Suzaku detections of luminosity-dependent spectral changes from the two ultraluminous X-ray sources, X1 and X2, in NGC 1313

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Abstract

A Suzaku follow-up observation of the nearby galaxy NGC 1313 was performed on 2008 December 5 – 8. The 0.5 – 10 keV luminosity of the two ultraluminous X-ray sources (ULXs), X1 and X2, in the galaxy was measured as 7.1×10^{39} ergs s^{-1} and 1.9×10^{39} ergs s^{-1}, respectively, both of which are by a factor of 4 lower than those of the scientific working group (SWG) observation in 2005. The X-ray spectrum of X1 is described with a composite model, consisting of a power-law (PL) component with a high energy cut off and a cool accretion disk emission. In comparison with the SWG observation, the innermost disk temperature stayed relatively unchanged ($T_{\rm in} \sim 0.25$ keV), while the cut off energy became slightly higher ($E_{\rm cut} = 6.8^{+4.9}_{-2.2}$ keV). On the other hand, X2 exhibited a transition from the disk-like spectrum to the PL-dominated one with a photon index of $\Gamma = 1.84^{+0.15}_{-0.19}$, between the SWG and this follow-up observations. These results re-confirmed that the spectral properties of these two ULXs are successfully interpreted, on the basis of the very high and slim disk states of Galactic black holes at the sub- or trans-Eddington luminosities. As a result, the intermediate-mass-black-hole interpretation for ULXs are supported.

Key words: accretion, accretion disks — black hole physics — galaxies: individual (NGC 1313)

1. Introduction

In numbers of nearby normal galaxies, luminous non-nuclear X-ray sources with an X-ray luminosity of $L_{\rm X} \gg 10^{39}$ ergs s^{-1} are frequently found (Fabbiano & Trinchieri, 1987). They are called ultraluminous X-ray sources (ULXs; Makishima et al. 2000). In spite of more than two decades from their discovery, a definitive consensus on the nature of the ULXs has not yet been obtained. Especially, there are mainly two conflicting interpretations; intermediate mass black holes (BHs) with a mass of $M \gg 10 M_\odot$ (where $M_\odot$ is the solar mass) radiating at sub- or trans-Eddington luminosities, and stellar-mass BHs with a super critical mass accretion.

A luminosity-dependent spectral change or transition is regarded as one of the important clues to solve the nature of the ULXs. X-ray spectra of the ULXs are naively divided into two types; a power-law (PL) like and a multi-color-disk (MCD; Mitsuda et al. 1984) like ones. Some PL-like ULXs are reported to exhibit a cool MCD component (e.g., Miller et al. 2004). Moreover, a transition between these two spectral states are reported from an increasing number of ULXs (e.g., Kubota et al. 2001, Isobe et al. 2009). Recent progress in observational (e.g., Mizuno et al. 2001, Kubota & Makishima 2004, Tsunoda et al. 2008, Miyawaki et al. 2009) and theoretical (e.g., Watarai et al. 2000) studies of ULXs and Galactic BHs revealed that the MCD-like state of the ULXs is interpreted as a theoretically predicted "slim disk" state, in which a high accretion rate makes important the effects of optically thick advection and/or photon trapping (Ohsuga et al. 2005), while the PL-like one corresponds to a very high state (VHS) in which Comptonization of disk photons in hot corona surrounding the disk effectively works. The Galactic BHs are reported to make transitions between these states (and the classical high/soft state) typically at the X-ray luminosity of $\eta = L_{\rm X}/L_{\rm E} = 0.2 - 1$ (e.g., Kubota and Makishima 2004, Abe et al. 2005), where $L_{\rm E}$ in the Eddington limit. Therefore, the detection of the transition between these two states from an ULX gives a rough estimation of its

Table 1. Summary of the model fitting to the X-ray spectra of X1 and X2.

