X-RAY SPECTRAL CUTOFF AND THE LACK OF HARD X-RAY EMISSION FROM TWO ULTRALUMINOUS X-RAY SOURCES M81 X-6 AND HOLMBERG IX X-1

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ABSTRACT

We present broadband X-ray spectral study of two ultraluminous X-ray sources (ULXs), M81 X-6 and Holmberg IX X-1, based on Suzaku and XMM-Newton observations. We perform joint broadband spectral analysis of the brightest sources in the field, i.e., the two ULXs and the active galactic nucleus (AGN) in M81, and demonstrate that the X-ray spectra of the ULXs cut off at energies ≥3 keV with negligible contribution at high energies in the Suzaku HXD/PIN band. The 90% upper limit on the 10–30 keV band luminosity of an underlying broadband power-law component is 3.5 × 1038 erg s−1 for M81 X-6 and 1.2 × 1039 erg s−1 for Holmberg IX X-1. These limits are more than an order of magnitude lower than the bolometric (0.1–30 keV) luminosity of 6.8 × 1039 erg s−1 for M81 X-6 and 1.9 × 1040 erg s−1 for Holmberg IX X-1. Our results confirm earlier indications of spectral cutoffs inferred from the XMM-Newton observations of bright ULXs and show that there is not an additional high-energy power-law component contributing significantly to the X-ray emission. The spectral form of the two ULXs is very different from those of Galactic black hole X-ray binaries (BHBs) or AGNs. This implies that the ULXs are neither simply scaled-up versions of stellar-mass BHBs nor scaled-down versions of AGNs.

Key words: accretion, accretion disks – X-rays: binaries – X-rays: galaxies – X-rays: individual (M81 X-6, Holmberg IX X-1)

Online-only material: color figures

1. INTRODUCTION

Generally, galaxies host numerous X-ray sources. Most off-nuclear, compact X-ray sources are believed to be X-ray binaries (XRBs) with a compact object—white dwarf, neutron star, or black hole (BH). A few of the brightest X-ray sources at the high end of the point-source luminosity function can exceed the Eddington limit of even the most massive stellar-mass BH, sometimes by large factors. The nature of these sources, known as ultraluminous X-ray sources (ULXs), continues to remain an enigma since their dynamical mass measurements have not been possible.

Possible explanations for the high luminosities of ULXs include (1) XRBs with intermediate-mass ($M_{BH} \approx 10^2-10^5 M_\odot$) black holes (IMBHs; e.g., Colbert & Mushotzky 1999; Miller & Colbert 2004), (2) XRBs with anisotropic emission (King et al. 2001), (3) beamed XRBs with relativistic jets directly pointing toward us, i.e., scaled-down versions of blazars (Mirabel & Rodríguez 1999; Kording et al. 2002), and (4) XRBs with super-Eddington accretion rates (Begelman 2001, 2002). Chandra and XMM-Newton observations of ULXs have shown a variety of spectral shapes, e.g., simple power law similar to the low/hard state of black hole X-ray binaries (BHBs; Winter et al. 2006) and soft excess (blackbody $kT \sim 0.1–0.4$ keV) plus power law. The soft X-ray excess emission has been interpreted as optically thick emission from a thin accretion disk with temperatures in the range of ~100–300 eV, suggestive of an IMBH accreting at sub-Eddington (~0.1 $L_{Edd}$) rates (Miller et al. 2003, 2004a, 2004b; Miller & Colbert 2004; Fabian et al. 2004). However, the cool disk plus power-law spectra of ULXs may not always correspond to the high/soft state of BHBs (Roberts et al. 2005).

High signal-to-noise XMM-Newton observations of bright ULXs have revealed curvature in the spectra at high energies ≥5 keV (Stobbart et al. 2006; Dewangan et al. 2006; Agrawal & Misra 2006; Gladstone & Roberts 2009). However, it is not known if the X-ray spectrum actually has a cutoff or there is a deficit of emission near 7 keV due to perhaps an absorption edge. Observation of strong X-ray emission above 10 keV will put strong constraints on the nature of ULXs. The presence of a strong hard X-ray power law will establish ULXs to be either scaled-up BHBs or scaled-down versions of active galactic nuclei (AGNs) and the lack of emission near 7 keV may then be explained as the blurred iron K edge due to reflection from the innermost regions. On the other hand, absence of such a strong hard X-ray component will make ULXs very different from BHBs or AGNs, probably accreting in a state that is not usually attained by them.

