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A TRANSITION TO A LOW/SOFT STATE IN THE ULTRALUMINOUS COMPACT X-RAY SOURCE HOLMBERG II X-1

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ABSTRACT

We present three *XMM-Newton* observations of the ultraluminous compact X-ray source Holmberg II X-1 in its historical brightest and faintest states. The source was in its brightest state in 2002 April with an isotropic X-ray luminosity of $\sim 2 \times 10^{40}$ ergs s^{-1} but changed to a peculiar low/soft state in 2002 September in which the X-ray flux dropped by a factor of ∼4 and the spectrum softened. In all cases, a soft excess component, which can be described by a simple or multicolor disk blackbody ($kT \sim 120$–170 eV), is statistically required in addition to a power-law continuum ($\Gamma \sim 2.4$–2.9). Both spectral components became weaker and softer in the low/soft state; however, the dramatic variability is seen in the power-law component. This spectral transition is opposite to the "canonical" high/soft–low/hard transitions seen in many Galactic black hole binaries. There is a possible contribution from an optically thin thermal plasma. When this component is taken into account, the spectral transition appears to be normal—a drop of the power-law flux and a slightly softer blackbody component in the low state.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (Holmberg II X-1) — X-rays: stars

On-line material: color figures

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are the compact, off-nuclear galactic X-ray sources with isotropic luminosity exceeding the Eddington limit for a stellar mass ($\lesssim 20\ M_\odot$) black hole (BH). Isotropic emission from intermediate-mass (~ 20–$10^5\ M_\odot$) BHs and anisotropic emission from stellar-mass BHs are both attractive interpretations for the nature of ULXs; however, there is no definite proof for either of the two scenarios (Miller & Colbert 2004). Several observations suggest that ULXs may be similar to the X-ray binaries. The discovery of orbital modulations from several ULXs (Bauer et al. 2001; Sugiho et al. 2001) implies a binary nature. The *ASCA* X-ray spectra of ULXs have been described as the emission from optically thick accretion disks (Makishima et al. 2000 and references therein); however, the inferred disk temperatures, in the range of ∼1–2 keV, are too high for the BH masses implied by their X-ray luminosity. Recent observations with *Chandra* and *XMM-Newton* suggest lower temperatures in the range of ∼100–500 eV (see review by Miller & Colbert 2004 and references therein). Observations of spectral transitions between the low (hard) and the high (soft) state from two ULXs in IC 342 (Kubota et al. 2001) further demonstrate their similarity to the Galactic BH binaries. These observational facts suggest that ULXs may be more massive or scaled up versions of X-ray binaries. Recently, Ebisawa et al. (2003) argued that the high temperatures inferred from the X-ray spectra of some ULXs are high even for an accreting Kerr BH, and they explained the X-ray spectra in terms of a slim disk model without requiring intermediate-mass BHs.

Holmberg II X-1 (hereafter HoII X-1) is nearby (3.39 Mpc; Karachentsev et al. 2002) and is one of the brightest ULXs in the sky. Its X-ray luminosity ($L_X \sim 10^{40}$ ergs s^{-1}) corresponds to the Eddington luminosity of an 80 $M_\odot$ BH. It resides near the edge of a dwarf star-forming galaxy and is embedded in an H II region. Also, a compact He II emission-line cloud has been discovered at the position of HoII X-1, indicating that this ULX is actually photoionizing the surrounding gas (Pakull & Mirioni 2001; Lehmann et al. 2004). The *ROSAT* HRI and PSPC observations of HoII X-1 revealed a pointlike, variable source on scales of days and years (Zezas et al. 1999). The *Chandra* ACIS-S observations also revealed a pointlike X-ray source and an indication for a weak extended component (Lehmann et al. 2004). Miyaji et al. (2001) presented the joint *ROSAT* and *ASCA* spectrum, which is well described by a power law ($\Gamma_X \sim 1.9$) and a soft excess component modeled either as an multicolor disk (MCD; $kT \sim 170$ eV) or a MEKAL plasma ($kT \sim 300$ eV). In this Letter, we present puzzling X-ray spectral variability of this well-known ULX, HoII X-1, observed with *XMM-Newton*.

