for the reference sources. The only difference in values of $N_{bmc}$ for these four sources is in a ratio of BH mass to the squared distance, $M_{BH}/d^2$. Figure 8 shows the index saturation value, $A$ is approximately the same for the target and reference sources (see also the second column in Table 3). For example, the shapes of the correlations for ESO 243-49 HLX-1 (black line) and H 1734-322 (green line]) are similar and the only difference of these correlations is in the BMC normalization values (proportional to $M_{BH}/d^2$ ratio).

To estimate BH mass, $M_t$ of ESO 243-49 HLX-1 (target source) we shifted the reference source correlation along $N_{bmc}$−axis to that of the target source (see Fig. 8).

$$M_t = M_r \frac{N_t}{N_r} \left(\frac{d_t}{d_r}\right)^2 f_G, \quad (2)$$

where t and r correspond to the target reference sources, respectively and a geometric factor,
\( f_G = (\cos \theta)_r/(\cos \theta)_t \), the inclination angles \( \theta_r \) and \( \theta_t \) are distances to the reference and target sources respectively (see ST09). The values of \( \theta \) are listed in Table 4 and when some of these \( \theta \)-values were unavailable then we assumed that \( f_G \sim 1 \).

In Figure 8 we show the \( \Gamma - N_{bmc} \) correlation for ESO 243-49 HLX-1 (black points) obtained using the Swift spectra along with the correlations for three Galactic reference sources [XTE J1550-564 (blue), 4U 1630-47 (pink), and H 1743-322 (green), see left panel] and one extragalactic reference source M101 ULX-1 (red, see right panel). The BH masses and distances for each of these target-reference pairs are shown in Table 4.

The BH mass, \( M_t \) for HLX-1 can be evaluated using a formula (see TS16)

\[
M_t = C_0 N_t d_t^2 f_G \tag{3}
\]

where \( C_0 = (1/d_r^2)(M_r/N_r) \) is the scaling coefficient for each of the pairs (target and reference sources), masses \( M_t \) and \( M_r \) are in solar units and \( d_r \) is the distance to a particular reference source measured in kpc.

We used values of \( M_r \), \( M_t \), \( d_r \), \( d_t \), and \( \cos(i) \) from Table 4 and then we calculated the lowest limit of the mass, using the best-fit value of \( N_t = (4.2 \pm 0.1) \times 10^{-6} \) taken at the beginning of the index saturation (see Fig. 8) and measured in units of \( L_{39}/d_{10}^2 \) erg s\(^{-1}\) kpc\(^{-2}\) [see Table 3 for values of the parameters of function \( F(N_t) \) (see Eq. 1)]. Using \( d_r \), \( M_r \), \( N_r \) (see ST09) we found that \( C_0 \sim 2.0, 1.9, 1.72 \) and 1.83 for M101 ULX-1, XTE J1550-564, H 1723-322 and 4U 1630-472, respectively. Finally, we obtained that \( M_{HLX} \geq 7.2 \times 10^4 M_\odot \) \( (M_{HLX} = M_t) \) assuming \( d_{HLX} \sim 95 \) Mpc \( (\text{Soria et al. 2010}) \) and \( f_G \sim 1 \). We summarize all these results in Table 4.

It is worth noting that the inclination of ESO 243-49 HLX-1 may be different from those for the reference Galactic sources \( (i \sim 60 - 70^\circ) \), therefore we take this BH mass estimate for ESO 243-49 HLX-1 as the lowest BH mass value because that \( M_{HLX} \) is reciprocal function of \( \cos(i_{HLX}) \) [see Eq. 3 taking into account that \( f_G = (\cos \theta)_r/(\cos \theta)_t \) there]. The obtained BH mass estimate agrees with a high bolometrical luminosity for ESO 243-49 HLX-1 and \( kT_s \) value which is in the range of 50–140 eV. A very soft spectrum is consistent with a relatively cold disk for a compact object of high mass. For example, Shakura & Sunyaev, (1973) (see also Novikov & Thorne, 1973) provide an effective temperature of the accretion material of \( T_{\text{eff}} \propto M_{BH}^{-1/4} \).

