X-RAY VARIABILITY AND HARDNESS OF ESO 243–49 HLX-1: CLEAR EVIDENCE FOR SPECTRAL STATE TRANSITIONS

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ABSTRACT

The ultraluminous X-ray (ULX) source ESO 243–49 HLX-1, which reaches a maximum luminosity of \(10^{42}\) erg s\(^{-1}\) (0.2–10 keV), currently provides the strongest evidence for the existence of intermediate-mass black holes (IMBHs). To study the spectral variability of the source, we conduct an ongoing monitoring campaign with the Swift X-ray Telescope (XRT), which now spans more than two years. We found that HLX-1 showed two fast rise and exponential decay type outbursts in the Swift XRT light curve with increases in the count rate of a factor \(\sim 40\) separated by \(375 \pm 13\) days. We obtained new XMM-Newton and Chandra dedicated pointings that were triggered at the lowest and highest luminosities, respectively. From spectral fitting, the unabsorbed luminosities ranged from \(1.9 \times 10^{40}\) to \(1.25 \times 10^{42}\) erg s\(^{-1}\). We confirm here the detection of spectral state transitions from HLX-1 reminiscent of Galactic black hole binaries (GBHBs): at high luminosities, the X-ray spectrum showed a thermal state dominated by a disk component with temperatures of 0.26 keV at most, and at low luminosities the spectrum is dominated by a hard power law with a photon index in the range 1.4–2.1, consistent with a hard state. The source was also observed in a state consistent with the steep power-law state, with a photon index of \(\sim 3.5\). In the thermal state, the luminosity of the disk component appears to scale with the fourth power of the inner disk temperature, which supports the presence of an optically thick, geometrically thin accretion disk. The low fractional variability (rms of 9% \pm 9%) in this state also suggests the presence of a dominant disk. The spectral changes and long-term variability of the source cannot be explained by variations of the beaming angle and are not consistent with the source being in a super-Eddington accretion state as is proposed for most ULX sources with lower luminosities. All this indicates that HLX-1 is an unusual ULX as it is similar to GBHBs, which have non-beamed and sub-Eddington emission, but with luminosities three orders of magnitude higher. In this picture, a lower limit on the mass of the black hole of \(>9000\) M\(_\odot\) can be derived, and the relatively low disk temperature in the thermal state also suggests the presence of an IMBH of a few \(10^3\) M\(_\odot\).

Key words: accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individuals (ESO 243-49 HLX-1)

Online-only material: color figures

1. INTRODUCTION

At present, only two families of black holes have convincing observational evidence: stellar-mass black holes detected in some X-ray binaries (e.g., Remillard & McClintock 2006) and super-massive black holes (SMBHs, \(10^6–10^9\) M\(_\odot\)) which are ubiquitous in the center of galaxies (Kormendy & Richstone 1995), sometimes revealing themselves as active galactic nuclei (AGNs). Remarkably, the existence of intermediate-mass black holes (IMBHs, \(10^2–10^5\) M\(_\odot\)) remains to be proven. Such objects may have been ejected following an interaction with the central SMBH and may remain in the halo of galaxies (Micic et al. 2011). They may be found in globular clusters, and the strongest case is the massive cluster G1 in M31, where dynamical, X-ray, and radio studies are consistent with a mass of \(2 \times 10^5\) M\(_\odot\) (Gebhardt et al. 2002; Kong et al. 2010). However, radio observations of Galactic globular clusters currently provide only upper limits on the mass (e.g., Maccarone & Servillat 2008; Lu & Kong 2011). IMBHs may also be the nuclei of satellite galaxies captured during hierarchical merging (King & Dehnen 2005). Finally, they may be the engine of some ultraluminous X-ray (ULX) sources (e.g., Miller et al. 2004).

A ULX is a non-nuclear extragalactic X-ray source that has an X-ray luminosity that exceeds the Eddington luminosity—\(1.3 \times 10^{38}\) (M\(_{\text{BH}}\)/M\(_\odot\)) erg s\(^{-1}\)—for a stellar-mass black hole (\(\sim 10\) M\(_\odot\)), supposing isotropic emission (see Roberts 2007, for a review). Different solutions have been proposed for the high luminosity problem of ULXs: (1) they are stellar-mass black holes emitting up to a factor of 10 above their Eddington limit (Begelman 2002) in a new “ultraluminous” state with super-Eddington accretion rates (e.g., Gladstone et al. 2009), (2) they are stellar-mass black holes with geometric (e.g., King 2009) or relativistic (Körding et al. 2002) beaming, or (3) the objects are IMBHs (e.g., Miller et al. 2004). It could also be a combination of these possibilities. For the most luminous ULXs above \(10^{41}\) erg s\(^{-1}\), the mass argument seems to be the main one that can convincingly explain the extreme luminosities.

One of the keys to further constraining the nature of the black hole in such sources is the study of their spectral and timing variability. Indeed, Galactic black hole binaries (GBHBs) containing stellar-mass black holes have been commonly observed to undergo transitions between different spectral states (e.g., Tananbaum et al. 1972; Kubota & Makishima 2004, see Remillard & McClintock 2006; Done et al. 2007; Belloni 2010...
for reviews). In the thermal state, the emission is dominated by an optically thick, geometrically thin accretion disk component (Shakura & Sunyaev 1973), with temperatures of \(\sim 1\) keV (e.g., Remillard & McClintock 2006). For such a disk extending down to the innermost stable circular orbit (ISCO), the luminosity \(L_{\text{disk}}\) inner temperature \(T_{\text{in}}\), and mass of the black hole \(M_{\text{BH}}\) are theoretically related: \(L_{\text{disk}} \propto T_{\text{in}}^4\) for a given \(M_{\text{BH}}\) and \(T_{\text{in}} \propto M_{\text{BH}}^{1/4}\) (Shakura & Sunyaev 1973; Makishima et al. 2000). In the hard state, the accretion disk appears to be fainter and cooler, and may be truncated at a large radius. The physical condition of material within this radius remains uncertain. Investigations of GBHBs in the hard state suggest that both synchrotron and Compton components contribute to the broad-band, power-law-like spectrum with typical photon indices of 1.4 < \(\Gamma\) < 2.1 (e.g., Remillard & McClintock 2006). Quasi-steady radio jets are commonly observed during this state, and clear correlations between the radio and X-ray intensities have been reported (Fender et al. 2004). Some GBHBs also showed a steep power-law state (\(\Gamma > 2.4\), e.g., Remillard & McClintock 2006).