2. OBSERVATION AND DATA REDUCTION

XMM-Newton observed HoII X-1 3 times on 2002 April 10, April 16, and September 18 for 12.6, 13.8, and 6.9 ks, respectively. The EPIC PN (Strüder et al. 2001) and MOS (Turner et al. 2001) cameras were operated in full-frame mode using the thin filter. The raw events were processed and filtered using the most recent updated calibration database and analysis software (SAS, ver. 5.4.1) available in 2003 December. Cleaning of the flaring particle background resulted in "good" exposure times of 4.66, 3.95, and 4.25 ks for the EPIC PN observations of 2002 April 10, April 16, and September 18, respectively. Events in the bad pixels and those adjacent pixels were discarded. Only events with patterns 0–4 (single and double) for the PN and patterns 0–12 for the MOS were selected.

3. ANALYSIS AND RESULTS

We extracted full-band light curves for HoII X-1 from the PN data using circular regions of 40″ radii centered at the source position. We also extracted the corresponding background light curves from source-free regions with the same bin sizes and exposure requirement. The background-corrected PN light curves of HoII X-1 are shown in Figure 1 for the three *XMM-Newton* observations. Small-amplitude ($\lesssim 20\%$) fluctuations are seen in each of the three observations. A constant count rate

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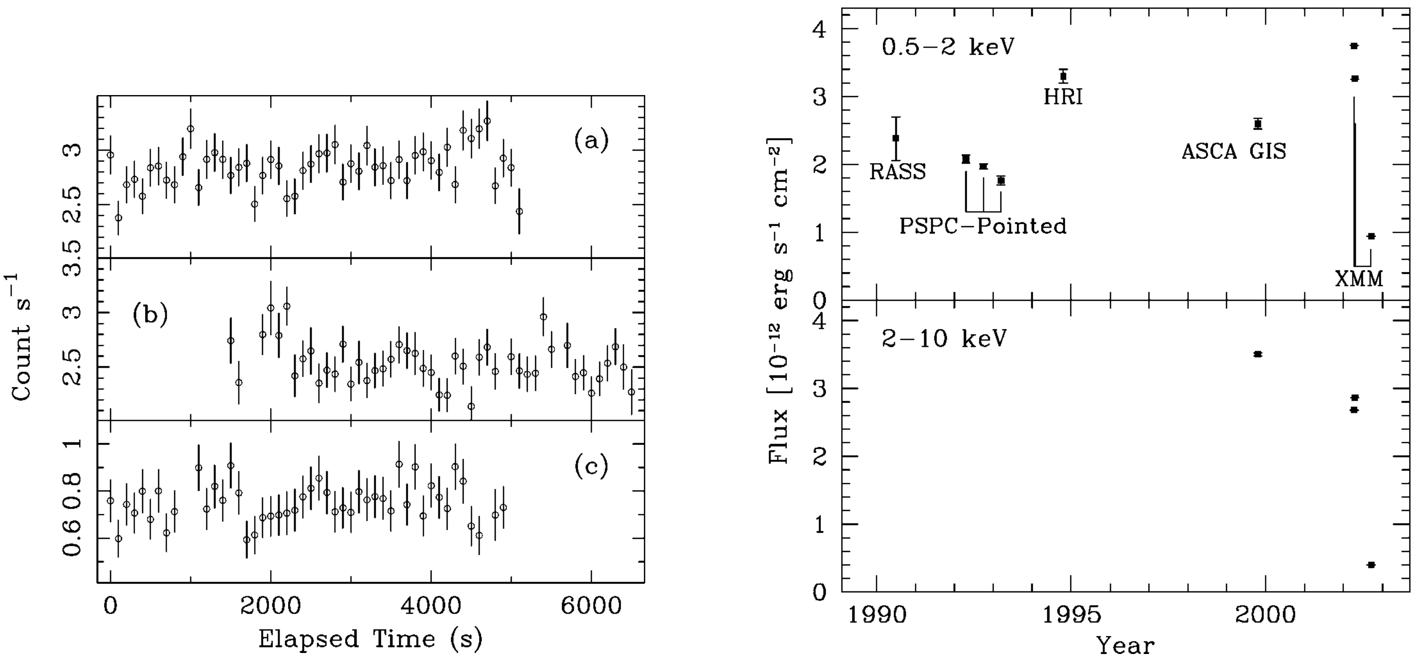