Yan et al. (2015), suggested that the soft-to-hard state transition luminosity of HLX-1 is at 2% of \( L_{Edd} \) based on an analogy to the Galactic BHs, and estimated the mass of the accreting compact object as \((8 \pm 4) \times 10^4 M_\odot \). It is also important to emphasize that this original mass estimate for the central source in HLX-1, based on a particular X-ray luminosity, is consistent with our scaling BH mass estimate for HLX-1. In addition, our
HLX-1 mass estimate is also consistent with an IMBH mass of $\sim 10^4 - 10^5 \, M_\odot$ derived using a detailed X-ray spectral modelling (Farrell et al. 2010; Davis et al. 2011; Servillat et al. 2011; Godet et al. 2012; Webb et al. 2012) and with the results obtained by Cseh et al. (2014) ($M_{BH} < 10^6 \, M_\odot$).

We derived a bolometric luminosity between $3 \times 10^{41} \, \text{erg/s}$ and $4 \times 10^{42} \, \text{erg/s}$ based on the normalization of the BMC model. It is evident that this high luminosity is difficult to achieve in a X-ray binary unless the accretor has a mass greater than $10^3 \, M_\odot$ to be consistent with the Eddington limit. Our luminosity estimate agrees with that previously obtained for HLX-1 with different instruments (see Farrell et al. 2009; Godet et al. 2009; Yan et al. 2015). However, using optical observations (FORS2 spectrograph on the Very Large Telescope), Soria et al. (2013) found that the H$_\alpha$ emission from HLX-1 ($L_{H_\alpha} \approx \text{a few times of} \, 10^{37} \, \text{erg/s}$) could be excited by X-ray luminosity of $\sim 10^{40} \, \text{erg/s}$, which is an order of magnitude smaller than the mean luminosity observed over 2009 – 2012. Soria et al. suggested that the observed H$_\alpha$ emission comes not from the disk surface (it does not have a disk-like profile) but from some material further out, or perhaps from the remnants of previous outflows.

4.4. Possible effects on an estimate of BH mass in ESO 243–49

Now we discuss some potential sources of systematic errors which can affect the validity of our method.

4.4.1. Suggestion on a similarity of Galactic BHs binaries and HLX–1

This similarity is based on comparative analysis of spectral properties for these two classes of objects that are revealed during X-ray outbursts (see Sect. 3.2). In particular, we clearly observe softening of X-ray emission with X-ray outburst flux in HLX–1 (e.g., Fig. 1), which is similar to that in the bright Galactic low-mass X-ray binaries.

The hardness-intensity diagram shown in Fig. 1 are model independent. We demonstrate that spectra of HLX–1 are poorly fitted by power-law, bbody models and their combination (see Table 2). The detailed modeling of X-ray spectral shape reveals a strong rise of the low-energy component (for photon energies less than 1 keV) along with a steepening of the higher energy tail during outburst development. This observational effect is a strong confirmation of the converging inflow paradigm in the case of a BH source [see Shaposhnikov & Titarchuk (2009)].
4.4.2. Validity of BH mass determination in ESO 243–49 using Galactic BH mass values

In this paper, we used Galactic X-ray binaries to compare their spectral characteristic with those established in ESO 243–49 HLX–1. We used XTE J1550–564 for which the mass of compact object (BH) is evaluated applying “gold standard” dynamical measurements (Orosz, 2002). Therefore, BH mass scaling for a pair of ESO 243–49 HLX–1 and XTE J1550–564 provides a reliable BH mass estimate for ESO 243–49 HLX–1. However, the BH mass values of other objects used for scaling procedure, such as 4U 1630–47, H 1743–322, are not based on dynamical measurements and can not be considered as “traditional” BH estimates. It is worth noting that the BH mass value for ESO 243–49 using these BH estimates for 4U 1630–47, H 1743–322 well agrees with that applying BH mass of XTE J1550–564.