Consideration of simple properties such as X-ray spectral hardness and fractional variability has led to a better understanding of the physical processes in action (e.g., Belloni 2010). In a hardness–intensity diagram (HID), the source shows a hysteresis curve between the thermal state and the hard state (Miyamoto et al. 1995; Maccarone & Coppi 2003). The root-mean-square (rms) variability amplitude is generally low in the thermal state (<10%), and can reach higher values in the hard state, with typical rms of \(\sim 30\%\). As seen in a hardness–rms diagram (HRD), the rms is anti-correlated with flux and positively correlated with hardness (Belloni 2010).

The lack of a canonical thermal state, with a dominant disk component, seems to be a common feature of ULXs (Feng & Kaaret 2005; Winter et al. 2006; Soria et al. 2009). Two ULXs showed such a thermally dominated spectrum: M82 X41.4+60 = X-1 (\(T_{\text{in}} = 1.1–1.5\) keV and \(L_{\text{X}} = 2–8 \times 10^{40}\) erg s\(^{-1}\); Feng & Kaaret 2010) and M82 X37.8+54 (0.9–1.6 keV and \(L_{\text{X}} = 4.4 \times 10^{39}\) erg s\(^{-1}\); Jin et al. 2010). Those sources could harbor a fast spinning black hole of 200–800 \(M_{\odot}\), and \(< 100 \ M_{\odot}\), respectively. ULXs with \(T_{\text{in}} \sim 0.1\) keV soft disk spectra may be good candidates for IMBHs in the thermal state. Some ULXs have shown soft excesses that could be fitted by such a cool disk emission (e.g., Miller et al. 2003). However, this component is not dominant, thus the sources are not in the canonical thermal state. A few intriguing ultraluminous supersoft sources show temperatures of \(\sim 0.1\) keV (e.g., Fabbiano et al. 2003; Mukai et al. 2003; Kong et al. 2004; Jin et al. 2011), but they could be explained by matter outflow from super-Eddington accretion (King & Pounds 2003).

ULXs do not generally show qualitative spectral changes when the luminosity varies (Feng & Kaaret 2005; Kaaret & Feng 2009; Grisé et al. 2010). Possible state transitions have been reported for some ULXs but they are subtle and not clearly similar to GBHBs, e.g., Holmberg IX X-1 (La Parola et al. 2001; Vierdayanti et al. 2010) or M82 X37.8+54 (Jin et al. 2010).

ULXs are generally highly variable sources showing variations of fluxes by a factor of \(\sim 5–15\) on timescales of hours to years (La Parola et al. 2001; Grisé et al. 2010; Kong 2011). On shorter timescales, six ULXs showed intrinsic variability with power spectra in the form of either a power-law- or a broken-power-law-like continuum (Heil et al. 2009) and in some cases quasi-periodic oscillations (QPOs; Casella et al. 2008; Strohmayer & Mushotzky 2009). In some ULXs the variability is significantly suppressed compared to bright GBHBs and AGNs (Heil et al. 2009).

To date, one of the best IMBH candidates is the most luminous ULX ESO 243–49 HLX-1 (HLX-1 for short) which reaches a luminosity of \(10^{42}\) erg s\(^{-1}\) (Farrell et al. 2009). The distance and thus the high X-ray luminosity of HLX-1 have been firmly confirmed through the detection of an H\(_\alpha\) line at a redshift consistent with that of its host galaxy (Wiersema et al. 2010). The \(\text{H}\alpha\) line has been found in the spectrum of the optical counterpart which falls inside the Chandra error circle of the source (\(0.3\) at a 95% confidence level; Webb et al. 2010; see also Soria et al. 2010). Observations of HLX-1 with the Swift X-ray Telescope (XRT) in 2009 August showed a hardening of the source at low luminosities which was interpreted as the first evidence for a change to the hard spectral state (Godet et al. 2009).

Our aim in this paper is to measure the spectral hardness and the variability of HLX-1 at different luminosity states, using all the X-ray data available from current observatories\(^6\) in order to test similarities with GBHBs or other ULXs. For this purpose, we obtained new XMM-\textit{Newton} and Chandra dedicated pointings that were triggered at the lowest and highest luminosities, respectively. The X-ray data sets are described in Section 2. Spectral analysis of firstly the high-luminosity states (Section 3) and then the low-luminosity state (Section 4) follows. A global analysis is given in Section 5 and the final Section 6 discusses the properties of HLX-1 compared to GBHBs and other ULXs.

**2. DATA AND LONG-TERM VARIABILITY**

**2.1. Swift XRT Data**

HLX-1 has been regularly monitored by the Swift XRT since 2008 October. Since 2009 August, observations occurred on average every \(\sim 1–2\) weeks. All the data were processed with the Swift XRT pipeline\(^7\) version 0.12.4. We used the grade 0–12 events, giving slightly higher effective area at higher energies than grade 0 events. The background extraction region, chosen to be close to the source extraction region, is the same for all epochs. No \textit{XMM-Newton} sources are present inside the background extraction region.

We generated a light curve from all the \textit{Swift} pointings with a binning of a minimum of 50 counts bin\(^{-1}\) for the energy band 0.3–10 keV (Figure 1) using the Web interface (Evans et al. 2007, 2009). There is a recurrence in the light curve of 375 ± 13 days between the two increases that may be periodic, but this will have to be confirmed by further observations. If the behavior is indeed periodic, the next maximum would occur in 2011 August-September.\(^8\) The cause of this variability has been investigated in more details by Lasota et al. (2011).

We combined the data into different epochs labeled S1 to S10 in Figure 1, and extracted a spectrum for each epoch. A 20 pixel (47′′.2) radius circle was used to extract the source and the background spectra using XSELECT v2.4a. The ancillary files were created with XRTMKARF v0.5.6 and exposure maps generated with XRTEXPOMAP v0.2.7. The response file swxpc0to12s6_20070901v011.rmf was used in the spectral fitting process. We used a binning of a minimum of 20 counts

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\(^6\) Except two \textit{Chandra} HRC-I observations (Webb et al. 2010) as this instrument does not provide spectral information.