Suzaku observations have shown that the broadband spectrum of M82 X-1 is slightly curved (Miyawaki et al. 2009; Caballero-García 2011). However, M 82 X-1 is in a crowded field and it is not clear if the contribution of nearby multiple unresolved sources both in the XIS and PIN field of view (FOV) can alter the broadband spectral shape. Here we study the broadband spectral shape of two bright ULXs M81 X-6 and Holmberg IX X-1 (Ho IX X-1) located in the dwarf irregular galaxy Holmberg IX, a companion of M81. Ho IX X-1 is also known as M81 X-9. We constrain the 0.6–30 keV spectral shape of the two ULXs for the first time based on joint spectral modeling of multiple sources observed with Suzaku.

2. OBSERVATIONS AND DATA REDUCTION

We used the on-axis Suzaku observations of M81 (observation ID: 906004010) and Ho IX X-1 (observation ID: 707019020) performed during 2011 September 15–16 and 2012 April 13–17 for exposure times of 45.6 ks and 182.5 ks, respectively. We also used XMM-Newton observation of Ho IX X-1 performed during
2011 September 26 for an exposure time of 25 ks (observation ID: 0657801801).

We processed the unfiltered Suzaku data with aepipeline available with HEASOFT version 6.13 and used the recent calibration database (CALDB) available as of 2013 January 20. We extracted the spectra of Ho IX X-1 from the filtered XIS event lists using a circular region of radius 220\arcsec, and the corresponding background spectra from two circular regions each with radius 110\arcsec. The ULX M81 X-6 is 3\arcmin away from the AGN. Therefore, we extracted the XIS spectra for M81 AGN and M81 X-6 using smaller circular regions of radii 180\arcsec and 80\arcsec, respectively. We extracted common background spectra applicable to both the AGN and ULX using two circular regions of radius 110\arcsec each. The circular regions used to extract the spectral products are shown in Figure 1. The XIS0 and XIS3 are the front illuminated (FI) CCDs and the two spectra for each object were combined using the tool addaspec. We also extracted the PIN source and background spectra from both the observations using the task hxdpinxbpi from the PIN event lists and the tuned non-X-ray background files appropriate for the observations.

Since the HXD/PIN is a non-imaging instrument with an FOV of 34\arcmin × 34\arcmin FWHM, there may be contribution from sources within the FOV. To identify the potential contaminating sources, we analyzed the XMM-Newton observation of Ho IX X-1. We processed the EPIC-pn data in a standard manner. We show the EPIC-pn image of the field containing Ho IX X-1 in Figure 1. In the EPIC-pn FOV of 30\arcmin diameter, apart from Ho IX X-1, there are two bright sources, M81 AGN and ULX M81 X-6, that can contribute to the PIN spectrum. Over the long term, these three sources are variable by a factor of ∼3. We have analyzed six XMM-Newton observations and found that the EPIC-pn count rates with 1\sigma errors for the AGN varied from 1.97 ± 0.02 (2002 April 19) to 5.57 ± 0.04 counts s\(^{-1}\) (2011 March 24). Ho IX X-1 varied from 0.85 ± 0.03 (2011 April 17) to 2.63 ± 0.01 counts s\(^{-1}\) (2011 September 26) while M81 X-6 varied from 0.20 ± 0.01 (2011 April 17) to 0.52 ± 0.007 counts s\(^{-1}\) (2011 September 26). However, none of the other next brightest seven point sources in the field ever became bright enough to contribute even 50% of the flux of M81 X-6 when it was faintest. Thus, we assume that these fainter sources do not contribute in the XIS and PIN bands.

