SPECTRAL STUDY OF ULTRA-LUMINOUS COMPACT X-RAY SOURCES WITH *XMM-NEWTON* AND *CHANDRA*

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ABSTRACT

Using the *ASCA*, *XMM-Newton*, and *Chandra* data, luminosity-dependent spectral changes of the ultra-luminous X-ray source (ULX) M 81 X-9 were studied. When the luminosity was below a threshold of $\sim 1.5 \times 10^{40}$ erg s^{-1}, the source consistently exhibited power-law spectra. In contrast, the spectra at higher luminosities were more convex, favoring a multi-color-disk modeling. A p-free disk model with $p \sim 0.6$ gave a still better fit to the high-luminosity spectra of M81 X-9, suggesting the presence of a slim disk. Another ULX, NGC 1313 Source B, also showed a similar luminosity-dependent spectral change. These results agree with the *ASCA* report on the two ULXs in IC 342 (Kubota et al., 2001).

Key words: galaxies: individual (M 81 / NGC 1313) ; X-rays: galaxies.

1. INTRODUCTION

Ultra-luminous compact X-ray sources (ULXs) are point-like off-center X-ray sources in nearby galaxies, with their luminosity reaching 10^{39-40} erg s^{-1}. Since their luminosity largely exceeds the Eddington limit of a neutron star, ULXs are important and interesting objects as possible candidates for intermediate-mass black holes (Colbert & Mushotzky, 1999, Makishima et al., 2000).

Detailed spectral study of ULXs have become possible since the *ASCA* era. Spectra of about 10 ULXs obtained with *ASCA* were mostly described successfully by multi-color disk (MCD) blackbody model from a standard accretion disk, and others by power-law (PL) model (Makishima et al., 2000, Mizuno et al., 2001). Moreover, two ULXs in IC 342 showed spectral transitions between the MCD-type and PL-type states (Kubota et al., 2001), as clearly seen in figure 1.

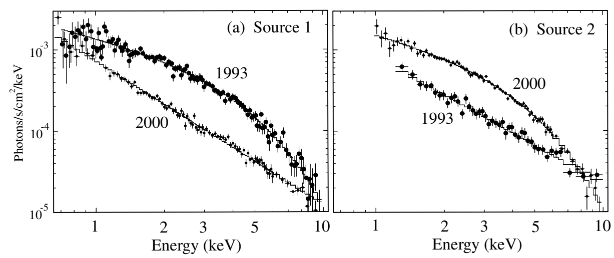

Figure 1. The ASCA spectra of IC 342 Source 1 (panel a) and Source 2 (panel b) obtained in two observations. The detector response and absorption are removed. From Kubota et al. (2001)

Recently, *XMM-Newton* and *Chandra* are providing us with a much large sample of ULXs. In contract to the *ASCA* results, spectra of most ULXs obtained with these satellites prefer the PL model to the MCD model (e.g., Roberts et al., 2004, Swartz et al., 2004), and there is evidence for very cool disks in several ULXs (Miller et al., 2003, 2004). There seems to be a systematic difference between the *ASCA* results and those from *XMM-Newton* and *Chandra*. In order to examine this issue, we analyzed archival data of two luminous nearby ULXs which have been observed repeatedly, namely, M81 X-9 and NGC 1313 Source B.

2. SPECTRAL ANALYSIS OF M 81 X-9

2.1. Observation and Data Reduction

As a typical ULX observed repeatedly over a decade since *ASCA*, we have selected M 81 X-9 ULX, located in a dwarf galaxy Holmberg IX in the M 81 group. Because

Table 1. A summary of observations and spectral studies of M 81 X-9.

	Observation date	L_x^{**}	χ^2/d.o.f(PL)	χ^2/d.o.f(MCD)	Preferred model parameter***
*ASCA**	1993-1998(average)	1.4	66/72	486.3/72	PL 1.58±0.03
	1999-04	1.9	486.5/318	359.3/318	MCD 1.24±0.03 keV
XMM-Newton	2001-04-22	2.1	508.7/324	392.0/324	MCD 1.36±0.03 keV
	2002-04-10	1.1	663.3/644	1178.5/644	PL 1.77±0.03
	2002-04-16	1.3	739.5/747	1262.4/747	PL 1.82±0.03
Chandra	2002-12-28	1.1	236.3/225	447.8/225	PL 1.63±0.04
	2003-06-09	1.3	254.4/240	396/240	PL 1.82±0.04
	2003-09-03	0.9	268.0/200	430.0/200	PL 1.62±0.06