\(^7\) http://heasarc.gsfc.nasa.gov/docs/swift/analysis/

\(^8\) A new outburst was detected on 2011 August 15 (Godet et al. 2011), consistent with the possible period reported here.
Figure 1. Swift XRT light curve of HLX-1. The epochs that were grouped to generate spectra are shaded with labels S1 to S10. The dates of the XMM-Newton and Chandra observations are represented by vertical lines. (A color version of this figure is available in the online journal.)

| Table 1 |
|---------|
| XMM-Newton Observations of HLX-1 |
|----------------------------------|
| Obs. Name | ObsID       | Date         | MJD  | Exp. Time (ks) | Instrument | Mode       | Source Region | Background Region |
|-----------|-------------|--------------|------|----------------|------------|------------|---------------|-------------------|
| XMM1      | 0560180901  | 2004 Sep 23  | 53271| 21             | MOS1&2, pn | Full-frame | 22'5          | 50°0–63'4         |
| XMM2      | 0560180901  | 2008 Nov 28  | 54798| 50             | MOS1&2    | Full-frame | 27'/2          | 60°–76'           |
|           |             |              |      |                | pn         | Small window | 27'/2         | 3 × 27'           |
| XMM3      | 0655510201  | 2010 May 14  | 55330| 100            | MOS1&2    | Full-frame | 14'/2         | 40°–47'/2         |
|           |             |              |      |                | pn         | Small window | 14'/2         | 3 × 14'/2         |

bin$^{-1}$ for each spectrum except the S2 and S6 spectra in order to use the χ² statistic within Xspec 12.6 (Arnaud 1996). For the S2 and S6 spectra, we used the Cash statistic (Cash 1979) due to the lower number of counts in these spectra.

2.2. XMM-Newton EPIC Data

The field of ESO 243–49 and HLX-1 was observed three times with XMM-Newton (Table 1). HLX-1 was detected serendipitously at an off-axis angle of 9·29 in XMM1, and XMM2 was obtained to show the spectral variability of HLX-1 (Farrell et al. 2009). Following a transition to a very low flux state, we triggered the XMM3 observation.

The data were processed using the XMM-Newton Science Analysis System⁹ (SAS) v10.0 software with the most recent calibration files as of 2010 December 13. The observation data files (ODFs) were reduced using the epproc and emproc tasks to produce event lists. Single event light curves with energies exceeding 10 keV were generated for each camera in each observation in order to identify periods of high background related to soft proton flares. In the XMM1 and XMM2 observations the background levels were low in each camera with no flaring events, and so no good time interval (GTI) filtering was applied. However, during the XMM3 observation significant flaring events were present at the start and end of the exposure, with an additional small short-duration flare occurring ~16 ks into the observation. For the XMM3 data we therefore generated GTI files for the spectral extraction using the SAS task tabgtigen and cutoff count rates of 0.3 counts s$^{-1}$ and 0.1 counts s$^{-1}$ in the flare background light curves for the MOS and pn cameras, respectively. This filtering resulted in net exposure times of ~98 ks and ~99 ks (for pn and MOS, respectively). The same event filtering criteria as used for the production of pipeline products for the 2XMM catalog were used to produce light curves and spectra for each camera in each observation (e.g., single to double events for the pn and single to quadruple events for the MOS; Watson et al. 2009).

Source and background spectra were extracted for each camera for each observation, with response and ancillary files generated in turn using the tasks rmfgen and arfgen. The source extraction region radii (reported in Table 1) were chosen so as to optimize the signal to noise based on the detected count rates and off-axis position of HLX-1 in each of the observations (V. Braito 2011, private communication). The background extraction regions were chosen to be three times the area of the source extraction regions, so as to provide a robust estimate of the average background level at the position of HLX-1. The spectra were grouped to have at least 20 counts bin$^{-1}$ to provide sufficient statistics for spectral analyses using χ² statistic.

Source light curves were extracted using events in the energy range of 0.3–2 keV for the pn camera of all observations. They were binned at the frame time, which is 73.4 ms for XMM1 and is 5.9 ms for XMM2 and XMM3.

Figure 2 shows the count rates for each camera as a function of a hardness ratio. We see a discrepancy between the XMM1 MOS1 and MOS2 hardness ratios, with the MOS2 data showing a deficit in counts in the 0.3–1 keV energy band compared to both the MOS1 and pn data.¹⁰ We thus excluded energies below 1 keV for MOS2.

⁹ http://xmm.esa.int/sas/

¹⁰ This discrepancy had been noted earlier by Farrell et al. (2009), leading them to exclude energies below 0.5 keV for MOS2.
0.5 keV for MOS2. Despite this inconsistency between the MOS hardness ratios in the XMM1 data, a clear trend is observed indicating significant spectral hardening at lower luminosities, which is most clearly shown by the pn data (Figure 2, top panel).

2.3. Chandra ACIS-S Data

We obtained a 10 ks observation with the AXAF CCD Imaging Spectrometer (ACIS) on board Chandra on 2010 September 6 (ObsID 13122, MJD 55445) in the director’s discretionary time program after the source showed a re-brightening in X-rays (Godet et al. 2010). In order to limit pile-up, this observation was performed with the ACIS-S3 chip only and using a 1/4 chip subarray with a frame time of 0.8 s, leading to 5% dead time (0.041 s). The ACIS-S3 chip was chosen for its higher sensitivity to softer X-ray photons.

The data were processed using CIAO12 4.2 and CALDB 4.3.0 (Fruscione et al. 2006). We recreated the evt2 file following the corresponding thread13 to apply the latest calibration files. We extracted the source spectrum using psextract with an extraction circle of radius 2′ which includes 90% of the energy at 8 keV. The background spectrum was extracted in an annulus surrounding the source with inner and outer radii of 15″ and 50″, respectively (thus excluding the host galaxy). We then ran the tasks mkacisrmf and mkarf to obtain the instrument response files as recommended for ACIS-S data. The spectrum was binned with a minimum of 15 counts, and we discarded bins below 0.3 keV where the response of the instrument is not calibrated.