Source		X1			X2	
Model	PL	PL+MCD	cutoffPL+MCD	PL	PL+MCD	cutoffPL+MCD
$N_{\rm H}(10^{21}$ cm$^{-2})$	0.67 ± 0.14	2.44 ± 0.76	$1.56^{+0.68}_{-0.57}$	$1.54^{+0.28}_{-0.27}$	$2.39^{+1.19}_{-0.85}$	$2.42^{+1.14}_{-0.96}$
$F_{\rm X}$ *	3.58	3.55	3.48	0.93	0.94	0.94
$L_{\rm X}$ †	7.33	7.27	7.12	1.90	1.93	1.93
Γ	1.71 ± 0.03	1.73 ± 0.05	$1.11^{+0.27}_{-0.35}$	$2.02^{+0.07}_{-0.06}$	$1.84^{+0.15}_{-0.19}$	$1.83^{+0.15}_{-0.69}$
$E_{\rm cut}$ (keV)	–	–	$6.8^{+4.9}_{-2.2}$	–	–	≥ 9.2
$T_{\rm in}$ (keV)	–	$0.18^{+0.03}_{-0.02}$	$0.25^{+0.06}_{-0.04}$	–	$0.26^{+0.11}_{-0.07}$	$0.25^{+0.12}_{-0.06}$
$R_{\rm in}$ (km)	–	$7.7^{+5.7}_{-3.9} \times 10^3$	$3.1^{+2.5}_{-1.4} \times 10^3$	–	$1.6^{+3.6}_{-1.0} \times 10^3$	$1.7^{+3.3}_{-1.1} \times 10^3$
$L_{\rm disk}$ ‡	–	6.0	3.3	–	1.1	1.1
χ^2/d.o.f	243.0/183	219.3/181	202.3/180	154.9/128	133.7/126	133.8/125

$*$ Absorption-uncorrected 0.5 – 10 keV model flux in 10^{-12} ergs cm^{-2} s^{-1}.
† Absorption-uncorrected 0.5 – 10 keV model luminosity in 10^{39} ergs s^{-1}.
‡ Bolometric luminosity of the MCD component in 10^{39} ergs s^{-1}.

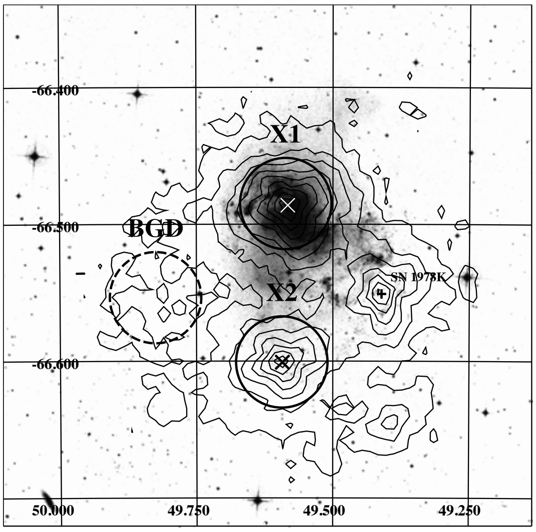

Fig. 1. The 0.5 – 10 keV Suzaku XIS contour image of MGC 1313, overlaid on the gray-scale optical one. The circles indicate the integration regions for the X1, X2 and background signals.

mass under the assumption that the ULXs and Galactic BHs share common physical nature. Actually, Isobe et al. (2009) successfully applied this technique to the spectral variation of the ULX, NGC 2403 source 3, and estimated its mass as 10–20$M_{\odot}$.

2. Targets and Observation

Locate at a distance of 4.13 Mpc (Mendez et al. 2002), the nearby normal Sb galaxy NGC 1313 hosts two bright ULXs, called X1 and X2 (Colbert et al. 2005). Although both sources are extensively studied with ASCA (e.g., Mizuno et al. 2001) and XMM-Newton (e.g., Feng & Kaaret 2006), a comprehensive picture to interpret their spectral variation, and hence their nature, has not yet been constructed.

Thanks to its high sensitivity up to 10 keV, the Suzaku X-ray imaging spectrometer (XIS) has a great advantage in distinguishing the spectral states of ULXs. In 2005 October, the first Suzaku exposure on NGC 1313 was performed, as a part of the scientific working group (SWG) observations. A close examination in their spectral variation revealed that X1 and X2 resided in the VHS and slim disk state, respectively, during the SWG observation (Mizuno et al. 2007).