FIG. 1.—*Left panels :* EPIC PN light curves of HoII X-1 obtained from the three observations of (*a*) 2002 April 10, (*b*) 2002 April 16, and (*c*) 2002 September 18. The light curves have been corrected for the background contribution and are shown with time bins of 100 s. *Right panels:* Long-term light curve of HoII X-1. *ROSAT* and *ASCA* fluxes were taken from Miyaji et al. (2001).

fitted to each light curve resulted in χ^2/dof = 62.0/51, 56.5/46, and 40.3/46 for the observations of 2002 April 10, April 16, and September 18. This suggests that X-ray emission was variable during the first two observations of 2002 April. The mean flux level remained similar in these two observations. However, the X-ray intensity from HoII X-1 dropped by a factor of ∼3–4 during the third observation of 2002 September. For comparison, we show the long-term light curve of HoII X-1 in Figure 1, derived for the common energy band of *ROSAT*, *ASCA*, and *XMM-Newton*. The *ROSAT* and *ASCA* fluxes were taken from Miyaji et al. (2001). It is clear that the source was in its brightest and faintest flux levels during the *XMM-Newton* observations of 2002 April 10 and September 18, respectively.

Source spectra and the associated background spectra were extracted using similar extraction regions as described above. The source spectra were grouped to a minimum of 20 counts

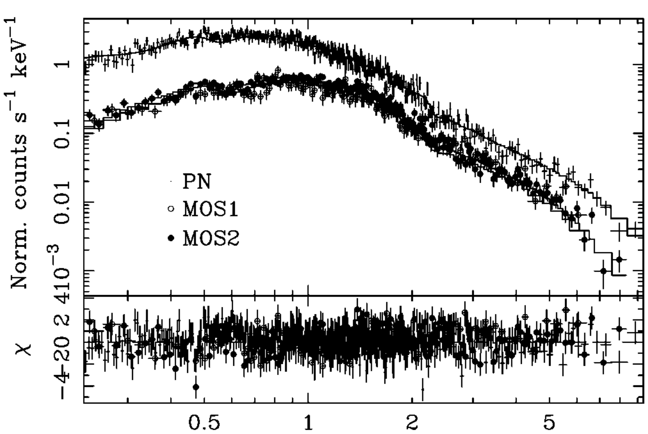

FIG. 2.—Observed spectra of HoII X-1 and the best-fit model consisting of a power law and a BB modified by the Galactic as well as the intrinsic absorption. The bottom panel shows the deviations of the observed data points from the best-fit model in units of σ. [*See the electronic edition of the Journal for a color version of this figure.*]

and 15 counts per channel for the 2002 April and September observations, respectively. The spectra were analyzed using XSPEC version 11.3. All the errors quoted below were calculated at a 90% confidence level for one interesting parameter. We found generally good agreement between MOS and PN cameras in the 0.3–10 keV bands. Therefore, we present the spectral results obtained by fitting the same model jointly to the PN and MOS data while leaving the relative normalizations to vary. We fitted an absorbed power-law model to the spectra of 2002 April 10; this resulted in χ^2 = 933.4 for 758 degrees of freedom (dof). The best-fit absorption column is $N_H \sim 1.9 \times 10^{21}$ cm^{-2}, much higher than the Galactic column of 3.4×10^{20} cm^{-2} (Dickey & Lockman 1990) along the direction of Ho II X-1. The excess column, inferred from an additional absorption model, is $1.6^{+0.2}_{-0.1} \times 10^{21}$ cm^{-2}. The addition of a blackbody (BB) model improves the fit significantly (model 1; $\Delta\chi^2 = -62.5$ for two additional parameters). The BB temperature is $kT \sim 140$ eV, and the power-law photon index is $\Gamma_X \sim 2.6$. The EPIC spectral data of 2002 April 10 and the best-fit model are shown in Figure 2. Replacing the simple BB component by an MCD (model 2), appropriate for a standard thin accretion disk, resulted in a slightly higher temperature. The best-fit model parameters are listed in Table 1. We followed the above steps to model the EPIC spectra of HoII X-1 obtained on 2002 April 16 and September 18 and found that these spectra too are well described by the absorbed power-law and BB models, with the addition of the later component improving the fit significantly ($\Delta\chi^2 = -61.8$ and -26.7 for the spectra of April 10 and September 18, respectively). The best-fit parameters for the three spectra are listed in Table 1. The X-ray spectrum of 2002 September 18 is weakest and steepest among the three spectra. The power-law normalization decreased by a factor of about 4 in 5 months. However, the X-ray spectrum of HoII X-1 is not the flattest at its brightest phase; i.e., there is no evidence of a correlation between the spectral slope and the flux.