11 http://cxc.harvard.edu/proposer/POG, Proposers’ Observatory Guide
12 http://cxc.harvard.edu/ciao/
13 http://cxc.harvard.edu/ciao/threads/createL2

3. HLX-1 AT HIGH LUMINOSITIES

3.1. Re-analysis of XMM1 and XMM2 Spectra

Spectral fits of the XMM2 data with the relativistic model BHSPEC have been performed by Davis et al. (2011), and a more detailed analysis of all spectra with physically motivated accretion disk models used for GBHBs and ULXs is presented by O. Godet et al. (2011, in preparation). We used here simple models to fit the X-ray spectra, e.g., an absorption on the line of sight, a power-law model (pow), and a multi-temperature blackbody model (diskbb, Makishima et al. 1986). We used the wabs absorption model (Morrison & McCammon 1983). The Galactic absorption along the line of sight of ESO 243–49 is 1.8 × 10^20 atom cm^{-2} (Kalberla et al. 2005).

For XMM1, we fitted simultaneously the MOS1, MOS2, and pn spectra using Xspec and ignored channels with energy lower than 0.3 keV as well as channels tagged as bad. The spectra are well represented by a simple absorbed steep power law of index 3.5^{+0.3}_{-0.2} giving a reduced χ^2 of 0.93. The addition of a diskbb component improved the χ^2 by 3.4. To test the significance of this component we used the method of Bayesian posterior predictive probability values (e.g., Protassov et al. 2002), as was already done by Farrell et al. (2009). We generated 3000 simulated set of spectra with the Xspec fakeit command using the absorbed power-law model and the response files corresponding to the XMM1 spectra. We then computed the distribution of the χ^2 improvement of the fit when adding a diskbb component. The χ^2 improvement of 3.4 for XMM1 translates to a significance of 73% for the diskbb component, insufficient to claim it is real (Farrell et al. 2009 derived a significance of 70% with a similar method).

For the XMM2 spectra, we included channels with energy higher than 0.2 keV due to the higher signal to noise at low energies. The spectra are poorly fitted with a simple absorbed power-law mode (χ^2 of 577.7 and 348 degrees of freedom). When adding a diskbb component the reduced χ^2 significantly dropped to an acceptable value of 1.14, indicating that this model better represents the spectra.

For XMM1 and XMM2, we thus obtained best fits in agreement with Farrell et al. (2009). We show the corresponding folded spectra in Figure 3. The calibration was improved in the low-energy range with respect to that used by Farrell et al. (2009), which led to smaller error bars in this work. We thus present new estimates of the parameters in Table 2.

3.2. Chandra Spectrum and Pile-up

The spectrum was fitted in Xspec with an absorbed diskbb model which gave a reduced χ^2 of 1.43 for 49 degrees of freedom. A clear hard excess appeared in the residuals that could correspond to the effect of pile-up (Davis 2001). We estimated a possible level of pile-up of 5% with the Chandra Proposal Planning Toolkit14 based on PIMMS v4.2. We added a pileup component (Davis 2001) to the model and obtained a satisfactory fit with a single absorbed diskbb model with a reduced χ^2 of 1.18 (see Figure 4 and Table 2). We let the parameter alpha free and found a value of 1.0^{+0.0}_{-0.3}. This parameter is related to the probability of events being retained as a good grade after filtering and we would expect a value between 0.5 and 0.7. We note that the value of the diskbb temperature is not significantly affected by this parameter. Large contributions to the χ^2 seem to come from features around 0.6 keV (emission),
and 1.1 and 1.3 keV (absorption). However, given the low number of degrees of freedom, there is a large uncertainty on the expectation of the reduced $\chi^2$ being 1 ($\sigma$ of 0.2 on the estimate of the reduced $\chi^2$; see, e.g., Andrae 2010), so we cannot claim that these features are real. We therefore consider the continuum well fitted by the diskbb model. We found that an additional power-law component with a fixed photon index of 2 would contribute to at most 10% of the 0.2–10 keV absorbed flux, indicating that the disk component is dominant in the spectrum.

The Chandra observation was simulated to better characterize the emission of HLX-1. We used the ray tracing tool ChaRT dedicated to Chandra (Carter et al. 2003) and generated an image with MARX for the ACIS-S detector (Wise et al. 1997). The best-fit spectral model of the source, obtained as explained above, was used as an input in the energy range 0.3–8 keV. A simulated image is presented in Figure 5.

In the band 0.3–8 keV, the results from the simulation gave $1294\pm36$ counts. After running the pileup tool in MARX, we obtained $1182\pm34$ expected counts (95% ± 5% loss). We detect $1130\pm34$ counts (14% ± 5% loss), which is consistent within the errors with the MARX simulation with pile-up effects. The point-spread function (PSF) in the observation shows a deficit of counts in the central pixels compared to the simulation without pile-up. It is however consistent with the image of the simulation with pile-up applied. We are therefore confident that the use of the pile-up model in our spectral fitting is justified.

3.3. Emission from the Galaxy

No significant point source is detected inside the galaxy contours except HLX-1. We looked for an excess of counts in an extended 5″ radius region encircling the bulge of the galaxy. In the 0.3–8 keV energy band, we expect $5\pm2$ background counts in such a region and we may have in addition $5\pm2$ counts from HLX-1 due to the scattering of its emission on the detector (Figure 5, lower panel). Finally, we expect a maximum of $10\pm3$ counts, while 19 counts were detected. We repeated the same estimation for different positions on the detector and found no other excess of counts (Figure 5, upper panel). We found a similar excess in the 0.5–6 keV energy range where the signal to noise is the best for ACIS-S: 15 counts detected, background of 3 ± 2 counts and HLX-1 emission of $3\pm2$ counts. The median energy from those photons is $0.92\pm0.10$ keV suggesting a soft emission. The emission from the bulge of spiral galaxies has previously been modeled by a mekal model at temperatures of 0.3–0.6 keV (e.g., Humphrey et al. 2004). Assuming a solar metallicity and fixed absorption of $1\times10^{22}$ cm$^{-2}$, we find a temperature $kT = 0.30\pm0.15$ keV and a flux of $\sim5\times10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in the 0.2–10 keV range. At the distance of the galaxy, this converts to an unabsorbed X-ray luminosity of $\sim6\times10^{39}$ erg s$^{-1}$. This level of luminosity is consistent with the integrated X-ray luminosity of spiral galaxies in general ($10^{38}$–$10^{42}$ erg s$^{-1}$; Fabbiano 1989). This emission might contaminate XMM-Newton and Swift HLX-1 data at low luminosities given their lower angular resolution.

