Suzaku Observation of Two Ultraluminous X-Ray Sources in NGC1313

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We report about the Suzaku observation of two ultraluminous X-ray sources (ULXs), X-1 and X-2, in NGC1313, together with their spectra by XMM-Newton. During the observation, both showed intensity-correlated spectral changes. The brighter source, X-1, exhibited the highest luminosity ($\sim 3 \times 10^{40}$erg s^{-1}) ever recorded from this source. Its spectral variation is ascribed to a strong power-law like component with a mild high energy curvature, while about 10% of the flux is carried by a stable soft component modeled by a cool disk emission. These properties suggest that the source was in the "very high" state, wherein the disk emission is strongly Comptonized and the optically-thick disk is truncated at a large radii or cooled off. The spectrum of X-2 is best represented, in its fainter phase, by a multicolor disk model with the innermost disk temperature of 1.2–1.3 keV, and becomes flatter as the source gets brighter. Hence X-2 is interpreted to be in a slim disk state. These results suggest that the two ULXs host black holes of a few tens to a few hundreds solar masses.

§1. Introduction

Ultraluminous X-ray sources (ULXs) are promising candidate for intermediate-mass black holes because of their high luminosity and time variability.[1)] A study of ULXs has progressed dramatically in past 10 years. ASCA observed more than a dozen ULXs[2),3)] and reinforces the black-hole scenario with masses of 30–100 $M_\odot$, through the discovery of an accretion disk emission represented by a so-called multi-color disk model (MCD model[4)]) and the spectral transition between the MCD-type state and the power-law (PL) type state.[5),6)] XMM-Newton, with its unprecedented throughput, enlarged the ULX sample and found that many ULXs also exhibited a PL-like spectrum often accompanied by soft excess below 1 keV.[7),8)]

Another important clue to the nature of ULXs has been provided through the study of Galactic black hole binaries (BHBs). Besides the established low/hard state and high/soft state, two novel states, namely a very high state[9)] and a theoretically predicted "slim disk" state,[10)] have been identified mainly with RXTE observations.[11)] The former state is characterized by a PL-like spectrum presumably due to the strong Comptonization by a hot optically thick plasmas, and the latter one is characterized by a hot MCD-like spectra from an optically-thick, moderately geometrically-thick disk where advective cooling is important. These two states successfully explain the spectra of some ULXs.[12)–14)]

§2. Observation

NGC 1313 is a nearby face-on, late-type Sb galaxy at a distance of 3.7 Mpc[15)] hosting two famous ULXs called X-1 and X-2.[16)] Although they have already been studied extensively with ASCA and XMM-Newton,[13),17),18)] a unified picture of these two ULXs (and other ULXs) has not yet obtained, due to the difficulty to unambiguously distinguish the different modelings of their spectra. We therefore conducted a Suzaku observation of this galaxy on 2005 October 15.

§3. Data analysis and discussion

3.1. *Time-averaged spectra*

To investigate the time-averaged spectral property, we calculated the Crab ratio of two ULXs. As shown in Fig. 1, the X-1 spectrum has a PL-like shape up to 3 keV and then falls off above 5 keV, and the X-2 spectrum shows a similar shape. Thus, neither spectrum can be modeled by a single PL. In the following sections, we first analyze the fainter source, X-2, and then study the brighter one, X-1.

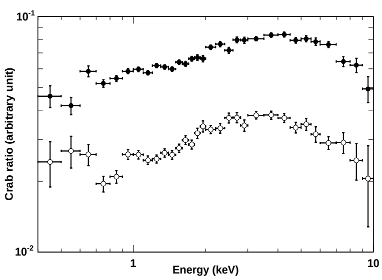

Fig. 1. The Crab ratio of the time-averaged FI spectra of X-1 (filled circles) and X-2 (open ones).

3.2. *Spectral variability of X-2*

The light curve of X-2 shown in Fig. 2 (right) indicates the variability by ∼50%. Accordingly, we extracted a brighter phase spectrum and a fainter phase one. We then fitted two spectra individually with a PL plus MCD model, a standard model widely used to describe the ULXs spectra, and plotted "unfolded" spectra in Fig. 3 (right) with those created from XMM archival data for comparison.

