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A STELLAR-MASS BLACK HOLE IN THE ULTRALUMINOUS X-RAY SOURCE M82 X-1?

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ABSTRACT

We have analyzed the archival *XMM-Newton* data of the bright ultraluminous X-ray source M82 X-1 with a 105 ks exposure when the source was in the steady state. Thanks to the high photon statistics from the large effective area and long exposure, we were able to discriminate different X-ray continuum spectral models. Neither the standard accretion disk model [where the radial dependency of the disk effective temperature is $T(r) \propto r^{-3/4}$] nor a power-law model gives a satisfactory fit. In fact, observed curvature of the M82 X-1 spectrum was just between those of the two models. When the exponent of the radial dependence [p in $T(r) \propto r^{-p}$] of the disk temperature is allowed to be free, we obtained $p = 0.61^{+0.03}_{-0.02}$. Such a reduction of p from the standard value $\frac{3}{4}$ under extremely high mass accretion rates is predicted from the accretion disk theory as a consequence of the radial energy advection. Thus, the accretion disk in M82 X-1 is considered to be in the *slim-disk* state, where an optically thick advection-dominated accretion flow is taking place. We have applied a theoretical slim-disk spectral model to M82 X-1 and estimated the black hole mass $\approx$19–32 $M_\odot$. We propose that M82 X-1 is a relatively massive stellar black hole that has been produced through evolution of an extremely massive star, shining at a super-Eddington luminosity by several times the Eddington limit.

Subject headings: accretion, accretion disks — black hole physics — X-rays: individual (M82 X-1)

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) in nearby galaxies have typical X-ray luminosities from 10^{39} to 10^{41} ergs s^{-1} (e.g., Makishima et al. 2000; Ptak & Colbert 2004). M82 X-1 is the most luminous ULX that is located off the nucleus of the galaxy and has exhibited X-ray flares as bright as $\sim 10^{41}$ ergs s^{-1} (Matsumoto & Tsuru 1999; Matsumoto et al. 2001; Kaaret et al. 2001). If one assumes that its luminosity is less than the Eddington luminosity ($L_{\rm Edd}$), the mass of the central object must be at least $\sim$700 $M_\odot$. Hence, M82 X-1 has been considered an *intermediate*-mass black hole candidate (Matsumoto & Tsuru 1999; Kaaret et al. 2001).

However, M82 X-1 exhibits an X-ray energy spectrum that is much harder than what is expected from standard accretion disks around intermediate black holes. In fact, the characteristic color temperature of the standard disk shining at the Eddington luminosity is $\approx$1 keV$(M/10\ M_\odot)^{-1/4}$, which has been confirmed through observations of many Galactic black hole candidates. Therefore, if M82 X-1 has the standard disk around an intermediate-mass black hole with $\gtrsim$700 $M_\odot$, the characteristic disk temperature is expected to be $\lesssim$0.3 keV. To the contrary, M82 X-1 indicates a much harder, power-law–type spectrum (e.g., Strohmayer & Mushotzky 2003; Fiorito & Titarchuk 2004; Agrawal & Misra 2006). Such apparently high disk temperatures have been also reported from other ULXs (e.g., Okada et al. 1998; Makishima et al. 2000).

There are two major models to explain the "too hot a disk" problem of M82 X-1 and other ULXs. The first model assumes that the accretion disk is not in the standard disk state where the gravitational energy released is converted into optically thick radiation but in a *slim-disk* state where radial energy advection is dominant (Watarai et al. 2001; Mizuno et al. 2001; Ebisawa et al. 2003). The competing model assumes that the ULX disks have low temperature ($\lesssim$1 keV), as expected for intermediate-mass black holes. Such disks are assumed to be shrouded by hot, Compton thick clouds, and the observed X-ray spectra above $\sim$1 keV are due to the inverse Compton process (approximated by a power law) of the seed photons from the low-temperature disk (e.g., Miller et al. 2003, 2004; Fiorito & Titarchuk 2004; Wang et al. 2004).

In general, it is difficult to distinguish the two competing ULX spectral models, since these two models have similar spectral shapes in the energy range where most X-ray sensors are sensitive. In this Letter, we present a precise spectral analysis of *XMM-Newton* data of M82 X-1 for a 105 ks exposure. Thanks to the much better statistics than those for previous observations, we were able to tightly constrain the spectral models. We show the slim-disk model can explain the M82 X-1 energy spectrum above $\sim$3 keV (where contamination of the starburst component is negligible), which suggests the presence of a *stellar* black hole in the center of M82 X-1.

