Spectral Analyses of the Nearest Persistent Ultraluminous X-Ray Source M33 X-8

Shan-Shan Weng¹, Jun-Xian Wang², Wei-Min Gu¹ and Ju-Fu Lu¹

¹Department of Physics and Institute of Theoretical Physics and Astrophysics, Xiamen University, Xiamen, Fujian 361005, P.R.China
guwm@xmu.edu.cn

²Center for Astrophysics, University of Science and Technology of China, Hefei, Anhui 230026, P.R.China

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Abstract

We provide a detailed analysis of 12 XMM observations of the nearest persistent extragalactic ultraluminous X-ray source (ULX), M33 X-8. No significant spectral evolution is detected between the observations, therefore we combine the individual observations to increase the signal-to-noise ratio for spectral fitting. The combined spectra are best fitted by the self-consistent p-free disk plus power-law component model with \( p = 0.571^{+0.032}_{-0.030}, kT_{\text{in}} = 1.38^{+0.09}_{-0.08} \) keV, and the flux ratio of the p-free disk component to the power-law component being 0.63:0.37 in the 0.3 – 10 keV band. The fitting indicates that the black hole in M33 X-8 is of \( \sim 10M_\odot \) and accretes at a super-Eddington rate (\( \sim 1.5 L_{\text{Edd}} \)), and the phase of the accretion disk is close to a slim disk (\( p = 0.5 \)). We report, for the first time, that an extra power-law component is required in addition to the p-free disk model for ULXs. In super-Eddington cases, the power-law component may possibly result from the optically thin inner region of the disk or a comptonized corona similar to that of a standard thin disk.

Key words: accretion, accretion disks — black hole physics — X-rays: binaries — X-rays: stars — X-rays: individual (M33 X-8)

1. Introduction

Ultraluminous X-ray sources (ULXs) are point-like, non-nuclear X-ray sources with isotropic luminosities of about \( 10^{39} - 10^{41} \) ergs s\(^{-1}\) in nearby galaxies (Fabbiano 1989). These objects are interesting since their luminosities are intermediate between the luminosities of Seyfert galaxies (\( L_X \sim 10^{42} - 10^{44} \) ergs s\(^{-1}\)) and those of black hole X-ray binaries (BH XRBs; typically \( L_X \lesssim 10^{38} \) ergs s\(^{-1}\)). If X-rays are emitted isotropically below the Eddington limit,
the intermediate luminosity would indicate that ULXs harbor intermediate-mass black holes (IMBHs; $M_{\text{BH}} \sim 20-10^3 M_\odot$). However, IMBHs are not required if the emission is anisotropic or relativistically beamed (King et al. 2001; King 2009; Körding, et al. 2002), or the accretion is super-Eddingtonian by a factor of a few (Begelman 2002; Poutanen et al. 2007).

X-ray spectral fitting is one of the best methods known to weigh the black hole in ULXs while the dynamical method is unavailable. The sum of a multicolor disk (MCD; Shakura & Sunyaev 1973) and a power-law (PL) model is widely used to describe the X-ray spectra of black hole binaries. This canonical MCD+PL model reflects the expectation of the thermal emission from a standard thin disk around a Schwarzschild black hole along with the hard emission from the inverse Compton scattering of disk photons. Fitting ULX spectra with the same canonical model often shows that the PL component dominates the 0.3-10.0 keV spectrum and the disk component characterizes the feature of the soft spectrum significantly below 1 keV (Miller et al. 2003; Gonçalves & Soria 2006). The disk temperature is inversely related to the black hole mass ($T_{\text{eff}} \propto M^{-1/4}$; e.g., Makishima et al. 2000) in a MCD model, i.e., a heavier black hole tends to accrete with a cooler disk. The obtained disk temperature around 0.15 - 0.2 keV in many ULX spectra was used to suggest the existence of IMBHs with masses of $\sim 10^3 M_\odot$ (Kaaret et al. 2003; Lorenzin & Zampieri 2009).