4. HLX-1 AT LOW LUMINOSITIES

4.1. XMM-Newton Spectrum XMM3

We fitted simultaneously the MOS1, MOS2, and pn spectra using Xspec and ignored channels with energy lower than 0.3 keV as well as channels tagged as bad. We used an absorbed power law and obtained a reduced $\chi^2$ of 1.42 with 60 degrees of freedom (Table 2). The highest contributions to the $\chi^2$ are associated with a possible soft excess around 0.7 keV and a hard...
excess at high energies (Figure 6, first panel). We thus tested two possible additive components to the model to account for those features: (1) a diskbb component to test for the presence of a thermal disk and (2) a mekal component which would correspond to a possible contamination from the galaxy bulge to the spectrum (see Section 3.3).

When adding a diskbb component to the single absorbed power-law model, the reduced $\chi^2$ is lowered to 1.20. However, a marked soft excess appears in the residuals and the hard excess is still present (Figure 6, second panel). The best fit is found for an $N_H \sim (6.5 \pm 1.5) \times 10^{21}$ atom cm$^{-2}$, an order of magnitude higher than the XMM2 value and a lower temperature.
is thus higher than in the high luminosity state (Section 3).

The bolometric unabsorbed luminosity of the disk component of $z_{\text{law}}$ improved the reduced $\chi^2$ to an acceptable value of 1.08 and resulted in a lower photon index for the power law (2.0 ± 0.3). The absorption of HLX-1 is not well constrained, so we fixed it to the XMM2 value which is the most precise estimate we obtained (see Table 2). We note that if the absorption is thawed, it tends to zero while the power-law index further decreases. The residuals are shown in Figure 6 (third panel) and the folded spectrum is shown in Figure 3. We found a temperature of $kT = 0.43 \pm 0.09$ keV consistent with the expected emission from the galaxy (Section 3.3). Moreover, the flux found for this absorbed mekal component is $(3.3 \pm 1.3) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ which is comparable to the estimate of the possible galaxy contribution found in the Chandra data (Section 3.3). We are thus confident that some emission from the galaxy contaminates the XMM3 spectrum of HLX-1, at a level of ~17% in flux at most.

Finally, we tested the presence of a diskbb component in this last model. The resulting reduced $\chi^2$ is 1.02, the power law is harder ($1.6 \pm 0.4$), and the residuals seem featureless for this fit (Figure 6, fourth panel). We tested the significance of the diskbb using the method of Bayesian posterior predictive probability values. In the same way as in Section 3.1, we generated 3000 simulated set of spectra based on the absorbed power-law plus mekal model and the XMM3 response files. We then computed the distribution of the $\chi^2$ improvement of the fit when adding a diskbb component. The $\chi^2$ improvement of 5.6 for XMM3 translates to a significance of 93% for the diskbb component. We note that a diskbb component is not needed to adequately describe the spectrum, but this possibility is intriguing and cannot be ruled out.

4.2. Astrometry Consistency

We aligned all images on the Chandra image, taking as a reference three point-like X-ray sources surrounding HLX-1. This allowed us to reduce the positional error by replacing the XMM-Newton Absolute Measurement Accuracy$^{15}$ of 4″ by a residual error of less than 1″ after alignment. We still have to take into account the Relative Pointing Error of 2″ and the error on the centroid of the source, which yielded an uncertainty lower than the size of the pixels (3′′2) for all the images presented in Figure 7. We also note that the relative astrometry within all EPIC cameras is accurate to better than 1″.5. All errors are 95% confidence.

We can expect that ESO 243–49 contributes to the X-ray emission of HLX-1 in XMM3, as determined using the higher angular resolution Chandra data (Section 3.3), since the bulge diffuse emission should be constant. The source is slightly offset from the Chandra position which falls just outside the 95% error circle. It is shifted toward the center of the galaxy ESO 243–49, indeed suggesting a contamination from the bulge of the galaxy. However, the source detection task emldetect did not split the source into two sources, indicating that the statistic is not sufficient to claim the presence of a contaminating source in the imaging data such as the galaxy bulge. The PSF full width half-maximum (FWHM) is 5″ and 6″ for MOS and pn, respectively, and the half-energy width (HEW) is 14″ and 15″. The distance between HLX-1 and the galaxy center is about 8″ so the images cannot be used as evidence for contamination.

5. HARDNESS–INTENSITY AND HARDNESS–rms DIAGRAMS

5.1. Swift XRT Spectra

We completed the study of the Chandra and XMM-Newton spectra with the spectral fitting of grouped spectra from Swift XRT (Figure 1). We fitted each Swift XRT spectrum using Xspec. For all spectra, given the reduced statistical quality, we performed a basic fitting of the data using the XMM2 model (i.e., abs(diskbb+pow), see Table 2) multiplied by a constant factor in order to estimate the unabsorbed luminosity. For each spectrum we estimated the hardness as the ratio of the count rates in the 1–10 and 0.3–1 keV bands. We then used WebPIMMS$^{16}$ to convert those ratios into flux ratios: in the low and high states (power law with photon index ~2.1 and ~4.0, respectively) we found a conversion factor of 1.5 and 0.9, respectively. We also used the following model: $abs(C_1 \times diskbb + C_2 \times pow)$ where $C_1$ and $C_2$ are two constants. The spectral parameters of the diskbb and power-law models were fixed at the values found in XMM2. The goal is to investigate the evolution in the contribution between the soft and hard components. All results are reported in Table 3.

For the S3 and S7 spectra (high luminosity states, see Figure 1), we used a simple absorbed diskbb model and reported the parameters of the fits in Table 2. There is no evidence in these spectra of the need for a hard energy component. We note that the temperature for S7 is consistent with that derived from the Chandra observation which was performed at a similar time.

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15 See Section 4.7 in the XMM-Newton Users Handbook, http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb/index.html.