* From Ezoe et al. (2001), La Parola et al. (2001), and Wang (2002).
** The X-ray luminosity (0.5-10 keV) in units of 10^{40} erg s^{-1}, assuming a distance of 3.6 Mpc.
*** The MCD $T_{\rm in}$ or the PL photon index, whichever is preferred.

of the explosion of SN 1993J, this object was observed 19 times with *ASCA* over 1993-1998, and the spectra from these observations were successfully described by the PL model with photon index of 1.58 (Ezoe et al., 2001). However, La Parola et al. (2001) and Wang (2002) reported from the observation on April 1999 that it became more luminous, and its spectrum turned into the MCD type with the innermost disk temperature of $T_{\rm in} = 1.24$ keV.

Observations of this object have been repeated also with *XMM-Newton* and *Chandra*, and 3 observation data with the *EPIC* onboard *XMM-Newton* and 5 data with the *ACIS* onboard *Chandra* are archival by August 2005. Although the two *XMM-Newton* datasets acquired in 2002 were already analyzed by Miller et al. (2004) and the three *Chandra* data from December 2002 to September 2003 by Unks et al. (2003), here we re-analyzed these data by ourselves. We did not utilize two Chandra datasets obtained in 2004, because they suffered from significant ($\geq$ 10 %) pile up. Table 1 summarizes the datasets employed in the present work.

We extracted spectra from each observation using the data reduction software *SAS* version 6.5.0 for *XMM-Newton* and *CIAO* version 3.2.2 for *Chandra*. Background data were extracted from regions neighboring to the source. For the 2001 April 21 observations with *XMM-Newton*, we used only the MOS1 data because the fields of view of PN and MOS2 did not fully cover the source region, which is located about 13 arcminutes off the telescope aim-points.

2.2. Spectral Properties

We fitted each spectrum of M 81 X-9 by PL (*powerlaw*) or MCD (*diskbb*) models using the software *XSPEC* version 11.0.2. Table 1 summarizes the luminosity, the fit goodness of the two models, and the parameter of the more favored model. Figure 3 shows $\Delta\chi^2$ as a function of luminosity. Here, $\Delta\chi^2$ was calculated as a difference

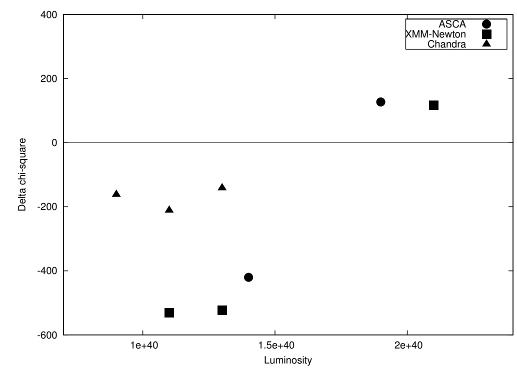

Figure 3. The difference in the fit goodness between the MCD and PL models, namely $\Delta\chi^2 \equiv \chi^2_{PL} - \chi^2_{MCD}$, plotted as a function of the 0.5-10 keV luminosity. Circles, squares, and triangles stand for ASCA, XMM-Newton, and Chandra, respectively.

between the χ^2 by the PL model and that by the MCD model; positive values mean an MCD-preferred spectrum and negative values a PL-preferred one. As was the case with *ASCA*, the most luminous *XMM-Newton* data showed an MCD-like spectrum, and the fainter two PL-type spectra. In the three *Chandra* observations, the object was rather dim, and the spectrum was PL-like. Thus, the three satellites give consistent results in that the spectrum becomes MCD-like when the source is luminous, while it becomes PL-like when the luminosity is low, with the threshold luminosity at about 1.5×10^{40} erg s^{-1}.

In figure 2, we show two typical spectra acquired on the brighter (2.1×10^{40} erg s^{-1}) and the fainter (1.1×10^{40} erg s^{-1}) occasions. Thus, the brighter spectrum clearly exhibits a convex shape, in contrast to the fainter one which is much more straight in shape. Our results on the fainter spectrum roughly agree with the results by Miller et al. (2004).