4.4.3. Validity of BH mass estimate in ESO 243–49 using scaling with M101 ULX–1

We used the extragalactic source M101 ULX–1 for a BH mass estimate in ESO 243–49. We should point out a wide range of the BH mass estimates for M101 ULX–1 obtained by applying X-ray (Kong et al. 2004; Kong & Di Stefano, 2005; TS16) and optical data (Liu et al. 2013). In particular, Kong et al. (2004) based on Chandra and XMM-Newton observations of this source during the 2004 July outburst, obtained an estimate for the BH mass greater than 2800 M⊙, while, Kong & Di Stefano (2005) suggested that \( M_{m101} \) is in the range of \( 1.3 \times 10^3 \) – \( 3 \times 10^4 \) M⊙. In our recent paper (see TS16) we found, using Swift (2006 – 2013) and Chandra (2000, 2004, 2005) data, that the BH mass in this source is of order of \( \sim 10^4 \) M⊙ using scaling method (ST09) (which is comparable with the Kong & Di Stefano’s BH values). On the other hand, based on HST optical data of M101 ULX–1 and using the dynamical method, Liu et al. (2013) estimated mass of the compact object as 5 – 1000 M⊙. We note that Liu et al. (2013) made this BH mass estimate based on radial velocity analysis and adopted a simple two-point mass model for a binary without taking into account a tidal influence and a heating effect to the optical star by the X-ray companion, which can significantly change the resulting BH mass value (Antokhina & Cherepashchuk 1994; Antokhina et al. 2016; Petrov et al. 2016).

This shows a tendency for smaller values of BH mass, \( M_{m101}^{opt} \) using optical data and higher values \( M_{m101}^X \) when X-ray data are used. We estimated the BH mass in ESO 243–49, \( 3 \times 10^3 < M_{ESO} < 7 \times 10^4 \) M⊙ by applying the scaling technique with X-ray mass \( M_{m101}^X \) \( (2.8 \times 10^3 – 3 \times 10^4 \) M⊙, see TS16). When we applied an optical BH mass estimate \( M_{m101}^{opt} \) \( (5 – 10^3 \) M⊙), we found lower masses within a wide interval of from 7 M⊙ to \( 2 \times 10^3 \) M⊙ for \( M_{ESO} \) which is inconsistent with so called fundamental plane’ results \( 10^3 < M_{ESO} < 10^5 \).
we therefore conclude that our scaling method applied to the pair of BH sources ESO 243–49 and M101 ULX–1 leads to better constraints with the case of the X-ray BH mass than that of optical BH mass.

We note that the massive BHs in ESO 243–49 and M101 ULX–1 are not located in galactic nuclei as it should be in the case of supermassive BHs (SMBHs). As is known, the stellar bulge of almost every massive galaxy contains a SMBH (Ferrarese & Ford 2000). When galaxies merge they can form two or more SMBHs with their stellar bulges which are outside of the galactic centre. Following a merger, a pair of inspiraling SMBHs can remain for a while in separation before forming a tight binary or finally merge (see Begelman et al. 1980). Similarly, the high mass of some IMBHs can be formed as a result of merging of galaxy nuclei. This scenario can be a valid argument for large masses in M101 ULX–1 and ESO 243–49.

There are still many open questions from a theoretical point of view how to explain a formation of massive BHs (such as IMBHs). Recently, Latif & Ferrara (2016) discussed possible formation mechanisms of supermassive BHs. In particular, they suggested that “seed” BHs were formed early on, and grow either through rapid accretion or BH/galaxy mergers. Latif & Ferrara offered three most popular BH formation scenarios: dynamical evolution of dense nuclear star clusters, a core-collapse of massive stars, and a collapse of a protogalactic metal free gas cloud.