16 http://heasarc.nasa.gov/Tools/w3pimms.html
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Table 3

Fit Results for Swift XRT Spectra

| Name | Start | End  | Hardness | Count Rate | Unabs. $L_X$ | $\chi^2$/dof | C1 | C2 | $\chi^2$/dof |
|------|-------|------|----------|------------|--------------|-------------|----|----|-------------|
| S1   | 54763 | 54784| 0.34 ± 0.04 | 1.20 ± 0.06 | 6.4 ± 0.6 | 21.2/17 | 0.9 ± 0.1 | 1.3 ± 0.4 | 19.4/16 |
| S2   | 55048 | 55050| 2.4 ± 1.2  | 0.15 ± 0.09 | 0.5 ± 0.3 | 30/35 | <0.09 | 0.4 ± 0.3 | 29.5/35 |
| S3   | 55059 | 55063| 0.34 ± 0.03 | 3.30 ± 0.13 | 11 ± 1 | 14.4/21 | ... | ... | ... |
| S4   | 55106 | 55164| 0.27 ± 0.03 | 1.86 ± 0.09 | 9.0 ± 0.6 | 26.6/19 | 1.4 ± 0.2 | 1.6 ± 0.5 | 25.5/18 |
| S5   | 55170 | 55225| 0.34 ± 0.05 | 1.12 ± 0.06 | 5.8 ± 0.6 | 15.8/12 | 0.7 ± 0.1 | 1.6 ± 0.5 | 10.0/11 |
| S6   | 55237 | 55421| 1.7 ± 1.0  | 0.12 ± 0.03 | 0.2 ± 0.1 | 70/63 | 0.3 ± 0.2 | 65.4/63 |
| S7   | 55437 | 55453| 0.21 ± 0.02 | 2.80 ± 0.10 | 11.8 ± 0.3 | 20.8/24 | ... | ... | ... |
| S8   | 55462 | 55490| 0.21 ± 0.03 | 2.00 ± 0.10 | 9.6 ± 0.6 | 8.6/8  | ... | ... | ... |
| S9   | 55498 | 55543| 0.26 ± 0.04 | 1.52 ± 0.09 | 8.3 ± 0.6 | 11.2/11 | 1.3 ± 0.2 | 1.5 ± 0.6 | 11.0/10 |
| S10  | 55548 | 55562| 0.32 ± 0.04 | 0.8 ± 0.3  | 5.9 ± 0.6 | 12.6/14 | 0.84 ± 0.14 | 1.2 ± 0.4 | 10.8/13 |

Notes. Columns: (1, 2, 3) name, start, and end day (MJD) of observation as reported in Figure 1; (4) hardness is given as the ratio of fluxes $F[1–10\text{keV}]/F[0.3–1\text{keV}]$; (5) count rate (10$^{-2}$ counts s$^{-1}$) in the band 0.3–10 keV; (6) unabsorbed luminosity in 10$^{41}$ erg s$^{-1}$ after fitting the XMM2 model multiplied by a constant; (7) $\chi^2$ and degrees of freedom (dof) for the fit; (8, 9, 10) result of the fit with the two XMM2 components multiplied by factors C1 and C2, and goodness of the fit.

$^a$ Cash statistic was used and the number of PHA bins is indicated instead of dof.

5.2. Timing Analysis

We calculated the power density spectra (PDS) for the light curves of HLX-1 from the three XMM-Newton observations. The light curves were split into four segments of equal lengths, and the PDS were calculated for each segment. For each light curve, all four PDS were merged and averaged by binning in frequency using a logarithmic factor 1.1, under the condition that each bin contains at least 20 individual PDS measurements. The errors were calculated from the sample standard deviation of PDS measurements in each bin.

The PDS of HLX-1 are shown in Figure 8. The black solid lines denote the average PDS above 1 Hz. Those values deviate from the expected Poisson level by less than 0.4%. We see that all PDS are flat, showing no significant intrinsic source variability, and no QPO. The fit results using a constant $C_P$ are given in Table 4. To obtain a constraint on the variability, we followed the procedure adopted by Goad et al. (2006) and Heil et al. (2009). In this procedure, the PDS are fitted with a broken power-law (BPL) model or a Lorentzian model plus a constant.

For the BPL, the indices below and above the break frequency ($f_b$) were assumed to be $-1$ and $-2$, respectively. The value $C_1/f_b$ corresponds to the power times the frequency below $f_b$ from this...
model. The upper limits of $C_{1/f}$ for two values of $f_b$ ($10^{-3}$ and 1 Hz) are shown in Table 4. We found that these limits are relatively independent of the assumed $f_b$ value, at least within the $10^{-3}–1$ Hz range. Similarly, it is found to be fairly constant across AGN and GBHBs in the range 0.005–0.03 (Papadakis 2004). The upper limits of $C_{1/f}$ for XMM1 are consistent with the values generally observed for AGN/GBHBs in the thermal state. For XMM3, they are larger and thus not constraining. In XMM2, the upper limits of $C_{1/f}$ are low compared with typical values for AGN and GBHBs, in the range 0.005–0.03.

For the Lorentzian model, we assumed the quality factor $Q$ to be 2 as in Goad et al. (2006) and Heil et al. (2009). The upper limits of the integrated power of the Lorentzian $R^2$ are given in Table 4 for two Lorentzian centroid frequencies: $10^{-3}$ and 1 Hz. They roughly increase with the centroid frequency assumed. Compared with the typical values of 0.01 for $R^2$ seen in the GBHB hard state (van der Klis 2006), the upper limits we obtained for HLX-1 are high for all three observations. Due to poor statistics, we thus cannot place any firm constraints on the spectral state using the timing analysis.

5.3. Combined Diagrams

We show the best-fit models for all the fitted spectra in Figure 9, which illustrates the evolution of the soft disk emission and the hard tail during spectral state transitions. For each Swift, XMM-Newton, and Chandra spectrum, we estimated the unabsorbed luminosity in the range 0.2–10 keV for the best fit, and calculated the flux ratio between the bands 0.3–1 and 1–10 keV. Those energy ranges were also used by Godet et al. (2009), so the HID shown in Figure 10 is an updated version of their Figure 2.