3. ANALYSIS AND RESULTS

We used the Interactive Spectral Interpretation System (ISIS version 1.6.2–18) for our spectral analysis. We quote the errors on the best-fit parameters at the 90% confidence level. We began with the spectral analysis of the Suzaku observation of M81. While M81 AGN and M81 X-6 are clearly resolved in the XIS data, the PIN data is additionally contaminated by the nearby bright ULX Ho IX X-1. We fitted an absorbed power-law model to the PIN and the AGN XIS data. We used the 16–30 keV band PIN data (as there is no detection above 30 keV) and the 2–10 keV band XIS data which excludes the low-energy thermal emission of the AGN (Page et al. 2003). M81 AGN is known to show an iron line (Dewangan et al. 2004) and therefore we also used a Gaussian line (GL). This simple model resulted in a good fit, $\chi^2 = 245$ for 290 degrees of freedom (dof) with $\Delta \chi^2 = -32.2$ for the addition of the GL with three parameters. Thus the line is detected at >99.99% confidence level according to an F-test. To find any contribution from the nearby bright ULXs to the HXD/PIN, we included an additional power-law component. We fixed the normalization of the second power law to zero for the XIS and varied it for the PIN data. This did not improve the fit and hence we calculated the 90% upper limit on the 10–30 keV flux by fixing the photon index $\Gamma_2$ at different values ranging from 1 to 2.5. We find that the maximum possible contribution by the nearby ULXs is <6.8 × 10\(^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) in the 10–30 keV band.

To estimate the hard X-ray contribution from the ULXs, we fitted their XIS spectra with absorbed power-law models and calculated the 10–30 keV band fluxes by extrapolating the best-fit models. We found $f_{X}(10–30 \text{ keV}) = 8.3^{+0.1}_{-0.2} \times 10^{-12}$ erg cm\(^{-2}\) s\(^{-1}\) for Ho IX X-1 and (3.6 ± 0.2) × 10\(^{-12}\) for M81 X-6. Thus, the estimated fluxes for the ULXs based on the extension of the power-law models are much higher than the 90% upper limit on the contribution by the nearby sources to the HXD/PIN data. This implies that the ULXs lack significant hard X-ray emission and their spectra cannot be described by a single power law from soft-to-hard X-rays. This confirms the earlier results of a high-energy cutoff in the XMM-Newton spectra of these ULXs (Dewangan et al. 2006; Stobbart et al. 2006).

To better constrain the broadband spectra ULXs, we performed joint analysis of the Suzaku XIS+PIN spectra of the
ULXs and AGNs. For this purpose, we created ISIS fit functions which are a combination of models for the ULXs and AGNs but a given model component is applied to a specific spectrum or a subset of spectra. First we fitted the spectra obtained from the on-axis Suzaku observation of M81 AGN. We used the combined XIS FI spectra of M81 X-6 and M81 AGN and the corresponding PIN spectrum of the field. We did not use the XIS spectrum of Ho IX X-1 as it is not in the FOV. We also did not account for its contribution to the PIN spectrum. This ULX is 12.4 away from M81 AGN. Thus, given the triangular response of HXD/PIN with an FWHM of 34', the ULX Ho IX X-1 contributes ~50% of its actual flux to the PIN data. As inferred above, Ho IX X-1 generally lacks the hard X-ray emission and its contribution to the PIN band is likely to be very small. We further deal with this issue below when we analyze the on-axis Suzaku observation of Ho IX X-1.