As shown in the figure, the source exhibited a PL-like spectrum when the flux is low, and turned into an MCD-like convex spectrum as the flux increases. To quantify the spectral change of the Suzaku data, we tried a single MCD model and obtained an acceptable fit ($\chi^2/\nu = 71/76$) to the fainter phase data. Since the model failed to reproduce the brighter phase data with $\chi^2/\nu = 172/144$, we employed a so-called p-free disk model, a modified MCD model where the disk temperature profile is given as a function of radius r and a free parameter p as $T(r) = T_{\rm in}(r/r_{\rm in})^{-p}$.[19)] This model has been utilized to represent the spectra of BHBs thought to be in the slim disk state.[11)] As summarized in Table I, the model successfully reproduced the brighter phase spectrum and observed decrease of the coefficient p (which is 0.75 for the MCD

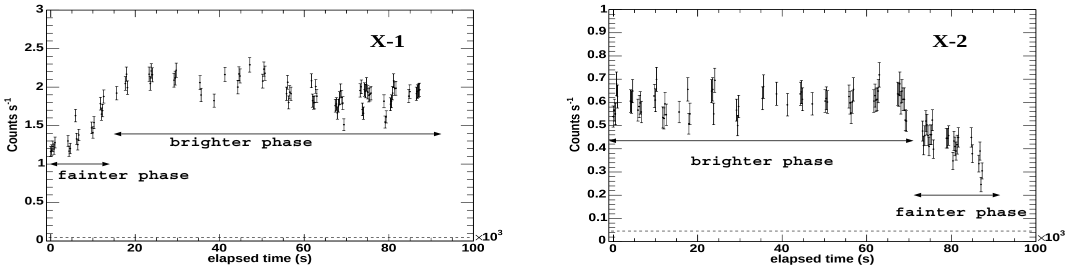

Fig. 2. Suzaku FI light curve of X-1 (left panel) and X-2 (right panel) in the 0.4–10 keV energy range with the background level indicated by dotted lines.

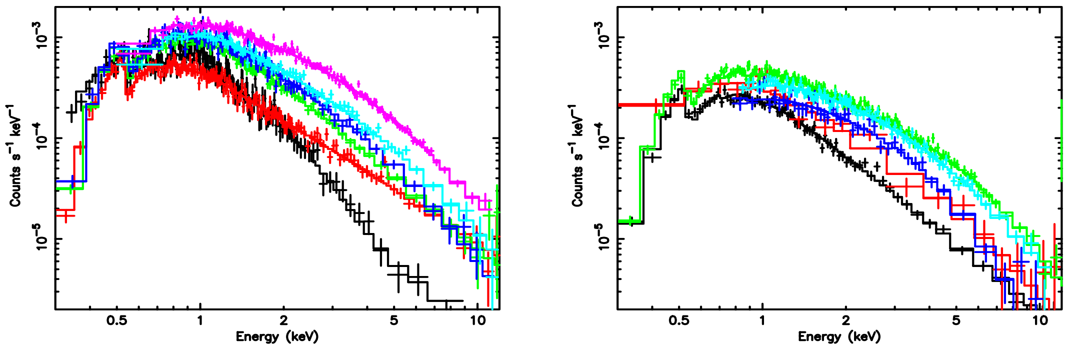

Fig. 3. Unfolded spectra of X-1(left) and X-2(right). For X-1, Suzaku spectra are shown as cyan and purple histograms and XMM spectra as histograms in black ('03 Aug 23), red ('00 Oct 17 and '05 Feb 7), green ('03 Dec 21, '04 Jan 8 and 17) and blue ('04 Jun 5). X-2 spectra of Suzaku are given as blue and cyan histograms, and those of XMM as histograms in black ('00 Oct 17, '04 Jan 8, 16 and 23), red ('03 Dec 25) and green ('03 Dec 21 and 23, '05 Feb 7 and '06 Jun 5). (See the online edition for the color version of Fig. 3.)

model) as the flux increase agrees with the slim disk prediction.[20] We thus concluded that the source is in the slim disk state when observed by Suzaku. Spectral change of this ULXs shown in Fig. 3 can be understood as the state transition between the very high state (low intensity) and the slim disk state (high intensity). BH mass of $\sim 50 M_\odot$ is required to satisfy the Eddington limit.