In order to reinforce the VHS and slim disk interpretation, it is important to confirm the spectral transition between these two states from these ULXs. Therefore, a follow-up Suzaku observation of NGC 1313 was conducted on 2008 December 5 – 8 during the AO3 phase.

3. Results

Figure 1 shows the XIS image of NGC 1313. The two ULXs, X1 and X2, are significantly detected, in addition to a supernova remnant SK 1978K in the galaxy. Since both ULXs exhibited no statistically significant variability during this observation, only their time-averaged X-ray spectra were analysed. The parameters for the spectral fitting discussed below are summarised in Table 1.

The Suzaku XIS spectrum of the NGC 1313 X1 in the AO3 observation is shown in Figure 2. The spectrum appears to be featureless and hard. First, a PL model subjected to a free absorption was examined. However, as shown in Figure 2 (b), the PL model give only a marginal fit (χ^2/d.o.f = 243.0/183). Next, a cool MCD component was introduced to the PL model (PL+MCD), like in the case of several PL-like ULXs, including NGC 1313 X1 during a XMM-Newton observation (Miller et al. 2003). The fit become slightly improved with the

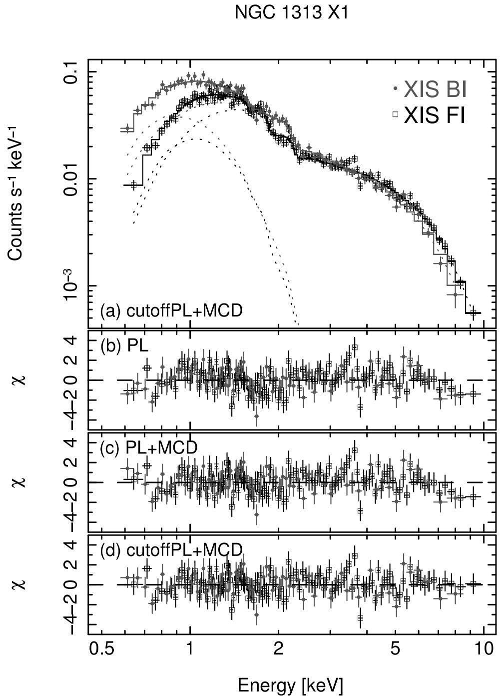

Fig. 2. The Suzaku XIS spectra of NGC 1313 X1 in the AO3 observation. The residuals for the PL, PL+MCD, cutoffPL+MCD models are shown in the panel (b), (c), and (d), respectively. The dotted lines in the panel (a) represent the best fit MCD and cutoffPL components.

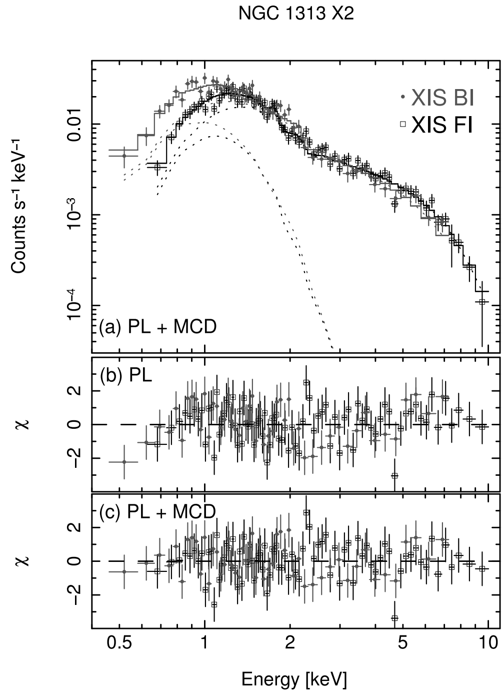

Fig. 3. The Suzaku XIS spectra of NGC 1313 X2. The residuals for the PL, PL+MCD, models are shown in the panel (b), and (c), respectively.

PL+MCD model (χ^2/d.o.f $= 219.3/181$).