To illustrate the flux and spectral variability of HoII X-1, we compared each of the observed spectra with the best-fit spectral

TABLE 1
Best-Fit Spectral Model Parameters for Holmberg II X-1[a]

Parameter	2002 April 10		2002 April 16		2002 September 18	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
$N_{\rm H}$ (10^{21} cm^{-2})	$1.6^{+0.2}_{-0.1}$	$1.6^{+0.2}_{-0.1}$	$1.4^{+0.3}_{-0.3}$	$1.5^{+0.3}_{-0.3}$	$1.4^{+0.5}_{-0.4}$	$1.5^{+0.7}_{-0.3}$
kT (eV)	141^{+18}_{-15}	187^{+28}_{-26}	128^{+22}_{-13}	170^{+27}_{-25}	120^{+22}_{-17}	149^{+28}_{-27}
$f_{\rm BB}$[b]	1.9	2.7	2.4	3.4	1.1	1.6
$\Gamma_{\rm X}$	$2.64^{+0.06}_{-0.06}$	$2.62^{+0.07}_{-0.07}$	$2.40^{+0.07}_{-0.08}$	$2.37^{+0.08}_{-0.07}$	$2.89^{+0.16}_{-0.17}$	$2.88^{+0.18}_{-0.17}$
$f_{\rm PL}$[c]	10.1	9.7	6.9	6.7	2.4	2.3
$f_{\rm int}$[d]	14.8	15.2	12.5	12.9	3.9	4.4
$L_{\rm int}$[e]	2.0	2.1	1.7	1.8	0.5	0.6
$\chi^2_{\rm min}$/dof	870.7/756	874.5/756	606.9/562	608.9/562	270.0/268	271.7/268

[a] Model 1 is a simple BB and power-law model modified by the Galactic as well intrinsic absorption; model 2 is the same as model 1, but with the simple BB replaced with MCD.
[b] Unabsorbed BB flux in units of 10^{-12} ergs cm^{-2} s^{-1} and in the 0.3–2 keV band.
[c] Unabsorbed power-law flux in units of 10^{-12} ergs cm^{-2} s^{-1} and in the 0.3–2 keV band.
[d] Unabsorbed flux in the 0.3–10 keV band and in the units of 10^{12} ergs cm^{-2} s^{-1}.
[e] The 0.3–10 keV intrinsic luminosity in units of 10^{40} ergs s^{-1} assuming a distance of 3.39 Mpc.

model to the spectrum of 2002 April 10. Figure 3 shows ratios of the individual spectra and the best-fit model spectrum of 2002 April 10. It is clear that the spectrum of HoII X-1 did not change appreciably during the two observations in 2002 April but became drastically weaker and steeper in 2002 September.