3.3. *Spectral variability of X-1*

The X-1 also exhibited the intensity change during the Suzaku observation (Fig. 2 left). Again, we utilized the PL+MCD model to obtain the unfolded spectra. As summarized in Fig. 3 (left), most of the XMM data exhibited the PL-like spectrum and Suzaku recorded the higest luminosity ever observed with a high energy cutoff around 3–5 keV. We tried the p-free disk model fit which successfully explains the X-2 spectra. A PL-type hard spectrum with soft excess below 1 keV has been widely observed in ULXs including this object.[17] Since the apparently PL-like continuum often exhibits a high-energy turn over,[12),21),22] we also employed a MCD plus cutoff power-law model (MCD+cutoff-PL) which approximates the disk Comptonization seen in the very high state of BHBs.

Either model is moderately successful on spectra of both phases, as summarized

Table I. Fits to time-sorted spectra with errors for 90% confidence for one interesting parameter.

model	$N_{\rm H}$ (10^{21} cm^{-2})	$T_{\rm in}$ (keV)	$R_{\rm in}$ ($\frac{1}{\cos i}$km)	Γ or p	$E_{\rm c}$ (keV)	$f_{\rm disk}{}^*$	$f_{\rm pow}{}^\dagger$	χ^2/ν
X-1, fainter phase								
p-free	2.3 ± 0.2	$2.69^{+0.88}_{-0.38}$	$21(\leq 31)$	0.514 ± 0.014		12.5		83.9/95
MCD+cutoff-PL	$3.0^{+2.1}_{-1.5}$	$0.20(\leq 0.41)$	$4500(\leq 25000)$	$1.59^{+0.33}_{-0.60}$	$6.0^{+6.9}_{-2.2}$	1.9	11.7	82.1/93
X-1, brighter phase								
p-free	1.8 ± 0.2	2.09 ± 0.10	60 ± 7	0.595 ± 0.012		15.6		243.4/219
MCD+cutoff-PL	$2.3^{+0.5}_{-0.8}$	$0.21^{+0.13}_{-0.03}$	3800^{+6700}_{-3200}	0.89 ± 0.20	$3.4^{+0.6}_{-0.4}$	1.5	15.1	237.9/217
X-2, fainter phase								
MCD	0.9 ± 0.3	1.24 ± 0.05	96 ± 9			2.3		71.2/76
X-2, brighter phase								
p-free	1.7 ± 0.4	1.86 ± 0.15	43^{+12}_{-9}	$0.627^{+0.036}_{-0.026}$		4.2		150.8/143

* observed 0.4–10 keV flux of the MCD or the p-free disk component in units of 10^{-12} erg s^{-1} cm^{-2}
† observed 0.4–10 keV flux of the cutoff-PL component in units of 10^{-12} erg s^{-1} cm^{-2}

in Table I. Although we employed the p-free disk model to examine the slim-disk interpretation, the derived results appear to be self-contradictory to this view. The model fits implies that the temperature profile coefficient p increases and $T_{\rm in}$ decreases as the source gets brighter, contrary to the theoretical predictions by the slim disk model.[20] Therefore, X-1 is not likely to be in the slim disk state.

As shown in Fig. 3 (left), the X-1 spectrum below 1 keV stayed nearly constant, and only the hard part of it varied. This behavior is better represented by the MCD+cutoff-PL fit, making the model promising. In fact, the MCD component in this fit is consistent with being constant (Table I), and the variation in the cutoff-PL component alone can account for the intensity and spectral changes. As the cutoff-PL model generally approximates the process of unsaturated Comptonization, the slightly convex continua of X-1 can be interpreted as a result of Comptonization of some soft photons by hot thermal electrons, which presumably form a disk corona. We thus concluded that the source is in the very high state. The apparently low-temperature and the large physical size of the disk given in Table I is understood as the disk is cooled down or truncated due to the strong Comptonization.[23],[24] Then, a reliable estimate on the BH mass may be obtained from the source luminosity: the bolometric luminosity for the brighter phase spectrum is 3.3×10^{40} erg s^{-1}, requiring a BH mass of $\sim 200\ M_\odot$.

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