We included M101 ULX–1 in a scaling BH mass sample for ESO 243–49, even though Soria & Kong (2016) presented strong arguments that the observed emission in M101 ULX–1 is not a classic accretion disk. Specifically, Soria & Kong re-examined the X-ray spectral and timing properties of M101 ULX–1 using a series of Chandra and XMM-Newton observations and showed that their model of an optically thick outflow is consistent with the data. They showed that the characteristic radius, $R_{BB}$ of a thermal emitter and its color temperature, $kT_{BB}$ are approximately related to each other as $R_{BB} \propto T_{BB}^{-2}$. In addition, they revealed absorption edges fitting the M101 ULX–1 spectra applying thermal plasma models. They interpreted this modeling along with the data as evidence of a clumpy, multi-temperature outflow around ULX–1, in particularly in the HSS. Soria & Kong highlighted that M101 ULX–1 belongs to ultraluminous supersoft sources (ULSs) rather than to ULX population. It might therefore be argued that if Soria & Kong are correct then the method of the BH mass determination applied here might not be applicable for M101 ULX–1.

Our arguments which are based on the correlation of the photon index with the mass accretion rate in M101 ULX–1 and its resemblance with those in a number of Galactic sources allow us argue that the innermost part of the accretion flow (the disk-Compton cloud-converging flow configuration) is similar in these sources (see TS16 and Fig. 5 here).
Moreover, this index-mass accretion rate correlation for M101 ULX-1 is almost identical in terms of the shape for that in ESO 243–49 HLX–1 and those in the chosen Galactic BHs. It is not by chance that we compared all these correlations with each other and found that they are self-similar.

It is worthwhile to point out that Soria & Kong (2016) described the hard tail of the Chandra ULX spectrum of M101 ULX-1 using higher temperatures. They revealed a relatively hard tail in the 0.3 – 6 keV energy range and applied three *mekal* components in addition to sample a soft blackbody component. The high count-rate spectra of three of these *mekal* components are associated with temperatures of 0.6 keV, 1 keV and $\geq 2$ keV. However, when Soria & Kong replaced this multiple component model by the single *Comptt* (Titarchuk 1994) component (see Table A3 there), they also obtained a good quality fit with the seed photon temperatures in the range of 90 – 135 eV.

5. Conclusions

We found the low–high state transitions observed in HLX-1 using the full set of *Swift*-XRT observations (2008 – 2015) and we showed the observed spectra can be fitted by the BMC model for all observations, independently of the spectral state of the source.

We investigated the X-ray outburst properties of HLX-1 and confirmed the presence of spectral state transitions during the outbursts using of hardness-intensity diagrams (Godet et al. 2009; Servillat et al. 2011) and the index–normalization (or $\dot{M}$) correlation observed in HLX-1, which were similar to those in Galactic BHs. In particular, we found that HLX-1 follows the $\Gamma - \dot{M}$ correlation previously obtained for extragalactic IMBH source M101 ULX-1 and Galactic BHs, 4U 1630-472, XTE J1550-564 and H 1743-322 taking into account the particular values of the $M_{BH}/d^2$ ratio (Figure 8). The photon index $\Gamma$ of ESO 243-49 HLX-1 spectrum is in the range $\Gamma = 1.6 - 3.0$. We also estimated the peak bolometric luminosity, which is about $4 \times 10^{42}$ erg s$^{-1}$.

We used the observed index-mass accretion rate correlation to estimate $M_{BH}$ in HLX-1. This scaling method was successfully implemented to find BH masses of Galactic (e.g. ST09, STS13) and extragalactic black holes [TS16, Sobolewska & Papadakis (2009); Giacche et al. (2014)]. An application of the scaling technique to the X-ray data from XRT/Swift observations of ESO 243-49 HLX-1 allowed us to estimate $M_{BH}$ for this particular source. We found values of $M_{BH} \geq 7.2 \times 10^4 M_\odot$.