2. OBSERVATION AND DATA ANALYSIS

There are three archival *XMM-Newton* data sets of M82. Two observations were made on 2001 May 6; for 10 ks (ObsID = 0112290401) and 29 ks (ObsID = 0112290201), respectively. The other was made on 2004 April 21 for 105 ks (ObsID = 0206080101), which we analyze in the present Letter. The observation was carried out employing the European Photon Imaging Camera (EPIC) PN and MOS in the full window and medium filter mode. Data screening, region selection, and event extraction were performed with the standard software package XMM-SAS version 6.1.0. In order to eliminate possible contamination from solar flares, events were selected only when the total off-source count rate is less than 0.17 (MOS) and 0.55 (PN) counts s^{-1} in 10–15 keV. This leaves 63 (MOS1), 65 (MOS2), and 50 (PN) ks of useful time with an average count rate of 0.7

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TABLE 1
FITTING PARAMETERS, PART 1

	CONTINUUM MODEL PARAMETERS				GAUSSIAN MODEL[a]		
MODEL NAME	Γ	T_{in} (keV)	p	N	E (keV)	EW (eV)	χ^2/dof
Power-law	1.73	...	...	0.00292[b]	6.61	87.1	96/43[c]
Disk blackbody	...	2.77 ± 0.07	0.75	0.0130[d]	$6.63^{+0.06}_{-0.05}$	61^{+23}_{-18}	81/43
p-free	...	$3.73^{+0.58}_{-0.40}$	$0.61^{+0.03}_{-0.02}$	$0.0034^{+0.0017d}_{-0.0014}$	$6.62^{+0.06}_{-0.04}$	72^{+23}_{-20}	55/42

NOTE.—Errors correspond to the single-parameter 90% confidence.
[a] Intrinsic line width is fixed to 0.01 keV.
[b] Normalization at 1 keV (in units of photons s^{-1} keV^{-1} cm^{-2}).
[c] Errors are not derived because reduced $\chi^2 > 2$.
[d] $[(R_{in}/1\ km)/(d/10\ kpc)]^2 \cos\theta$, where d is the distance, R_{in} is the innermost disk radius, and θ is the inclination.

(MOS) and 2.2 (PN) counts s^{-1}. In this Letter, we primarily analyze the PN data, which have better statistics. The MOS data give the same results with slightly larger statistical errors.

We extracted the spectrum of M82 X-1 within a radius of 18″ around the point source; this procedure is the same as described in Fiorito & Titarchuk (2004) and Strohmayer & Mushotzky (2003). *XMM-Newton*'s moderate spatial resolution (13″–15″ in half-power diameter) does not allow us to fully resolve the surrounding faint sources resolved by *Chandra*, including sources 4, 5, and 6 in Matsumoto et al. (2001). However, sources 4 and 6 are always at least a factor of 10 fainter than M82 X-1, and source 5 was a factor of 3.4 fainter when M82 X-1 was the faintest (Strohmayer & Mushotzky 2003). Thus, contamination from these point sources to our M82 X-1 spectral analysis is insignificant. *Chandra* also revealed diffuse emission in the central region of M82, which is obvious in the EPIC images and spectra as well. In order to concentrate on the point-source spectral analysis, we limit our spectral fitting to the energy range $E > 3$ keV, where we estimate the diffuse flux less than 10% of the point-source flux. The background spectrum was extracted from a ring of the 2′ outer radius and the 18″ inner radius (within which the M82 X-1 spectrum was extracted), and it was subtracted from the source spectrum after being normalized to the detector area.

The pulse-height spectral data were binned by 32 channels, which correspond to twice the energy resolution (FWHM). Fittings were performed from 3 to 11 keV using XSPEC version 11.3.2. We did not include the interstellar absorption model, since including it does not affect the fitting result above 3 keV at all. First, we employed a power-law model and found that there is a weak iron emission line near 6 keV, which may be modeled by a single Gaussian. The photon index is found to be 1.73. The Gaussian line is centered at 6.61 keV and has the equivalent width 87 eV. Such an iron emission line may originate either from a disk reflection or a diffuse starburst component, but an investigation for its origin is beyond the scope of the current Letter. We find χ^2 to be 96 with 43 degrees of freedom (dof). Next, we applied the disk blackbody model (Mitsuda et al. 1984) to approximate a standard accretion disk (Shakura & Sunyaev 1973), including a Gaussian line with similar parameters as above. The disk blackbody temperature is found to be 2.77 ± 0.07 keV (90% confidence level for a single parameter hereafter), and $\chi^2 = 81$ (43 dof). Other fitting parameters are shown in Table 1.