The soft X-ray linelike features in the low-state spectrum are suggestive of an optically thin emission. Unfortunately, the Reflection Grating Spectrometer data are too poor to constrain any line emission. The linelike feature at 2.5 keV, seen in the low-state spectrum only (see Fig. 3), is detected at the 2.8 σ level or a 98% confidence level based on a maximum likelihood ratio (MLR) test ($\Delta\chi^2 = -7.8$ for two additional parameters) using model 1 (see Table 1) as the continuum and a Gaussian line. This feature, also seen in the *ASCA* spectra ($\Delta\chi^2 = -7.1$ for GIS+SIS data using the same continuum model), is likely the S XV Kα emission line. There may be some contribution from the radiative recombination continuum (RRC) due to Si XIII. To investigate the effect of the presence of thin thermal emission on the spectral variability, we created a multicomponent model consisting of a MEKAL plasma, a BB, and a power law modified by the Galactic as well excess absorption. We fitted this model jointly to the PN spectra corresponding to the brightest flux state of 2002 April 10 and the faintest flux state of 2002 September 18. The parameters of the BB and the power-law components for the two data sets were varied independently, while the parameters of the MEKAL component for the low-state spectrum were tied to the corresponding parameters for the high-state spectrum. This model resulted in a good fit ($\chi^2 = 504.2$ for 499 dof). The unfolded spectra along with the models for the low and high states are plotted in Figure 4. The best-fit parameters are $kT_{\rm MEKAL} = 0.90^{+0.22}_{-0.12}$ keV, emission measure EM $= 9.3 \times 10^{60}$ cm^{-3}, $kT_{\rm BB}$(high) $= 140^{+7}_{-10}$ eV, Γ(high) $= 2.6^{+0.1}_{-0.1}$, $kT_{\rm BB}$(low) $= 106^{+7}_{-13}$ eV, and Γ(low) $= 2.7^{+0.2}_{-0.1}$. The power-law normalization in the low state is a factor of 5.2 lower than that in the high state (2.4×10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV). The two photon indices are similar within errors. Thus, the softer spectrum in the low state can be explained as the drop of the flux in the power-law component, without significantly changing

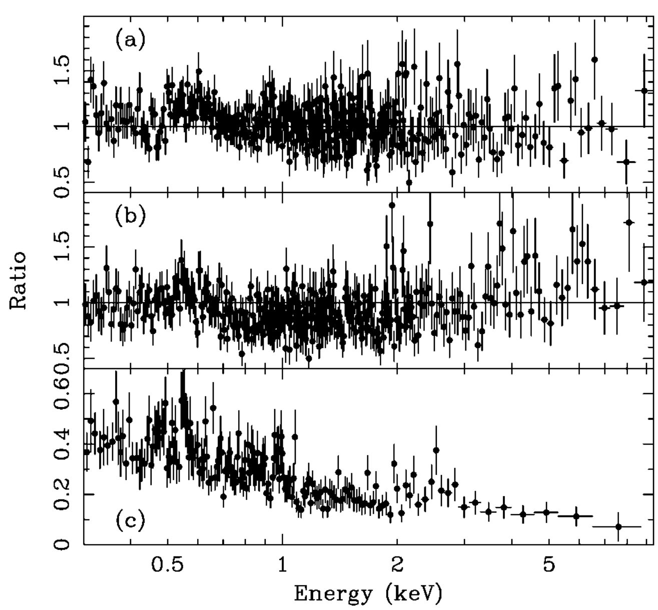

Fig. 3.—Comparison of the observed EPIC PN data of (*a*) 2002 April 10, (*b*) 2002 April 16, and (*c*) 2002 September 18 and the best-fitting model of 2002 April 10 consisting of a power law and a BB modified by absorption. The ratios are shown for the normalization of the PN spectrum. The drop in flux below 0.5 keV in the spectrum of 2002 April 10 is present only in the PN data and is not seen in any of the MOS data. [*See the electronic edition of the Journal for a color version of this figure.*]