Furthermore, our BH mass estimate agrees the previously established IMBH mass of $\sim 10^4 - 10^5 M_\odot$ derived using the detailed X-ray spectral modelling (Farrell et al. 2010;
Combining all these estimates with the inferred low temperatures of the seed disk photons $kT_s$, we can state that the compact object of ESO 243-49 HLX-1 probably is an intermediate-mass black hole with a mass at least $M_{BH} > 7.2 \times 10^4 M_\odot$.

This research was performed using data supplied by the UK *Swift* Science Data Centre at the University of Leicester. We also acknowledge the interesting remarks and points of the referee.

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This preprint was prepared with the AAS L\TeX macros v5.2.
Table 1. List of *Swift* observations of ESO 243-49 HLX-1

| Obs. ID                     | Start time (UT) | End time (UT) | MJD interval        |
|-----------------------------|-----------------|---------------|---------------------|
| 00031287(001-164, 233, 235-238 240-246, 248-250, 252, 254, 255)\(^1,2,3,4\) | 2008 Oct. 24    | 2012 Sept.     | 54763.6 – 56198.9   |
| 00032577(001-100)\(^4\)     | 2012 Oct. 2      | 2015 Apr. 10  | 56202.5 – 57122.5   |
| 00049794(001, 003)\(^4\)    | 2013 March 14    | 2013 March 17 | 56365.3 – 56369.3   |
| 00080013001\(^4\)          | 2012 Nov. 21 02:05:59 | 2012 Nov. 21 07:12:03 | 56252.1 – 56252.3   |
| 00091907(006-037)\(^4\)    | 2014 May 15      | 2015 March 5  | 56792.1 – 57086.5   |
| 00092116(001-020)          | 2015 April 5     | 2015 Sept. 22 | 57117.7 – 57287.1   |

References. (1) Soria et al. 2010; (2) Farrell et al. 2013; (3) Webb et al. 2010, 2014; (4) Yan et al. 2015.
Table 2. Best-fit parameters of the combined \textit{Swift} spectra of ESO 243-49 HLX-1 in the 0.3–10 keV range using the following four models\textsuperscript{1}: phabs*power-law, phabs*bbbody, phabs*(bbbody+power-law) and phabs*bmc