For the joint analysis of M81 X-6 and M81 AGN, we used a joint model which is a combination of the model for the ULX and AGN. We used a power law with high-energy exponential cutoff (cutoffpl) and a GL for the ULX, and a simple power law plus a GL for the AGN. We also multiplied all the components by an absorption model wabs. We refer to this as model 1. The ULX model only is applied to XIS spectrum of M81 X-6 and the AGN model alone applied to the XIS spectrum of the AGN but both models are combined to fit to the PIN data. We used a constant multiplicative factor of 1.16 for the PIN data. The model provided a statistically acceptable fit with \( \chi^2 = 418.4/435 \) and the best-fit parameters are listed in Table 1 while the unfolded spectral data and the best-fit model are shown in Figure 2. We also examined the continuation of the power law in the hard band by fixing \( E_{\text{cutoff}} \) at 100 keV. The fit became worse with \( \chi^2/\text{dof} = 679/436 \), ruling out the presence of such a power law at >99.99% confidence level. Further, we used an additional power law with \( \Gamma = 2 \) to the best-fit ULX model 1 and estimated the 90% upper limit on the 10–30 keV flux to be \( f_X = 2.3 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) and the corresponding luminosity \( L_X = 3.5 \times 10^{38} \) erg s\(^{-1}\) for an underlying power-law component. We also tested physical models that do not contribute significantly in the hard X-ray band. We replaced the cutoffpl in model 1 with the multicolor accretion disk model diskbb which resulted in a good fit (\( \chi^2/\text{dof} = 432.4/436 \)) with \( kT_{\text{in}} = 1.62_{-0.05}^{+0.04} \) keV, \( f_X(0.1–10 \text{ keV}) = (3.7 \pm 0.1) \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\). We also tested the p-free disk model diskpbb which allows the disk temperature to scale with radius as \( r^{-p} \). For standard disk model, \( p = 0.75 \) and lower values of \( p \) may indicate a slim accretion disk (Watarai et al. 2000). The p-free disk model resulted in a slightly better fit (\( \chi^2/\text{dof} = 421.5/435 \)) with \( kT_{\text{in}} = 1.8 \pm 0.1 \), \( p = 0.69 \pm 0.02 \) and \( f_X(0.1–30 \text{ keV}) = (4.3 \pm 0.1) \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) and \( L_X((0.1–30 \text{ keV}) = 6.8 \times 10^{39} \) erg s\(^{-1}\). The parameters of the AGN model remained similar for different ULX models cutoffpl, diskbb, and the p-free disk. Thus, we confirm that the M81 X-6 spectrum cuts off at high energies and does not contribute significantly to the PIN band. Moreover, any possible hard X-ray contribution by Ho IX X-1 (which we show below is unlikely) would further strengthen the result that M81 X-6 is dim in hard X-rays.

We next performed the joint spectral analysis of the on-axis Suzaku observation of Ho IX X-1. The ULX is well isolated spatially and its X-ray emission in the XIS band is not contaminated by any other strong source (see Figure 1). However, the PIN data is obviously contaminated by M81 AGN. We used a joint spectral model similar to the model 1 that combines the ULX model (wabs × (bboby + cutoffpl + gauss)) and the AGN model (wabs × (powerlaw + gauss)). We refer to this as model 2. As before, we used a relative normalization of 1.16 between the XIS spectrum of Ho IX X-1 and its contribution to the PIN spectrum. Since there is no simultaneous XIS spectrum of the AGN, we used the AGN XIS spectrum from the on-axis observation of M81. We used a variable relative normalization between the XIS spectrum of the AGN and its contribution to the PIN band to allow for flux variability of the AGN between the two Suzaku observation. Thus, the use of the XIS AGN spectrum in modeling the ULX

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3 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/watchout.html
Table 1

| Comp. | Par. | M81 AGN+M81 X-6 | M81 AGN+Ho IX X-1 |
|-------|------|-----------------|-------------------|
|       | wabs | Model 1<sup>a</sup> | Model 2<sup>b</sup> | Model 3<sup>c</sup> |
| PL    | N<sub>ee</sub> | 5.5 (fixed) | 5.5 (fixed) | 5.5 (fixed) |
|       | Γ    | 1.91±0.02       | 1.92±0.02        | 1.89±0.03     |
|       | n<sub>rel</sub> | 4.4±0.2        | 4.4±0.2         | 4.3±0.1       |
| GL    | E<sub>line</sub> (eV) | 6.57±0.09         | 6.57±0.09   | 6.57±0.09   |
|       | σ(eV) | 435±39           | 435±39         | 435±39       |
|       | f<sub>line</sub> | 1.46±0.04        | 1.46±0.04      | 1.3±0.5      |
|       | n<sub>per</sub> | 7.2±0.3         | 11.3±0.9   | 11.3±0.9   |
|       | n<sub>rel</sub> | 1.64±0.03        | 1.64±0.03      | 1.64±0.03 |
|       | kT<sub>e</sub> (eV) | ...         | 2.6±0.2        | 2.6±0.2    |
|       | kT<sub>rel</sub> | ...         | ...           | ...         |
|       | E<sub>rel</sub> (eV) | 2.7±0.1        | 2.7±0.1    | 2.7±0.1    |
|       | n<sub>rel</sub> | 1.16 (fixed) | 1.16 (fixed) | 1.16 (fixed) |
|       | ν<sub>rel</sub> | ...         | ...           | ...         |
|       | fX<sub>rel</sub> | 1.43×10<sup>−13</sup> | 1.43×10<sup>−13</sup> | 1.43×10<sup>−13</sup> |
|       | L<sub>X</sub> (erg/s) | 6.8×10<sup>39</sup> | 6.8×10<sup>39</sup> | 6.8×10<sup>39</sup> |
|       | M81 AGN | 6.7×10<sup>40</sup> | 6.7×10<sup>40</sup> | 6.7×10<sup>40</sup> |