Meanwhile, hotter disks with temperature $kT_{\text{in}} \sim 1-2.5$ keV were also reported in literature. In these cases, the disk component dominates the X-ray emission (Stobbart et al. 2006), in a way similar to Galactic BH candidates. The hot MCD model (HD model) with fitted temperature $kT_{\text{in}} \sim 1-2.5$ keV would imply super-Eddington luminosities and stellar-mass black holes in the ULXs. However, the MCD model is based on the standard thin disk model and is valid only for luminosities well below $L_{\text{Edd}}$ ($\lesssim 0.1 L_{\text{Edd}}$). It is known that the radial temperature of a standard thin disk follows a power-law form as $kT \propto r^{-0.75}$. Such a form is derived from the assumption of energy balance between the viscous heating and the radiative cooling. For sufficiently high accretion rates, the radiative cooling itself can not balance the viscous heating and the advective cooling becomes important or even dominant. In this case, the power-law form $kT \propto r^{-0.75}$ is invalid. In fact, there are observed deviations from the standard disk spectrum in BH XRBs as they approach their Eddington limit (Kubota & Makishima 2004). In the slim disk model, that is applicable to super-Eddington accretion (Abramowicz et al. 1988), the radial temperature follows $kT \propto r^{-0.5}$. This demonstrates that the HD model is not self-consistent for ULXs (Gonçalves & Soria 2006).

The so-called $p$-free model also obeys a power-law form as $T_{\text{eff}} \propto r^{-p}$, but the temperature gradient $p$ is allowed to vary from 0.5 to 0.75 (Mineshige et al. 1994). The $p$-free model is an extended MCD model and is a combination of two types of optically thick disk models, namely the standard thin disk and the slim disk. Vierdayanti et al. (2006) successfully applied the $p$-free model to the spectra of four ULXs, which were previously reported to contain cool disks and thus IMBHs. The fitting yields $p$ values of $\sim 0.5$, consistent with the slim disk model, suggesting
that the black holes in these four ULXs have stellar masses and accrete at super-Eddington rates instead. Note that in their fitting, no extra PL component was considered.

The ULX source M33 X-8 with an X-ray luminosity of \( \sim 10^{39} \) ergs s\(^{-1}\) was discovered by Long et al. (1981) with the Einstein satellite. Although the position of M33 X-8 coincides with the optical center of the galaxy (La Parola et al. 2003), the hypothesis of an active galactic nucleus (AGN) is inconsistent with the estimated upper limit of 1500 \( M_\odot \) on the central black hole mass in M33 (Gebhardt et al. 2001); moreover, no AGN activity has been found in other bands for this source. The source is of particular interest for many reasons. First, its X-ray spectra apparently prefer the HD model, but the model is unlikely to be appropriate at this luminosity. Second, it is the nearest persistent extragalactic ULX (Foschini et al. 2004). Third, it had up to 12 observation data available in the XMM-Newton Public Archive. In this paper, we present a detailed analysis of the 12 XMM exposures on M33 X-8, especially the combined spectra, which have much higher signal-to-noise (S/N) ratio and enables us to provide further constraints on the nature of this source.

2. Data Reduction

In Table 1 we list all the 12 XMM observations of M33 X-8, which were obtained from August 2000 to July 2003. Hereafter we refer them as Obs #1 through Obs #12 for convenience. The data were reduced with the XMM-SAS software version 7.1.0. To exclude intervals with background flares, we created light curves for photons above 10 keV, and used a count rate cut-off criterion to filter the light curves. The exact value of the cut-off was allowed to vary from field-to-field, to provide the best compromise in each case between excluding high background periods and facilitating the longest available exposure (Stobbart et al. 2006). We selected the data from good time intervals, by setting FLAG = 0 and PATTERN ≤ 4 for PN data, and PATTERN ≤ 12 for MOS data. The source spectra were extracted from circles with radius of 35\( '' \) and centered at the nominal position of M33 X-8 (\( RA = 01^h33^m50.s89, Dec = +30^\circ39'37.2'', J2000 \)), while the background spectra were extracted from the same CCD chips as the source and at a similar distance from the readout node. The high spatial resolution Chandra image has confirmed that there is no obvious contamination from neighbouring point sources within several arcminutes (Dubus et al. 2004). For Obs #1 that the MOS camera was operated in small window mode, we used the background in the closest chip. With the SAS task epatplot, we found that three observations (Obs #2, #4, and #8) were affected by pile-up. Only PN data for these three observations were used and the spectra were extracted in annulus regions with radius 15\( '' \) and 40\( '' \) to circumvent the effects of pile-up (Loiseau 2005). In these cases, ARF files were calculated to correct the missing part of PSF, thus the correct flux level could still be measured through spectra fitting. In several cases, PN or MOS data were unavailable because the source was not covered by the detector, or due to CCD gaps. When available, PN and MOS data from each individual observation were fitted together for spectral analyses.
The 0.3 – 10.0 keV band spectra were fitted with the HEAsoft X-ray spectral fitting package XSPEC 12.3.1. All spectra were rebinned to have at least 20 counts per bin to enable the use of $\chi^2$ statistics.