We plotted in this diagram values coming from different instruments with independent calibrations. There could be systematic errors in the different calibrations, leading to a discrepancy of up to 20% in the normalization of the flux as it could be observed during simultaneous observations (e.g., Tsujimoto et al. 2011). We indeed observed a difference between the Swift XRT S7 and Chandra ACIS-S spectra of HLX-1 (Figure 9) taken over a similar period. However, for these two spectra, hardness ratio and luminosity estimates are consistent within this range of errors. Consistent trends are seen in both the Swift and XMM-Newton data; we are thus confident that the spectral variations detected in this work are real and significant.

We also computed variability rms values and limits in the 0.0001–0.1 Hz range. They are reported in Table 4 and plotted on the HRD in Figure 10.

![Figure 9. Models of X-ray spectra of HLX-1 in different states as obtained from the best fit to the data (see Table 2). For XMM3, the abs(pow)+abs(mekal) model is shown as a dashed line, and the model without the mekal component as a thick line. For Chandra, the effect of pile-up has been corrected. (A color version of this figure is available in the online journal.)](image)

6. DISCUSSION

6.1. Spectral States and Transitions

The high-luminosity state of HLX-1 is associated with a soft emission with a dominant thermal disk emission, while the low-luminosity state is found to be significantly harder and power-law like. This is reminiscent of the behavior of GBHBs (e.g., Remillard & McClintock 2006), and the HID and HRD shown in Figure 10 are consistent with similar diagrams for GBHBs (e.g., Belloni 2010). HLX-1 therefore clearly showed transitions from one state to another, confirming the first evidence found by Godet et al. (2009). However, fewer luminosity states have been observed compared to well known GBHBs and therefore the diagrams are not equally sampled.

The high luminosity state of HLX-1 is well described by an optically thick disk model with temperatures of 0.18–0.26 keV (Table 2). Moreover, the low variability level in the XMM2 data (~10%) can reasonably be ascribed to the dominance of the thermal disk component. All this is consistent with HLX-1 being...

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**Table 4**

| Obs  | $C_P$ | $\chi^2_\nu$ (ν) | $C_{1/f}$ ($10^{-4}$, BPL) | $R^2$ ($10^{-2}$, BLN) | rms(%) |
|------|-------|------------------|-----------------------------|-------------------------|--------|
|      |       |                  | (10^{-3} Hz) | (1 Hz) | (10^{-3} Hz) | (1 Hz) |                                 |
| (1)  | (2)   | (3)              | (4)           | (5)       | (6)          | (7)      | (8)                          |
| XMM1 | 46.11 ± 0.22 | 1.13(83) | <98.8 | <58.3 | <4.2 | <326.3 | <32.3 |
| XMM2 | 16.02 ± 0.01 | 1.28(120) | <2.7 | <2.5 | <0.49 | <58.8 | 8.4^±3.4 |
| XMM3 | 898.11 ± 0.55 | 0.79(127) | <646.8 | <579.9 | <79.2 | <1293.7 | <96.7 |

**Notes.** Columns: (1) observations; (2) best-fitting constant Poisson level in (rms/mean)^2 Hz^{-1}; (3) reduced $\chi^2$ and degrees of freedom of the fits with a constant Poisson level; (4) best-fitting $C_{1/f}$ assuming a break frequency of $10^{-3}$ Hz; (5) best-fitting $C_{1/f}$ assuming a break frequency of 1 Hz; (6) best-fitting $R^2$ assuming a Lorentzian centroid frequency of $10^{-3}$ Hz; (7) best-fitting $R^2$ assuming a Lorentzian centroid frequency of 1 Hz; (8) fractional rms variability within 0.0001–0.1 Hz, assuming the Poisson level to be the average PDS above 1 Hz. All limits are at a 90% confidence level, except for the fractional rms (Column 8), which is 1σ.
in a thermal state. The temperature of the thermal component is 4–5 times lower than for typical GBHBs with stellar-mass black holes (∼1 keV, e.g., Remillard & McClintock 2006). If this soft component we measured is due to emission from the inner region of an accretion disk, and the disk extends close to the ISCO, then the temperature is related to the mass of the black hole by the relation $T_{\text{in}} \propto M_{\text{BH}}^{-1/4}$ (Makishima et al. 2000). It is thus possible that the lower temperature is due to the presence of a black hole with a higher mass—by a factor of ∼200 to 500—than a typical stellar-mass black hole (∼10 $M_\odot$), leading to a possible mass of few 10$^3$ $M_\odot$. This argument has already been used by Miller et al. (2004) for six bright ULXs (>10$^{40}$ erg s$^{-1}$) to strengthen their classification as IMBH candidates even if the thermal component was not dominant. In our observations of HLX-1 in the thermal state, this component is clearly dominant. A complementary study of HLX-1 in the thermal state by Davis et al. (2011) using the relativistic disk model BHSPEC provided robust lower and upper limits with 3000 < $M$ < 3 × 10$^5$ $M_\odot$, firmly placing HLX-1 in the IMBH regime. O. Godet et al. (2011, in preparation) tested additional models to physically constrain the nature of HLX-1 and they also found mass estimates in the IMBH range.

We report in Figure 11 the temperature and bolometric luminosity of the disk in the thermal state from the S3, S7, Chandra, and XMM2 observations (see also O. Godet et al. 2011, in preparation). All those measurements in the thermal state are consistent with the correlation between luminosity and temperature expected from a geometrically thin, optically thick accretion disk ($L \propto T^4$; Shakura & Sunyaev 1973). This supports the idea of HLX-1 being in a generic thermal state as this relation is also observed for GBHBs in this state (e.g., Kubota & Makishima 2004; Remillard & McClintock 2006). It is however different to the ULX branch reported, e.g., by Soria (2007), where an anti-correlation between disk luminosity and temperature is seen for two ULXs.

During the XMM3 observation at low luminosities, the spectrum of HLX-1 is mainly described by a power-law model with a photon index that falls in the range 1.4–2.1 (Table 2), indicating a hard state as observed for GBHBs (we presented preliminary results in Farrell et al. 2011). We could not constrain the rms variability of the source during the XMM3 observation due to low statistics. Therefore, a high rms value of ∼30%, as observed for GBHBs in the hard state (e.g., Belloni 2010), cannot be ruled out and would be consistent with our data. Assuming that this hard state is similar to the one observed for GBHBs, one would expect enhanced radio emission (Fender et al. 2004). Such a detection would further confirm this state as the canonical hard state of GBHBs and would allow a mass estimate using the fundamental plane (Merloni et al. 2003).