Notes.

<sup>a</sup> Model 1: AGN (wabs×(PL+GL1)) + M81 X-6 (wabs×cutoffpl);
Model 2: M81 AGN (wabs×(PL+GL1)) + Ho IX X-1 (wabs×(bbody + cutoffpl + GL2));
Model 3: AGN (wabs×(PL+GL1)) + Ho IX X-1 (wabs×(diskbb + nthcomp + GL2)).

Using the broadband <i>Suzaku</i> observations of the fields containing two bright ULXs, we measured X-ray luminosities of 6.8×10<sup>39</sup> erg s<sup>−1</sup> for M81 X-6 and 1.9×10<sup>40</sup> erg s<sup>−1</sup> for Ho IX X-1. With the joint spectral analysis of XIS and PIN spectra of the brightest sources in the field, we showed that the broadband spectra of M81 X-6 and Ho IX X-1 cutoff at 2.8 keV and 8 keV, respectively. This conforms the high-energy spectral curvature in these ULXs earlier found with the limited bandpass of <i>XMM-Newton</i> (Dewangan et al. 2006; Stobbart et al. 2006). In addition, we do not find additional high-energy spectral components similar to that observed from BHBs and AGNs. This demonstrates clearly that the two ULXs are in unusual spectral states that are distinctly different than that observed from BHBs and AGNs.

The spectrum of M81 X-6 is well described by the standard disk model with high temperature kT<sub>in</sub> = 1.62±0.04 keV similar to that observed from BHBs but without a hard power law and with large X-ray luminosity that exceeds the Eddington luminosity of 44 M<sub>☉</sub> BH. Generally, BHBs show standard disk spectra and steep power law in their high/soft state with the relative accretion rate in the range of ~0.1–0.5 (Esin et al. 1997). Thus, the observed X-ray luminosity of M81 X-6 corresponds to ~100 M<sub>☉</sub>. The temperature of the standard disk around such a large BH is unlikely to exceed 1 keV. Thus, M81 X-6 is not in the high/soft state generally observed in BHBs. The p-free disk fit showed that the temperature of disk (T < 10<sup>−68</sup>) at different radii is lower than that expected from a standard disk (T < 0.5). This suggests that M81 X-6 X-1 likely hosts a slim accretion disk.
$m/m_{\text{Edd}} \sim 0.2$ for a 30 $M_{\odot}$ BH. Thus, if there is mild beaming of the Comptonized component, a stellar-mass BH can explain the observed luminosity of Ho IX X-1.

Finally, we note that while many BHBs and AGNs show strong relativistic iron lines, these lines are rare in ULXs. Caballero-García & Fabian (2010) explained the soft excess and drop near 7 keV in the spectra of several ULXs including M81 X-6 and Ho IX X-1 in terms of relativistically blurred reflection from accretion disks. Such a model requires strong continuum above 7.1 keV. However, our finding of the spectral downturn and its continuation in the hard band above 10 keV in Ho IX X-1 and M81 X-6 imply the absence of a strong illuminating continuum. Thus, our findings rule out the possibility of explaining the spectral downturn near 7 keV as a blurred iron K edge. The absence of a strong illuminating continuum is most likely the reason behind the non-detection of broad iron lines from most ULXs.

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