| Parameter | Band-A | Band-B | Band-C | Band-D | Band-E | Band-F | Band-G |
|-----------|--------|--------|--------|--------|--------|--------|--------|
| Hardness ratio | HR | > 1 | 0.5 – 1 | 0.25 – 0.5 | 0.13 – 0.25 | 0.07 – 0.13 | 0.03 – 0.07 | < 0.03 |
| Model |        |        |        |        |        |        |        |
| phabs | N\textsubscript{H} | 5.1 ± 0.1 | 5.2 ± 0.2 | 5.1 ± 0.1 | 5.1 ± 0.1 | 5.2 ± 0.1 | 5.1 ± 0.1 | 5.05 ± 0.08 |
| Power-law | \(\Gamma\textsubscript{pow} \) | 1.4 ± 0.1 | 1.6 ± 0.2 | 1.9 ± 0.2 | 2.4 ± 0.1 | 2.6 ± 0.2 | 2.8 ± 0.3 | 3.9 ± 0.4 |
|             | \(N\textsubscript{bmc}^{\text{pow}} \) | 0.24 ± 0.05 | 0.43 ± 0.02 | 0.97 ± 0.05 | 2.7 ± 0.4 | 3.04 ± 0.06 | 4.3 ± 0.1 | 6.2 ± 0.1 |
|             | \(\chi^2\) (d.o.f.) | 1.15 (138) | 1.1 (180) | 1.3 (209) | 1.5 (223) | 2.6 (250) | 3.2 (93) | 2.1 (219) |
| phabs | N\textsubscript{H} | 5.0 ± 0.1 | 5.0 ± 0.2 | 4.9 ± 0.2 | 5.0 ± 0.1 | 5.0 ± 0.09 | 4.9 ± 0.2 | 5.03 ± 0.06 |
| bbbody | \(T_{BB} \) | 280 ± 10 | 170 ± 5 | 85 ± 9 | 97 ± 6 | 110 ± 9 | 85 ± 7 | 120 ± 10 |
|             | \(N\textsubscript{bb}^{\text{tr}} \) | 0.53 ± 0.04 | 0.9 ± 0.3 | 2.1 ± 0.5 | 3.1 ± 0.5 | 3.5 ± 0.4 | 4.1 ± 0.5 | 5.0 ± 0.3 |
|             | \(\chi^2\) (d.o.f.) | 6.1 (138) | 4.5 (180) | 3.8 (209) | 2.56 (223) | 1.4 (250) | 1.2 (93) | 1.1 (219) |
| phabs | N\textsubscript{H} | 5.1 ± 0.1 | 5.1 ± 0.1 | 5.1 ± 0.1 | 5.1 ± 0.1 | 5.2 ± 0.2 | 5.1 ± 0.1 | 5.08 ± 0.09 |
| bbbody | \(T_{BB} \) | 300 ± 10 | 180 ± 9 | 90 ± 6 | 100 ± 20 | 120 ± 8 | 92 ± 5 | 110 ± 8 |
|             | \(N\textsubscript{bb}^{\text{tr}} \) | 0.34 ± 0.05 | 0.7 ± 0.2 | 1.8 ± 0.6 | 2.6 ± 0.4 | 4.3 ± 0.5 | 4.9 ± 0.6 | 5.0 ± 0.2 |
| Power-law | \(\Gamma\textsubscript{pow} \) | 1.3 ± 0.2 | 1.7 ± 0.3 | 1.8 ± 0.1 | 2.3 ± 0.2 | 2.4 ± 0.2 | 2.6 ± 0.1 | 2.9 ± 0.3 |
|             | \(N\textsubscript{bmc}^{\text{pow}} \) | 0.82 ± 0.03 | 0.65 ± 0.03 | 0.48 ± 0.09 | 0.39 ± 0.07 | 0.4 ± 0.4 | 0.67 ± 0.02 | 0.52 ± 0.03 |
|             | \(\chi^2\) (d.o.f.) | 1.24 (136) | 1.18 (178) | 1.24 (207) | 1.23 (221) | 1.26 (248) | 1.19 (91) | 1.14 (217) |
| phabs | N\textsubscript{H} | 5.0 ± 0.1 | 5.0 ± 0.1 | 4.9 ± 0.1 | 5.0 ± 0.1 | 5.0 ± 0.1 | 4.9 ± 0.1 | 5.02 ± 0.04 |
| bmc | \(\Gamma\textsubscript{bmc} \) | 1.6 ± 0.2 | 1.76 ± 0.09 | 2.01 ± 0.05 | 2.68 ± 0.08 | 2.8 ± 0.1 | 2.96 ± 0.09 | 3.0 ± 0.1 |
|             | \(T_s \) | 54 ± 9 | 61 ± 8 | 52 ± 9 | 139 ± 8 | 142 ± 10 | 105 ± 9 | 130 ± 10 |
|             | \(\log A \) | 0.10 ± 0.04 | 0.17 ± 0.05 | 1.1 ± 0.3 | -1.09 ± 0.05 | -1.22 ± 0.09 | -1.06 ± 0.05 | -0.7 ± 0.3 |
|             | \(N\textsubscript{bmc}^{\text{tr}} \) | 0.36 ± 0.09 | 0.6 ± 0.2 | 0.98 ± 0.07 | 2.5 ± 0.3 | 3.08 ± 0.06 | 4.03 ± 0.05 | 5.2 ± 0.1 |
|             | \(\chi^2\) (d.o.f.) | 0.86 (136) | 0.89 (178) | 0.96 (207) | 0.93 (221) | 1.03 (248) | 0.79 (91) | 1.14 (217) |