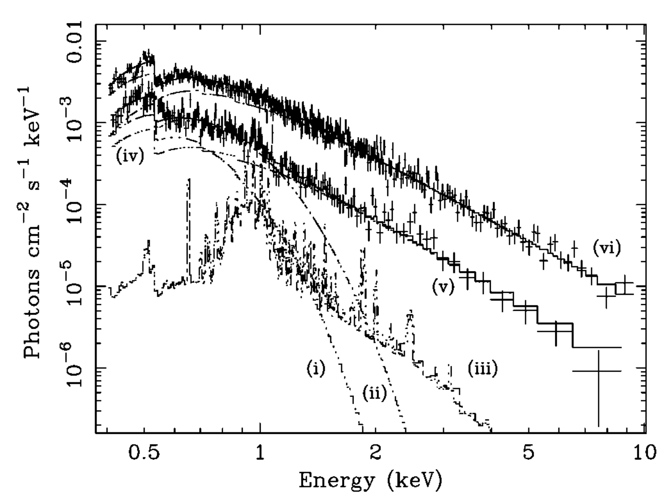

Fig. 4.—Comparison of the unfolded EPIC PN spectra of HoII X-1 in the high (2002 April 10) and low (2002 September 18) flux states. In both cases, the best-fitting model consists of a BB, a power law, and a MEKAL. The dotted lines are the model components: (i) BB (low state), (ii) BB (high state), (iii) MEKAL, and (iv) power law. The data points with the solid line are the observed spectra and the best-fit model for (v) the low state and (vi) the high state. [*See the electronic edition of the Journal for a color version of this figure.*]

its slope, and a slightly softer BB component. The exclusion of the MEKAL component worsened the fit, resulting in $\chi^2 = 512.6$ for 501 dof. Thus, the presence of the MEKAL component is significant at a confidence level of 98.5% based on the MLR test. In the low state alone, the presence of the MEKAL component is significant at the 99.3% level ($\Delta\chi^2 = -10.1$ for two additional parameters).

4. DISCUSSION

The three *XMM-Newton* observations of 2002 have caught HoII X-1 in its historical brightest and faintest flux levels (3.7×10^{-12} and 9.4×10^{-13} ergs cm^{-2} s^{-1} in the 0.5–2 keV band, respectively) ever observed with an X-ray satellite (see Fig. 1). Our spectral analysis of the three *XMM-Newton* observations of HoII X-1 confirm earlier *ROSAT* and *ASCA* results that the X-ray spectrum of HoII X-1 consists of three spectral components: intrinsic absorption, a soft excess, and a power-law component. The intrinsic absorption column densities and temperatures (150–190 eV) of the soft component inferred from the MCD fits to three observations are similar to that obtained from the joint *ROSAT* and *ASCA* spectral analysis (Miyaji et al. 2001). However, the power-law photon indices are steeper ($\Delta\Gamma \sim 0.5$–1.0) during the *XMM-Newton* observations than that during the *ASCA* observations.

A soft X-ray excess component, above a power-law continuum, is statistically required in all three observations and is well described by a simple BB or an MCD model. The best-fit temperatures are in the range 100–180 eV. Similar cool thermal components have been recently observed by *Chandra* and *XMM-Newton* from a number of bright ULXs, e.g., M81 X-9 (Miller et al. 2004), NGC 4038/4039 X-37 (Miller et al. 2003), and NGC 5048 X-1 (Kaaret et al. 2003). If the soft X-ray excess emission is attributed to the disk emission, as thought to be the case in BH X-ray binaries, the accretion disk of HoII X-1 must be cool. In this scenario, the BB temperature provides a BH mass

$$M \simeq 10(kT/1.2\ \mathrm{keV})^{-4}(\dot{M}/\dot{M}_{\mathrm{Edd}})\ M_{\odot} \tag{1}$$

(see, e.g., Makishima et al. 2000). If we assume that a fraction ϵ of the bolometric luminosity is emitted in the X-ray band of 0.3–10 keV, then, using the expression for the Eddington luminosity,

$$\frac{L_{\mathrm{bol}}}{L_{\mathrm{Edd}}} = \frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} = \frac{L_{\mathrm{X}}}{1.28 \times 10^{38}\epsilon(M/M_{\odot})}, \tag{2}$$

where L_{X} is in units of ergs s^{-1}. Use of equation (1) with a BB temperature of $kT = 170$ eV for HoII X-1 gives

$$\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} \sim \sqrt{\frac{3.2 \times 10^{-42} L_{\mathrm{X}}}{\epsilon/0.1}}. \tag{3}$$

For $L_{\mathrm{X}} \sim 2 \times 10^{40}$ ergs s^{-1} as observed on 2002 April 10, $\dot{M}/\dot{M}_{\mathrm{Edd}} \sim 0.2$. If we adopt a BB temperature, $kT = 110$ eV, as suggested from the multicomponent model including MEKAL plasma, the relative accretion rate is ~0.1.