3. Spectral fitting

3.1. Individual observations

We first fit the 12 individual spectra with an absorbed MCD+PL model (diskbb+po in XSPEC) and a p-free disk model (diskpbb), respectively. We get similarly good fits for both models (Table 1). During the fitting, the absorption column density is allowed to vary (Feng & Kaaret 2006). Due to the limited number of photons, it is difficult to judge whether the MCD+PL model or the slim disk model is preferred. However, by examining the fitting residuals of the $p$-free model, in three of the observations with the highest number of data bins (Obs #1, #5, and #12), we find a weak hard tail above 7 keV, which we will further investigate for the composite spectra in §3.2.

M33 X-8 was reported as a persistent source by Foschini et al. (2004), and a small flux variation was detected previously for a modulation of $\sim$ 20% with a period of 106 days (Dubus et al. 1997). Consistently, we obtain that the amplitude of the flux variation between the observations is at $<$ 20% level, except for Obs #4, and #8, which are about 1.5 – 1.7 times brighter than the average level of the other 10 observations. In Figure 1 we plot the X-ray light curve for the 12 observations of M33 X-8. The 0.3 – 10.0 keV luminosities are taken from the best-fitted MCD+PL model. While different models yield slightly different luminosities, the general pattern of the light curve will not be changed. The mean luminosity (with Obs #4 and #8 excluded) along with the ratio of the luminosities to the mean value are also shown. From the figure it is seen that M33 X-8 remains persistent during most of the observations, and we detected no significant spectral evolution through spectral fitting (see Table 1). No significant rapid variation was detected either within individual observations.

3.2. Combined spectra

Inspired by the fact of no significant spectral evolution between the individual observations, we combined all the observations except for Obs #4 and #8, and obtained one co-added PN spectrum, one co-added MOS1 and one MOS2 spectrum, respectively, in order to increase the S/N ratio of the spectra. The co-adding was performed with the FTOOLS “addspec” which adds pulse-height amplitude (PHA) spectra and background PHA files; detector redistribution and ancillary response were also combined with source net photon counts detected in each observation as co-adding weight. We fit the co-added PN, MOS1 and MOS2 spectra simultaneously. We excluded Obs #4 and #8 because they are at significantly higher flux level, however, we have checked that including them does not change our results in this paper.

We apply the same models mentioned in §3.1 to the combined high S/N spectra to test
whether these models can still provide adequate fits. Neither the HD model nor the simple $p$-free model can give good fits below $\sim 1$ keV (see Figs. 2a and 2b). La Parola et al. (2003) found that a thermal plasma component is required to represent the extended emission around the point source (also see Schulman & Bregman 1995). Accordingly, we add a Raymond-Smith component to the above models, then the $\chi^2$ is reduced by more than 50 with 3 additional free parameters, yielding an F-test probability lower than $10^{-9}$. After including the Raymond-Smith component, both models (HD and $p$-free) yield similar $\chi^2$, and the fitting results are also listed in Table 1. Since the HD model ($kT_{\text{in}} \sim 1.16$ keV) is known to be inconsistent for ULXs, we focus on the $p$-free model below.

Upon investigating the fitting carefully (see Figs. 2b and 2c), we see that the $p$-free disk model (plus the Raymond-Smith component or not) cannot provide an acceptable fit to the band above 7 keV. The hard tail above 7 keV shown in the plot suggests the existence of an additional hard component. Following previous works on BH XRBs (e.g., Kubota & Makishima 2004), we add to the $p$-free disk model an extra power-law component (Fig. 2d), and the fit is significantly improved with a confidence level above 99.99999% based on the F-Test. Noting that the F-test was questioned in testing the significance of an additional spectral component (Protassov et al. 2002), we performed Monte-Carlo simulations to demonstrate the significance of the power-law component. In terms of the best-fitted model without a power-law component, we made 1000 artificial spectra, and run spectral fitting by adding an extra power-law component. In the 1000 simulations, the extra power-law component can only improve the fitting with $\Delta \chi^2 < 16$, far below the actual $\Delta \chi^2 = 38.65$ in the real spectra, which means that the confidence level is far above 99.9%. Therefore, the extra power-law component is statistically solid, and the same statement applies to the Raymond-Smith component stated in the above paragraph.

Furthermore, with the following reasons we can rule out the possibility that the hard tail in the spectra is due to improper background subtraction. First of all, the hard tail is not only visible in the co-added spectra, it is also obvious while we fit all the individual PN, MOS1 and MOS2 spectra together. This implies that the hard tail is not due to the possible improper background subtraction during the spectrum co-adding. Secondly, the hard tail is also visible in three of the individual observations with the highest number of data bins. Spectral fitting to individual observations also rules out the possibility that the hard tail is dominated by one single observation.