The PL+MCD residuals in Figure 2 (c) suggest a spectral cut off around $E_{\rm cut} \sim 6$ keV. Then the observed spectrum was re-analysed by replacing the PL component with the cut-off PL one (cutoffPL+MCD), and a reasonable fit was obtained (χ^2/d.o.f $= 202.3/180$). The photon index was derived as $\Gamma = 1.11^{+0.27}_{-0.35}$. The cut-off energy, $E_{\rm cut} = 6.8^{+4.9}_{-2.2}$ keV, was slightly higher than those of the bright phase in the SWG observation, $E_{\rm cut} = 3.4^{+0.6}_{-0.4}$ keV (Mizuno et al. 2007). The innermost disk temperature and bolometric luminosity of the MCD component was measured as $T_{\rm in} = 0.25^{+0.06}_{-0.04}$ keV and $L_{\rm disk} = 3.3 \times 10^{39}$ ergs s^{-1}, respectively, where the disk inclination is assumed to be $i = 60°$. The innermost disk radius is calculated as $R_{\rm in} = 3.1^{+2.5}_{-1.4} \times 10^3$ km, using the relation of $L_{\rm disk} = 4\pi\sigma(R_{\rm in}/\xi)^2(T_{\rm in}/\kappa)^4$, where σ is the Stefan-Boltzmann constant, $\xi = 0.41$ is a correction factor for inner boundary condition (Kubota et al. 1998), and $\kappa = 1.7$ is the spectral hardening factor (Shimura & Takahara 1995).

In the manner similar to X1, the XIS spectrum of X2 shown in Figure 3 was investigated. Although the PL model was marginally acceptable (χ^2/d.o.f $= 154.9/128$), the fit was significantly improved by the PL+MCD model (χ^2/d.o.f $= 133.7/126$). In comparison with the PL+MCD model, the cutoffPL+MCD model is found to give no improvement (χ^2/d.o.f $= 133.8/125$). As a result, no spectral cut off is required for the X-ray spectrum of X2 in the XIS energy range ($E_{\rm cut} \geq 9.2$ keV). The photon index of the PL component was derived as $\Gamma = 1.84^{+0.15}_{-0.19}$. The innermost disk temperature and disk luminosity of the MCD component was measured as $T_{\rm in} = 0.26^{+0.11}_{-0.07}$ keV and $L_{\rm disk} = 1.1 \times 10^{39}$ ergs s^{-1}, respectively. These yielded the innermost disk radius of $R_{\rm in} = 1.6^{+3.6}_{-1.0} \times 10^3$ km.

4. Discussion

As shown in the left panel of Figure 4, the X-ray luminosity of NGC 1313 X1 in the AO3 observation ($L_{\rm X} = 7.1 \times 10^{39}$ ergs s^{-1} in $0.5 - 10$ keV) was by a factor of 4 lower than that in the SWG observation ($L_{\rm X} = 2.7 \times 10^{40}$ ergs s^{-1}). The source apparently exhibited different X-ray spectral shapes, between the two observations. However, these spectra can be commonly described with the cutoffPL+MCD model (Mizuno et al. 2007), which properly approximates the X-ray spectrum of the disk Comptonization for Galactic BHs. Therefore, it is regarded that X1 resided in the VHS in both occasions. Between the two observation, the parameters of the MCD component were found to stay relatively unchanged. The apparent spectral variation is supposed to be attributed to the change of the physical condition in the hot corona. Especially, an anti-correlation was suggested between