HoII X-1 resides within a starburst region; therefore, it is possible that part of the X-ray emission arises from the starburst region or from a supernova remnant. Our spectral modeling, after taking into account such a contribution as an optically thin emission, suggests that the observed unusual spectral transition to a low/soft state is due to the drop of the power-law flux alone without any change in the slope. A higher relative contribution of the optically thin emission in the low state resulted in an overall softer spectrum. Thus, we suggest that the X-ray emission from HoII X-1 consists of two distinct components: (1) a soft X-ray excess, described by an MCD ($kT \sim 140$ eV) and a power-law component ($\Gamma \sim 2.7$) similar to that observed from accreting BHs (AGNs and BH binaries), and (2) a thin thermal component [$kT \sim 0.9$ keV, $L(0.05$–$10\ \mathrm{keV}) = 3 \times 10^{38}$ ergs s^{-1}]. In this case, the spectral variability of the accreting BH in HoII X-1 is not unusual and is similar to many BH X-ray binaries. A *Chandra* ACIS-S observation barely resolved the X-ray emission from HoII X-1, suggesting that the thermal component arises from a compact region (~10 pc; Lehmann et al. 2004). The estimated luminosity of the thin thermal component arising from a compact region is not unusually large because the cooling time, $\tau_{\mathrm{cool}} \sim 50{,}000$ yr, is sufficiently long, where τ_{cool} was estimated from the temperature, electron density, size, and luminosity of the MEKAL plasma. A compact size and a high luminosity for the thin thermal component are suggestive of a young supernova remnant or a hypernova remnant. The thin thermal emission is the result of the line feature at ~2.5 keV, detected at the 2.8 σ level in the low-state spectrum only, being the S XV Kα line (see Figs. 3 and 4); however, there may be some contribution from the Si XIII RRC. High-resolution X-ray observations will be required to investigate the nature of the soft component modeled here as thin thermal emission.

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REFERENCES

Bauer, F. E., Brandt, W. N., Sambruna, R. M., Chartas, G., Garmire, G. P., Kaspi, S., & Netzer, H. 2001, AJ, 122, 182
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Ebisawa, K., Życki, P., Kubota, A., Mizuno, T., & Watarai, K. 2003, ApJ, 597, 780
Kaaret, P., Corbel, S., Prestwich, A. H., & Zezas, A. 2003, Science, 299, 365
Karachentsev, I. D., et al. 2002, A&A, 383, 125
Kubota, A., Mizuno, T., Makishima, K., Fukazawa, Y., Kotoku, J., Ohnishi, T., & Tashiro, M. 2001, ApJ, 547, L119
Lehmann, I., et al. 2004, A&A, submitted
Makishima, K., et al. 2000, ApJ, 535, 632
Miller, J. M., Fabbiano, G., Miller, M. C., & Fabian, A. C. 2003, ApJ, 585, L37
Miller, J. M., Fabian, A. C., & Miller, M. C. 2004, ApJ, 607, 931
Miller, M. C., & Colbert, E. J. M. 2004, Int. J. Mod. Phys. D, 13, 1
Miyaji, T., Lehmann, I., & Hasinger, G. 2001, AJ, 121, 3041
Pakull, M. W., & Mirioni, L. 2001, Astron. Ges. Meeting Abstracts, 18, 112
Turner, M. J. L., et al. 2001, A&A, 365, L27
Strüder, L., et al. 2001, A&A, 365, L18
Sugiho, M., Kotoku, J., Makishima, K., Kubota, A., Mizuno, T., Fukazawa, Y., & Tashiro, M. 2001, ApJ, 561, L73
Zezas, A. L., Georgantopoulos, I., & Ward, M. J. 1999, MNRAS, 308, 302