In the XMM3 spectrum, dominated by a power-law component, we found marginal evidence for a soft disk component with temperature $kT_{\text{in}} = 0.07 \pm 0.04$ keV, with a significance of 93%. Such a disk component would be consistent with the $L \propto T^4$ relation reported in Figure 11, as the expected temperature for a disk unabsorbed luminosity of 4 × 10$^{40}$ erg s$^{-1}$ is 0.09 keV. A disk could thus be either extending down to the ISCO or maybe truncated as the best-fit temperature value is lower than the temperature expected from the $L \propto T^4$ relation. This would again suggest a resemblance with GBHBs.

During the XMM1 observation of HLX-1, the spectrum is found to be well fitted with a steep power law of photon index ∼3.5. Such a spectral state is also observed for some GBHBs.
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The HLX-1 long term variability seen in Figure 1 presents similarities with some light curves of GBHB (e.g., Gierliński & Newton 2006; Done et al. 2007) and more generally of soft X-ray transients when they show outbursts (King & Ritter 1998). We observed a fast rise (∼10 days or less), followed by an exponential decay (100 to 200 days) of the X-ray flux from HLX-1 (fast rise and exponential decay (FRED) like outburst). This could be explained by theoretical models of the hydrogen ionization instability controlling the fast rise (King & Ritter 1998). The cause of this variability has been investigated in more details by Lasota et al. (2011). They concluded that HLX-1 is unlikely to be explained by a model in which outbursts are triggered by thermal-viscous instabilities in an accretion disk (Lasota 2001), and they argue that a more likely explanation is a modulated mass transfer due to tidal stripping of a star in an eccentric orbit around the IMBH. This would still explain a change in the accretion rate, leading to the state transitions we observe. This might also explain the possible periodic recurrence in the light curve, as well as the rarity of a source like HLX-1, which shows unique properties for a ULX.

6.2. Comparison with Other ULXs

It was suggested that most ULXs (few 10⁵⁹ to 10⁶ⁱ erg s⁻¹, with power-law spectra) are stellar-mass systems accreting at Eddington ratios of the order of 10–30, with mild beaming factors b ≥ 0.1 (King 2009). If a supercritical accretion disk—as proposed in the Galactic system SS433 for example—is seen face-on, the expected luminosity could indeed reach 10⁴¹ erg s⁻¹ (Fabrika et al. 2007). In the case of HLX-1 in the highest state, the Eddington ratio would reach 170 and the beaming factor b ∼ 2.5 × 10⁻³ (King 2011). Freeland et al. (2006) calculated the broadband radio–X-ray spectra predicted by micro-blazar and micro-quasar models for ULXs. They argued that a disk and a jet could be present in the system in a high/hard state close to the Eddington luminosity with a high accretion rate and gravitational energy released all the way down to the ISCO, leading to a hard spectrum (Γ = 1.4–2.1) at high observed luminosities (>4 × 10⁵⁹ erg s⁻¹). They also proposed the existence of milli-blazars (IMBH and beamed emission) with luminosities >10⁴¹ erg s⁻¹. The spectrum of HLX-1 in the low-luminosity state might be explained by such a model. However, the transition to a thermal state at even higher luminosities is not consistent with this picture. The increase in luminosity and softening of the source (decrease of the peak energy as can be seen in Figure 9) are not consistent with relativistic beaming variations which would have an opposite effect (e.g., King 2009). All this indicates that the spectral variability we observe for HLX-1 is not due to beaming variations.

Gladstone et al. (2009) showed that simple spectral models commonly used for the analysis and interpretation of some ULXs (power-law continuum and multicolor disk blackbody models) are inadequate for a small sample (12 ULXs) of nearby, low luminosity ULXs that have high-quality spectra. Two near ubiquitous features are found in the spectra: a soft excess and a rollover in the spectrum at energies above 3 keV. They suggested the existence of a new ultraluminous state with super-Eddington accretion flows. This would favor the presence of stellar-mass black holes rather than IMBHs for some ULXs. In the spectra of HLX-1, which reaches luminosities two orders of magnitude higher than the average ULX, we found no evidence of such a break above 3 keV. However, the number of counts, even in XMM2, is probably insufficient to detect this feature (Gladstone et al. 2009 claim the need for 10,000 counts). O. Godet et al. (2011, in preparation) discuss in more details the comparison with ULXs claimed to be in a ultraluminous state, but the variety of X-ray spectra we observe for HLX-1 in this work, all in the ultraluminous range, is clearly unique for a ULX. In particular, the thermal state observed at high luminosities (therefore probably at the highest accretion rate) for HLX-1 is clearly distinct to the proposed ultraluminous state spectrum for some ULXs.

Finally, the X-ray observations reported in this work indicate that HLX-1 more resembles GBHBs scaled to higher luminosities (three orders of magnitude) than any other category of ULXs. In this picture, the bolometric luminosity (hence the X-ray luminosity) of the source in the thermal state should be lower than the Eddington luminosity for the system, giving a limit on the mass of the black hole of >9000 M☉. The unabsorbed luminosity in the hard state is 2.2% of the highest luminosity recorded in this work for which we assume a sub-Eddington luminosity (see Table 2). This level of luminosity is consistent with the fraction of Eddington luminosity observed for GBHBs in the hard state (<2%, e.g., Maccarone & Coppi 2003; Gierliński & Newton 2006), further supporting the analogy of HLX-1 with GBHBs. It is generally observed for GBHBs that in the hard state and the steep power-law state, the X-ray luminosity is 1% and 100% of the Eddington luminosity (Remillard & McClintock 2006), respectively, leading to complete mass estimates of 16,000 and 20,000 M☉. The cause of this variability has been investigated in more details by Lasota et al. (2011). They concluded that HLX-1 more resembles GBHBs scaled to higher luminosities (three orders of magnitude) than any other category of ULXs.
has made use of data obtained from the Chandra Data Archive and software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, ChIPS, and Sherpa. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester.

Facilities: XMM, CXO, Swift (XRT)

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