\textsuperscript{1} Errors are given at the 90\% confidence level. \textsuperscript{†} The normalization parameters of blackbody and bmc components are in units of \(L_{33}^{\text{soft}} / d_{10}^2 \) erg s\(^{-1}\) kpc\(^{-2}\), where \(L_{33}^{\text{soft}}\) is the soft photon luminosity in units of 10\(^{33}\) erg s\(^{-1}\), \(d_{10}\) is the distance to the source in units of 10 kpc, and power-law component is in units of 10\(^{-6}\) keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV. \(N_H\) is the column density for the neutral absorber, in units of 10\(^{20}\) cm\(^{-2}\) (see details in the text). \(T_{BB}\) and \(T_s\) are the temperatures of the blackbody and seed photon components, respectively (in eV). \(\Gamma\textsubscript{pow}\) and \(\Gamma\textsubscript{bmc}\) are the indices of the power law and bmc, respectively.

Table 3. Parameterizations for the reference and target sources

| Reference source | \(A\) | \(B\) | \(D\) | \(x_{1r}\) | \(\beta\) |
|------------------|-------|-------|-------|----------|--------|
| XTE J1550-564 RISE 1998 | 2.84 ± 0.08 | 1.8 ± 0.3 | 1.0 | 0.132 ± 0.004 | 0.61 ± 0.02 |
| H 1743-322 RISE 2003 | 2.97 ± 0.07 | 1.27 ± 0.08 | 1.0 | 0.053 ± 0.001 | 0.62 ± 0.04 |
| 4U 1630-472 | 2.88 ± 0.06 | 1.29 ± 0.07 | 1.0 | 0.045 ± 0.002 | 0.64 ± 0.03 |
| M101 ULX-1 | 2.88 ± 0.06 | 1.29 ± 0.07 | 1.0 | [4.2±0.2]×10\(^{-4}\) | 0.61 ± 0.03 |

| Target source | \(A\) | \(B\) | \(D\) | \(x_{1r}[\times 10^{-6}]\) | \(\beta\) |
|---------------|-------|-------|-------|-----------------|--------|
| ESO 243-49 HLX-1 | 3.00 ± 0.04 | 1.27 ± 0.05 | 1.0 | 4.25 ± 0.03 | 0.62 ± 0.05 |
Table 4. BH masses and distances

| Source               | $M_{\text{dyn}}^a$ (M$_\odot$) | $i^a_{\text{orb}}$ (deg) | $d^b$ (kpc) | $M_{\text{lum}}$ (M$_\odot$) | $M_{\text{scal}}$ (M$_\odot$) |
|----------------------|---------------------------------|--------------------------|-------------|-----------------------------|-------------------------------|
| XTE J1550-564        | 9.5±1.1                         | 72±5                     | ∼6          | ...                         | 10.7±1.5$^c$                 |
| H 1743-322           | ...                             | 75±3                     | 8.5±0.8     | ...                         | 13.3±3.2$^c$                 |
| 4U 1630-47            | ...                             | ≤70                      | ∼10 – 11    | ...                         | 9.5±1.1                      |
| M101 ULX-1           | 5 – 1000                        | (6.4±0.5)×10$^3$, (7.4±0.6)×10$^3$ | ...         | ≥3.2 × 10$^4$, ≥4.3 × 10$^4$ |                               |
| ESO 243-49 HLX-1     | ...                             | ~95×10$^3$               | 8±4 × 10$^4$| ≥7.2 × 10$^4$               |                               |

References. (1) Orosz et al. 2002; (2) Sánchez-Fernández et al. 1999; (3) Sobczak et al. 1999; (4) Petri 2008; (5) STS14; (6) Shappee & Stanek 2011; (7) Mukai et al. 2005; (8) Kelson et al. 1996; (9) TS15; (10) Liu et al. (2013); (11) Farrell et al., 2009; (12) Soria et al. 2013