Both the power-law model and the disk blackbody model are rejected with a confidence level of 99.98%. Importantly, if we compare the two model fits, we notice opposite trends in the residuals (Fig. 1). Namely, the observed spectrum is slightly "curved" downward while the power law, of course, is not. Also, the observed curvature is not as large as that of the disk blackbody model. This indicates that the observed spectral curvature is just between that of the power-law model and the disk blackbody model.

Therefore, we then attempted the "p-free" disk model (Mineshige et al. 1994; Hirano et al. 1995; Kubota & Makishima 2004; Kubota et al. 2005), where the temperature profile of the accretion disk is given as $T(r) = T_{in}(r/r_{in})^{-p}$ with r_{in}, T_{in}, and p being free parameters.[2] The disk blackbody model has $p = 0.75$, and a smaller p-value reduces the spectral curvature and makes the spectral shape closer to the power law. We found the best-fit parameters $p = 0.61^{+0.03}_{-0.02}$, $T_{in} = 3.73^{+0.58}_{-0.40}$ keV with $\chi^2 = 55$ (42 dof). The Gaussian parameters are almost the same as those of the other two models. Statistically, the p-free disk model describes the spectral shape best among the three models. We can calculate the F-value as a measure of the improvement of the p-free model relative to the disk blackbody

[2] This model is now available in the standard XSPEC ver. 12.3.0 or later with the name "diskpbb."

TABLE 2
FITTING PARAMETERS, PART 2

				GAUSSIAN MODEL[a]		
SLIM-DISK MODEL ($\alpha = 1$)[b]	LOCAL SPECTRAL ASSUMPTION	$M/M_\odot$	$\dot{M}/(L_{Edd}/c^2)$	E (keV)	EW (eV)	χ^2/dof
1	Modified blackbody[c]	19	395	6.61	85	91/43[d]
2	Comptonization[e]	19	559	6.61	85	88/43[d]
3	Comptonization+gravitational redshift[f]	27^{+9}_{-4}	366^{+100}_{-190}	$6.61^{+0.07}_{-0.03}$	86^{+11}_{-22}	85/43
4	Comptonization+relativistic effects[g]	32^{+6}_{-5}	320^{+60}_{-140}	$6.61^{+0.07}_{-0.03}$	86 ± 21	84/43

NOTE.—Errors correspond to the single-parameter 90% confidence.
[a] Intrinsic line width is fixed to 0.01 keV.
[b] Source distance is fixed at 2.7 Mpc.
[c] Local emission at each radius is computed considering electron scattering opacity. See § 3.
[d] Errors are not derived because reduced $\chi^2 > 2$.
[e] Local emission at each radius is computed considering Compton effects.
[f] Gravitational redshift is included.
[g] In addition to gravitational redshift, the transverse Doppler effect is included.