In order to more directly visualize the difference between the two spectra, we show in figure 4 (left) their spectral

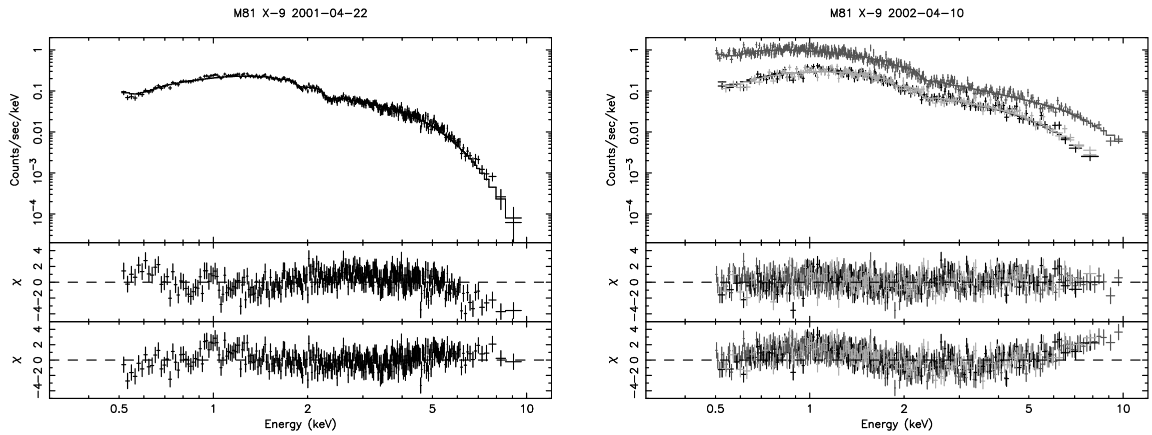

Figure 2. The left panel shows the XMM-Newton MOS1 spectrum of M 81 X-9 on the brighter occasion (2001-04-22), with the solid line describing the best-fit MCD model. The right panel shows the MOS1 (black), MOS2 (light gray), and PN (dark gray) spectra on the fainter occasion (2002-04-10), with the solid lines describing the best-fit PL model. The middle and bottom panels show the fit residuals from the PL and MCD model fits, respectively.

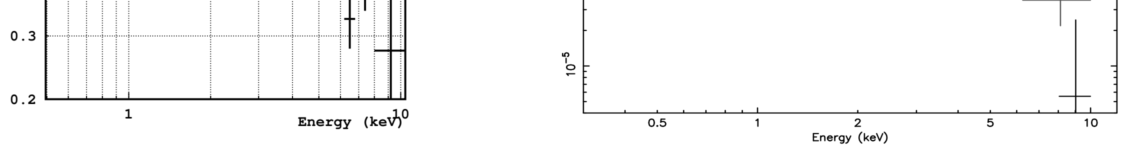

Figure 4. Comparison of the two spectra in figure 2, in the form of spectral ratios (left) and response-removed presentations (right).

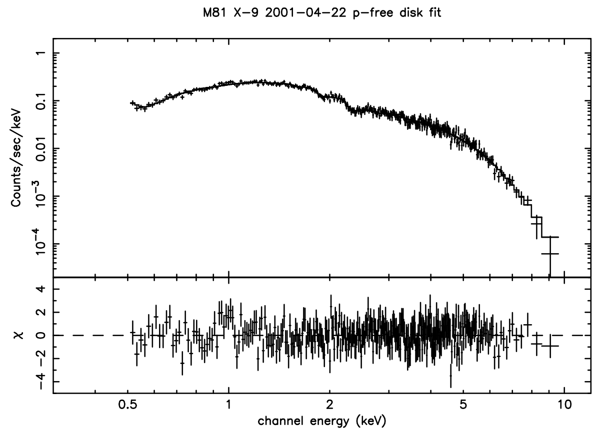

Figure 5. The same spectrum as the left panel of figure 2, but fitted with a p-free disk model.

ratios. Thus, the two spectra have very different shapes, in agreement with the model fitting results. Finally, in order to understand the actual shape of the two spectra, we show them in figure 4 (right) with the detector response removed. As expected from the ratio, the spectrum becomes clearly curved as the luminosity increases. This behavior is essentially the same as the *ASCA* results on the ULXs in IC 342 (Kubota et al., 2001), which are reproduced here as figure 1.