4. Discussion

Various models have been proposed to explain the spectra of ULXs in literature. However, due to limited photon counts, in many cases it is not possible to distinguish these models by spectral fitting only. Extra constraints on these models have been given by analyzing the spectral evolution, as reported for several ULXs, e.g., IC 342 (Kubota et al. 2001), NGC
(Soria et al. 2007), and Holmberg IX X-1 (La Parola et al. 2001). After investigating the spectral evolution of NGC 1313 X-2, Feng & Kaaret (2007) found that the variation of the accretion disk component deviated significantly from $L \propto T^4$ relation if fitted with MCD+PL model, while roughly consistent with $L \propto T^4$ if fitted with the $p$-free model. They suggested that this source supports the slim disk model and is against the MCD model. However, flux variations by more than one order of magnitude are rare in ULXs, thus such a technique can not be applied to most ULXs, such as M33 X-8 we studied here, which shows only small amplitude variations.

In this paper we present detailed X-ray spectral fitting to 12 XMM exposures on the ULX source M33 X-8. We found no significant rapid variations within individual observations. The X-ray flux remains persistent during 10 of these 12 observations with the flux variation amplitude $< 20\%$, and no significant spectral evolution was detected between observations. Then the data of these 10 observations were combined to derive composite spectra with much higher S/N ratio for spectrum fitting. We find that the MCD+PL model and the $p$-free disk model provide comparable fits to both individual and composite spectra.

However, a significant hard tail above 7 keV is detected in the residual spectra of the $p$-free disk model. We added a power-law component to the $p$-free disk model to represent this hard tail, and find that the $p$-free disk + PL model provides the statistically best fit comparing to other models. The probable reason for the power-law component in this model is that the inner disk becomes optically thin in super-Eddington cases (Artemova et al. 2006), or there is a comptonized corona (Gladstone et al. 2009) similar to that of a standard thin accretion disk. The fluxes of the $p$-free disk component and the power-law component in 0.3–10.0 keV band are $1.43 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ and $0.83 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, respectively, with a ratio of 0.63:0.37; this indicates that the $p$-free disk component dominates over the power-law component.

The X-ray luminosity of M33 X-8 is $1.7 \times 10^{39}$ ergs s$^{-1}$ for the given distance of 0.7 Mpc (Ho et al. 1997). The luminosity and the best-fitted inner disk temperature $kT_{\text{in}} = 1.38$ keV indicate that the mass of the black hole in M33 X-8 is $\sim 10M_\odot$ (see Fig. 1 of Watarai et al. 2001), in good agreement with previous works (Makishima et al. 2000; Foschini et al. 2004). Because the X-ray emission is dominated by the disk component, the mass derived here should be reliable (Vierdayanti et al. 2006). We note that the luminosity exceeds marginally the Eddington luminosity of a $\sim 10M_\odot$ black hole. In this case, the X-ray emission from the outer region of a standard thin disk could not be neglected, and the moderate value of $p = 0.571$ is well consistent with the theoretical calculation (Watarai et al. 2000). In Galactic black hole X-ray binaries, the very high state (or steep power-law state) is defined as a state in which the luminosity is exceedingly high ($L_X > 0.2 L_{\text{Edd}}$) and the X-ray spectrum displays substantial nonthermal radiation, which may constitute 40–90 % of the total flux, with a photon index larger than 2.4 (McClintock & Remillard 2006). The state of M33 X-8 is more like the thermal-dominant state of X-ray binaries in the Galaxy, but with much higher luminosity, occupying a
new ultraluminous accretion state (Gladstone et al. 2009).

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Fig. 1. The 0.3 – 10.0 keV lightcurve of M33 X-8. Obs #4 and #8, which show significantly higher luminosity level are marked as solid circles. The solid line marks the mean luminosity of the rest 10 observations. 120% and 80% of the mean luminosity are marked by the dashed lines to illustrate the amplitude of the variation.
Fig. 2. Fitting to the combined spectra of ULX M33 X-8. Panels (a) and (b) show the fitting residuals for the HD model and the $p$-free model, respectively. After adding a Raymond-Smith component to the models, panels (c) and (d) show the residuals for the $p$-free model and the $p$-free + power-law model, respectively. The combined spectra and the best fitted model (the $p$-free + power-law model) are plotted in the upper panel.
**Table 1. BEST-FIT SPECTRAL PARAMETERS OF M33 X-8**