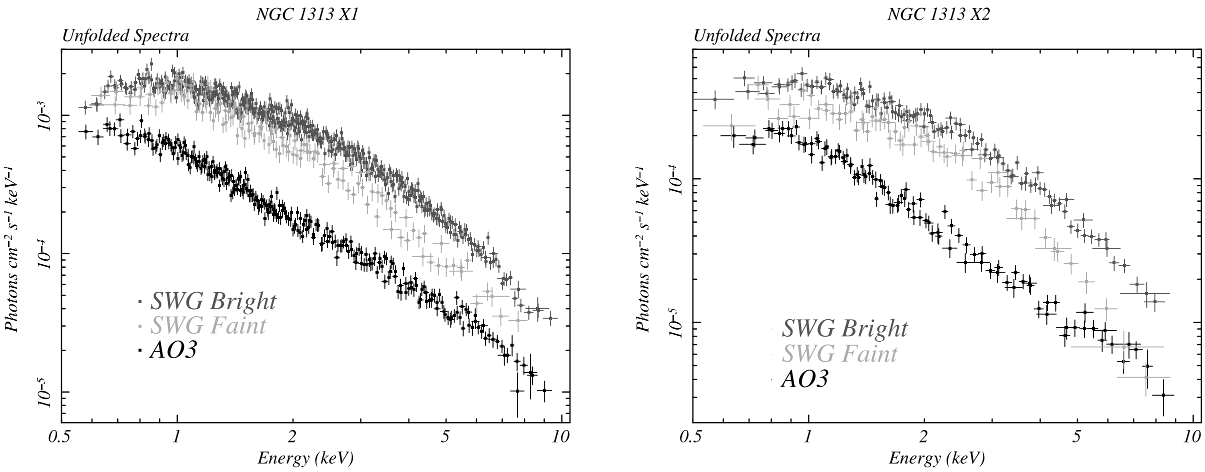

Fig. 4. Unfolded X-ray spectra of NGC 1313 X1 (left) and X2 (right). The data obtained in the AO3 observation are shown with the black points. Referring to Mizuno et al. (2007), the SWG data are divided into those in the bright (dark gray) and faint (light gray) phases.

$E_{\rm cut}$ and the source luminosity. This implies that the electrons in the corona are effectively cooled down, due to an enhanced Compton radiative cooling at the high luminosity phase. A complex change of the physical condition of the hot corona and accretion disk in the VHS was reported from the Galactic BH, XTE J1550+564 (Kubota & Done 2004).

The right panel of Figure 4 compares the unfolded X-ray spectra of NGC 1313 X2. Similar to X1, the source faded by a factor of 4, from the SWG observation ($L_{\rm X} = 8.0 \times 10^{39}$ ergs s^{-1}) to the AO3 one ($L_{\rm X} = 1.9 \times 10^{39}$ ergs s^{-1}). During the SWG observation, X2 exhibited convex X-ray spectra, which is successfully described by the MCD model (faint phase; Mizuno et al. 2007) or its extension (bright phase) in which the dependence of the local temperature on the radius r from the BH in the accretion disk is assumed to scale as r^{-p}, with $p = 0.75$ corresponding to the simple MCD model (Mineshige et al. 1994). Because this extension of the MCD model approximates the theoretically predicted X-ray spectrum from the slim disk (Watarai et al. 2000), X2 was concluded to harbor a slim accretion disk during the SWG observation (Mizuno et al. 2007). On the other hand, the AO3 spectrum of the source is significantly different, and is described by the PL+MCD model. This suggests that X2 turned into the VHS. Non detection of the spectral cut off ($E_{\rm cut} \geq 9.2$ keV) means that the electron temperature in the corona around X2 is higher than that in X1. Thus, Suzaku has succeeded in detecting the slim-disk-to-VHS transition from this ULXs.

Finally, the mass of these two ULXs are roughly estimated, applying the fact that the Galactic BHs typically make transitions between the slim disk state and VHS, at the luminosity of $\eta = L_{\rm X}/L_{\rm E} = 0.2 - 1$. For X2, the transition luminosity was expected to be in the range of $L_{\rm X} = (1.9\text{–}8.0) \times 10^{39}$ ergs s^{-1}. Based on this luminosity, the mass of X2 is calculated as $M \sim (15\text{–}50)\eta^{-1} M_\odot$. Throughout the Suzaku observations, X1 did not make any transitions from the VHS to slim disk state. Therefore, the transition luminosity of the source is inferred to be comparable to or higher than the highest luminosity during the Suzaku observation. As a result, the mass of X1 is estimated as $M \gtrsim 180\eta^{-1} M_\odot$. Interestingly, Dewangan et al. (2009) reported a similar value of $200 M_\odot$ for the mass of X1, on the basis of the energetics in the Comtonizing corona. These results support the idea that the ULXs are heavier than Galactic BHs.

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