2.3. A p-free Disk Model Fit

Although the spectrum of M 81 X-9 on the brighter occasion preferred the MCD model as shown in the previous sub-section, the fit is not yet fully acceptable.Actually in figure 2, the spectrum is slightly deviated in shape from the MCD model. Therefore, we may modify the MCD model to achieve a better fit. The simplest modification may be so-called p-free disk model (e.g., Mineshige et al., 2000, and Watarai et al., 2001). The model assumes that the disk temperature scales as r^{-p}, where r is the radius and p is a free parameter, whereas $p = 0.75$ implies the MCD model. The p-free disk model gives a good approximation to a slim disk (Watarai et al., 2001), which is expected to form under very high accretion rates. As the standard disk gradually changes into a slim disk, the value of p is predicted to start decreasing from 0.75, and finally approaches 0.5. When p gets smaller, the soft energy part of the spectrum becomes more enhanced.

In figure 5, We actually fitted the brighter *EPIC* spectrum by the p-free disk model. Comparing the fit residual with that in figure 2 left ($\chi^2_\nu = 1.21$), the fit has been significantly improved and has become acceptable ($\chi^2_\nu = 0.98$). The best-fit model parameters are $T_{\rm in} = 1.77 \pm 0.12$ keV and $p = 0.60 \pm 0.02$. Since the value of p is significant smaller than 0.75 of the MCD model, the MCD-type spectrum may be in fact emitted by a slim disk around the central object (most likely an intermediate-mass black hole), instead of a standard disk. Further details will be reported elsewhere (Tsunoda et al., in preparation).

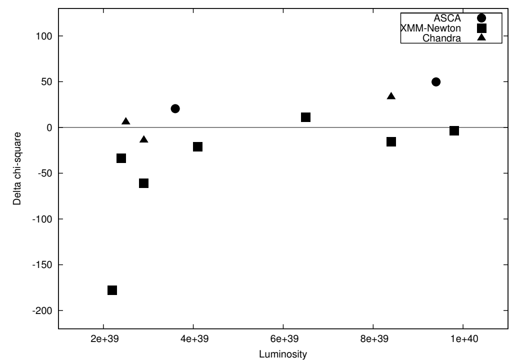

Figure 6. The same as figure 3, but for NGC 1313 Source B.

3. SPECTRAL ANALYSIS FOR NGC 1313 SOURCE B

As another target for our spectral analysis, we have selected NGC 1313 Source B, which is also a typical ULX observed repeatedly for a decade. Two observations were performed with *ASCA*, and both spectra were described successfully by the MCD model, when the 0.5-10 keV source luminosity was 9.4×10^{39} and 3.6×10^{39} erg s^{-1} at an assumed distance of 4.5 Mpc (Makishima et al. 2000, Mizuno et al. 2001). By August 2005, 9 *XMM-Newton EPIC* datasets and 5 *Chandra ACIS* data sets of this object became publicly available. We did not utilize two *XMM-Newton* datasets (2005 December 9 and 27) because they suffered from high background over the observations, and two *Chandra* datasets (2002 November 9 and 2004 February 22) suffering from significant pile up. Although some of these observations were reported by Miller et al. (2003), Wang et al. (2004), Zampieri et al. (2004), and Turolla et al. (2005), we re-analyzed these datasets by ourselves in order to study the luminosity-dependent spectral changes in a unified way.

As summarized in table 2, the luminosity of this object through the *XMM-Newton* and *Chandra* observations varied between 2.2×10^{39} and 9.8×10^{39} erg s^{-1}. In figure 6, we show $\Delta\chi^2$ calculated in the same way as in figure 3. Although the results are not as clear as those for M81 X-9, we can see a tendency that the spectrum changes into MCD-like as luminosity increases. Among them, we have selected the 2003 December 21 data (8.4×10^{39} erg s^{-1}) and the 2000 October 17 data (2.2×10^{39} erg s^{-1}), both with *EPIC* MOS1, as representing relatively brighter and fainter states, respectively. Other datasets had poorer statistics. Like in the case of M81 X-9, figure 7 (left) compares the two spectra in the form of spectral ratios, whereas figure 7 (right) in the response-removed representations. We can see that the spectrum becomes again curved as the luminosity increases. These results are similar to those of M 81 X-9.

Table 2. The same as table 1, but for NGC 1313 Source B.