Notes. $^a$ Dynamically determined BH mass and system inclination angle, $^b$ Source distance found in literature, $^c$ Scaling value found by ST09.
Fig. 1.— Hardness-intensity diagram for ESO 243-49 HLX-1 using *Swift* observations (2008 – 2015) during spectral evolution from the low/hard state to the high/soft states. In the vertical axis, the hardness ratio (HR) is the ratio of the source counts in the two bands: the hard (1.5 – 10 keV) and soft (0.3 – 1.5 keV) passbands. The HR decreases with a source brightness in the 0.3 – 10 keV energy range (horizontal axis). For clarity, we plot only one point with error bars (shown in the bottom right corner) to demonstrate typical uncertainties for the HR and count rate.
Fig. 2.— *Chandra*/HRC-I (0.1 – 10 keV) image of the ESO 243-49 HLX-1 field taken on UT 2009 July 4 where yellow small circle corresponds to the location of ESO 243-49 HLX-1 and white arrow points correspond to 2XMM J011050.4-460013 source. The large circles (labelled nominal and offset) show the two pointing positions used to extract the light curve and spectrum, to minimize contamination of ESO 243-49 HLX-1 by a nearby source.
Fig. 3.— *Swift*/XRT light curve of ESO 243-49 HLX-1 in the 0.3−10 keV energy range during 2008−2015. Red points mark the source signal (with 2-σ detection level) and green points indicate the background level. The Blue dashed line indicates the MJD of the *Chandra*/HRC-I observation presented in Figure 2.

Fig. 4.— Seven $E_{F_{E}}$ spectral diagrams which are related to different spectral states of ESO 243-49 HLX-1 using the BMC model. The data are taken from XRT/*Swift* observations related to different hardness ratios: (left:) $HR_{0.03}$ (black, HSS), $0.03 < HR < 0.07$ (bright blue, HSS), $0.5 < HR_{1}$ (pink, LHS); (right:) $0.1 < HR_{0.2}$ (blue, IS), $0.07 < HR_{0.2}$ (red, HSS), $0.2 < HR_{0.5}$ (orange, IS), $HR > 1$ (green, LHS).
Fig. 5.— A suggested geometry of the system. Disk soft photons are upscattered (Comptonized) off relatively hot plasma of the transition layer.
Fig. 6.— Examples of E*F(E) spectral diagram of ESO 243–49 HLX–1 during the hard, intermediate, and soft state events. The best-fit *Swift* spectra (top panel) using the BMC model, along with $\Delta \chi$ (bottom panel) for the hard (band-B) state ($\chi^2_{\text{red}} = 0.89$ for 178 d.o.f.), for the intermediate (band-E) state ($\chi^2_{\text{red}} = 1.03$ for 248 d.o.f.) and for the soft (band-G) state ($\chi^2_{\text{red}} = 1.04$ for 317 d.o.f.). The best-fit model parameters are $\Gamma = 1.76 \pm 0.09$, $T_s = 61 \pm 8$ eV (for the low/hard state), $\Gamma = 2.8 \pm 0.1$, $T_s = 142 \pm 10$ eV (for the intermediate state, and $\Gamma = 3.0 \pm 0.1$, $T_s = 130 \pm 10$ eV (for the high/soft state, see more details in Table 2).
Fig. 7.— Correlation of the photon index $\Gamma (= \alpha + 1)$ versus the BMC normalization $N_{BMC}$ (proportional to mass accretion rate) in units of $L_{39}/D_{10}^2$.

Fig. 8.— Scaling of the photon index $\Gamma$ versus the normalization $N_{BMC}$ for ESO 243–49 HLX–1 (black points indicate the target source) using the correlations for the Galactic reference sources, 4U 1630-472, XTE J1550-564, and H1743-322 (pink, blue, and green, left panel) and comparison of $\Gamma – N_{BMC}$ correlations for extragalactic sources, ESO 243-49 HLX–1 and M101 ULX-1 (red points, see right panel)