| Obs | XMM ObsId | Instruments | Exposure | $N_H$ | $kT$ | $kT_{in}$ | $p$ | $\Gamma$ | $f_X$ | $\chi^2$/dof |
|-----|------------|-------------|----------|-------|------|---------|----|------|------|-------------|
|     |            |             |          | cm$^{-2}$ | keV  | keV     |    |       |      |             |
| 1   | 0102640101 | PN/M1/M2    | 7.4      | 0.176$^{+0.015}_{-0.010}$ | 1.08$^{+0.05}_{-0.04}$ | 2.32$^{+0.11}_{-0.11}$ | 2.49 | 1252$^{+95}_{-116}$ |
| 2   | 0102640601 | PN          | 3.4      | 0.209$^{+0.014}_{-0.010}$ | 1.43$^{+0.01}_{-0.01}$ | 2.42$^{+0.07}_{-0.07}$ | 2.72 | 89$^{+83}_{-83}$ |
| 3   | 0102641001 | PN/M1/M2    | 1.7/9.4/9.5 | 0.184$^{+0.025}_{-0.024}$ | 1.28$^{+0.03}_{-0.03}$ | 2.3$^{+0.09}_{-0.09}$ | 2.43 | 570$^{+577}_{-577}$ |
| 4   | 0102642001 | PN          | 8.0      | 0.226$^{+0.115}_{-0.064}$ | 1.34$^{+0.20}_{-0.35}$ | 2.6$^{+0.69}_{-0.69}$ | 4.37 | 205$^{+188}_{-188}$ |
| 5   | 0102642101 | PN/M1/M2    | 9.0/12/12 | 0.175$^{+0.010}_{-0.022}$ | 1.11$^{+0.07}_{-0.07}$ | 2.27$^{+0.14}_{-0.14}$ | 2.45 | 1073$^{+1024}_{-1024}$ |
| 6   | 0102642301 | M1/M2       | 12/12/12 | 0.246$^{+0.044}_{-0.035}$ | 1.26$^{+0.10}_{-0.12}$ | 2.5$^{+0.41}_{-0.41}$ | 3.05 | 424$^{+466}_{-466}$ |
| 7   | 0141980101 | M1/M2       | 8.5/8.7  | 0.169$^{+0.048}_{-0.037}$ | 1.02$^{+0.17}_{-0.10}$ | 2.1$^{+0.43}_{-0.43}$ | 2.26 | 406$^{+381}_{-381}$ |
| 8   | 0141980301 | PN          | 10.0     | 0.284$^{+0.076}_{-0.076}$ | 1.17$^{+0.09}_{-0.09}$ | 3.3$^{+0.27}_{-0.27}$ | 3.97 | 234$^{+240}_{-240}$ |
| 9   | 0141980401 | M1/M2       | 8.3/8.6  | 0.181$^{+0.040}_{-0.060}$ | 1.03$^{+0.22}_{-0.17}$ | 2.04$^{+0.29}_{-0.29}$ | 2.81 | 417$^{+374}_{-374}$ |
| 10  | 0141980501 | M1/M2       | 1.5/7.9/8.1 | 0.212$^{+0.029}_{-0.027}$ | 1.35$^{+0.11}_{-0.13}$ | 2.4$^{+0.24}_{-0.24}$ | 2.28 | 757$^{+755}_{-755}$ |
| 11  | 0141980601 | PN          | 10.5     | 0.172$^{+0.045}_{-0.045}$ | 1.14$^{+0.14}_{-0.14}$ | 2.2$^{+0.29}_{-0.29}$ | 2.10 | 430$^{+455}_{-455}$ |
| 12  | 0141980801 | M1/M2       | 7.6/10/10 | 0.192$^{+0.010}_{-0.011}$ | 1.16$^{+0.17}_{-0.14}$ | 2.22$^{+0.06}_{-0.05}$ | 2.01 | 1297$^{+1162}_{-1162}$ |
|     | Combined   | M1/M2       | 41.0/79.0/80.8 | 0.184$^{+0.006}_{-0.007}$ | 1.14$^{+0.03}_{-0.02}$ | 2.2$^{+0.04}_{-0.04}$ | 2.39 | 1627$^{+1558}_{-1558}$ |

Instruments: data from which instrument, PN, MOS1(M1) or MOS2(M2), are used; Exposure: clean exposures for corresponding instruments after background flares excluded; $N_H$: column density along the line of sight; $kT$: plasma temperature; $kT_{in}$: inner disk temperature; $p$: the temperature gradient; $\Gamma$: power-law photon index; $f_X$: 0.3–10 keV intrinsic flux in the units 10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$; $\chi^2$/dof: $\chi^2$ and degree of freedom for the best-fit model. Combined: data from combining all observations except for Obs #4 and #8.