	Observation date	L_x^{**}	χ^2/d.o.f(PL)	χ^2/d.o.f(MCD)	Preferred model parameter***
*ASCA**	1993-07-12	9.4	174.2/130	124.5/130	MCD 1.47±0.08 keV
	1995-11-29	3.6	110.3/74	89.8/74	MCD 1.07±0.07 keV
XMM-Newton	2000-10-17	2.2	195.4/222	373.0/222	PL 2.32±0.07
	2003-11-25	6.5	53.0/50	42/50	PL 1.90±0.16 or MCD $1.34^{+0.14}_{-0.12}$ keV
	2003-12-21	8.4	336.0/314	351.7/314	PL 1.78±0.05 or MCD 1.62±0.06 keV
	2003-12-23	9.8	182.6/179	186.2/179	PL 1.72±0.06 or MCD 1.72±0.09 keV
	2003-12-25	4.1	70.5/82	91.8/82	PL 2.10±0.13
	2004-01-08	2.9	134.2/156	195.0/156	PL 2.39±0.09
	2004-01-16	2.4	57.0/67	90.5/67	PL 2.35±0.14
Chandra	2002-10-13	8.4	204.8/175	171.5/175	MCD 1.66±0.07 keV
	2003-10-02	2.9	75.6/56	89.6/56	PL 1.93±0.14 or MCD $1.41^{+0.06}_{-0.16}$ keV
	2004-03-10	2.5	41.9/26	36.1/26	PL $2.04^{+0.24}_{-0.22}$ or MCD $1.17^{+0.16}_{-0.14}$ keV

* From Makishima et al. (2000) and Mizuno et al. (2001).
** In units of 10^{39} erg s^{-1}, assuming a distance of 4.5 Mpc.
*** Both parameters were shown in case that a preferred model cannot be constrained.

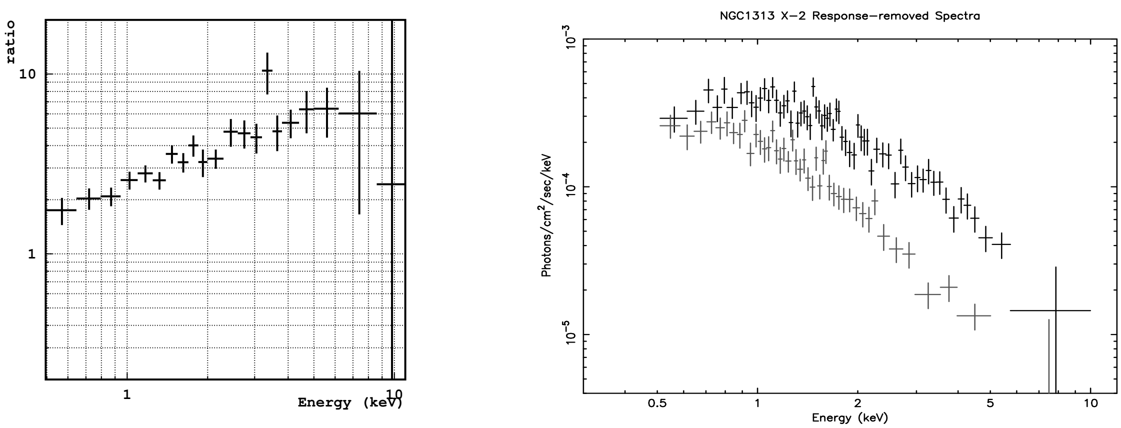

Figure 7. The same as figure 4, but for NGC 1313 Source B.

4. CONCLUSION

In order to investigate spectral properties and in particular search for spectral transitions, we analyzed *XMM-Newton* and *Chandra* archival data of two typical ULXs, M 81 X-9 and NGC 1313 Source B. Spectra of the two ULXs showed consistent luminosity-dependent changes through the three satellites including *ASCA*. That is, the spectrum exhibited a transition from PL-type ones to MCD-type ones, as the source luminosity increased across a certain threshold. Such a spectral transition is reminiscent of those observed with *ASCA* from two ULXs in IC 342. This means that the same spectral transition has been confirmed from four ULXs in total. As to M 81 X-9, a p-free disk model significantly improved the fit to the high-luminosity spectrum, and the obtained value of p was smaller, 0.60 ± 0.02, than that of the MCD model. This object possibly forms a slim disk when luminosity becomes higher than $\sim1.5\times10^{40}$ erg s^{-1}. We therefore conclude that the *XMM-Newton* and *Chandra* data are consistent with the original *ASCA* results, at least as to those four luminous ULXs.

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