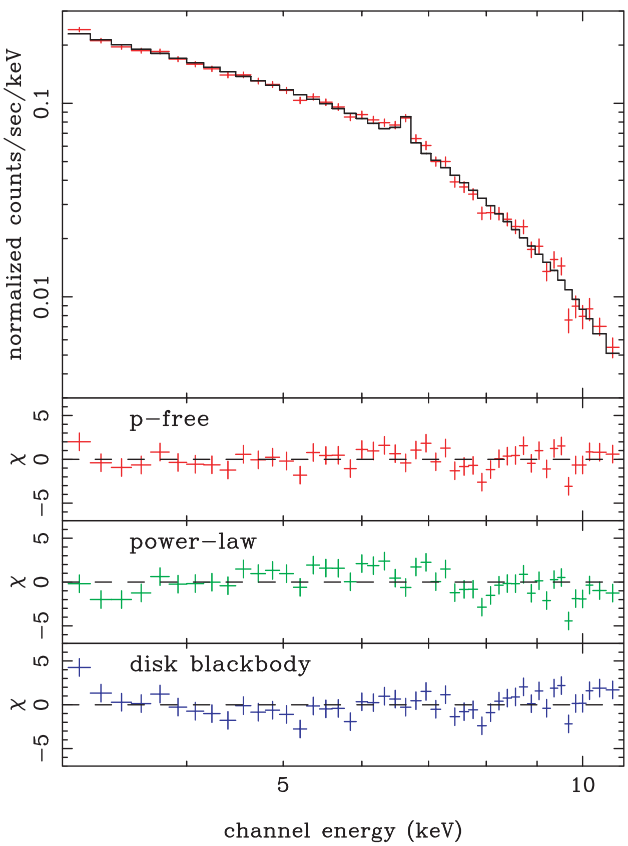

FIG. 1.—Folded spectrum of M82 X-1, fitted with the *p*-free disk blackbody and narrow Gaussian model (*top*), and residuals for fitting with three different models: *p*-free, power-law, and disk blackbody.

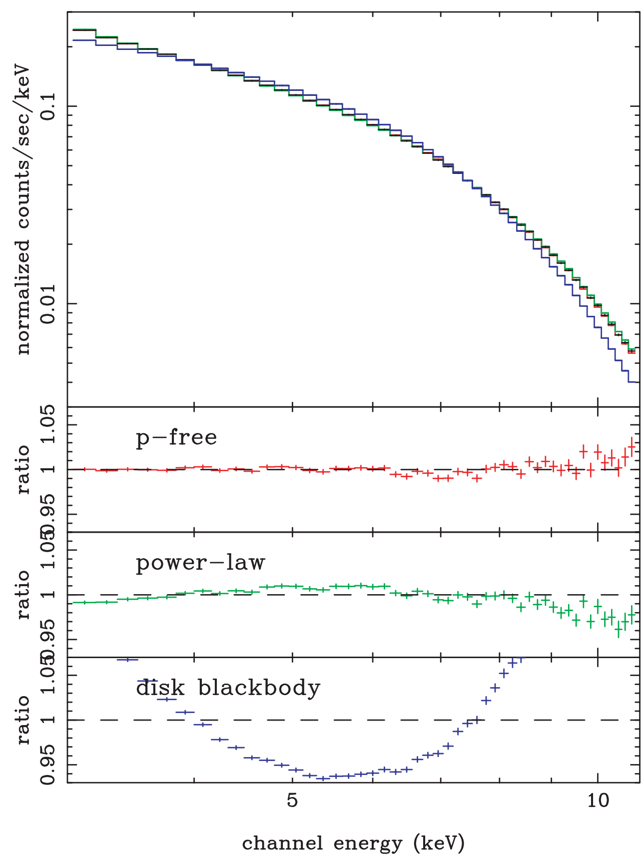

FIG. 2.—Comparison of the slim-disk model by Kawaguchi (2003) and other models used to fit M82 X-1. A simulated spectrum was made from Kawaguchi's model 4 (see text) with $\alpha = 1$, $M = 30\ M_\odot$, and $\dot{M} = 350 L_{\rm Edd}/c^2$ at 2.7 Mpc, and fitted with a power-law (index = 1.76), disk blackbody ($T_{\rm in} = 2.72$ keV), and *p*-free disk model ($p = 0.54$ and $T_{\rm in} = 7.60$ keV). The top panel shows the simulated slim-disk spectrum and the best-fit models, and the three bottom panels exhibit the ratios of the simulated data to the *p*-free, power-law, and disk blackbody models, respectively. Note that the slim-disk (*solid line*) and *p*-free (*dashed line*) models are almost identical.

model. We find $F(1, 42) = \Delta\chi^2/\chi^2_\nu = (81 - 55)/(55/42) = 19.9$. Thus, the improvement of the *p*-free model over the disk blackbody model is significant with the 99.99% confidence.

When the disk luminosity is as high as the Eddington luminosity, an optically thick advection-dominated accretion flow appears (Abramowicz et al. 1988). Such a flow, often called a *slim disk*, has very low radiation production efficiency due to photon trapping (Begelman 1978). The low-energy spectrum of the slim disk has the form $L_E \propto E^{-1}$ (Fukue 2000), while that of the standard disk is $L_E \propto E^{0.33}$. Since the disk spectral shape is related to the radial exponent p as $L_E \propto E^{3-2/p}$, the spectral change from the standard disk to the slim disk is equivalent to the reduction of p from 0.75 to 0.5 (Watarai et al. 2000).

Our result of $p = 0.61^{+0.03}_{-0.02}$ strongly suggests that energy advection is actually taking place and that the M82 X-1 disk is not in the standard state but in a slim-disk state. In this Letter, we employ our own slim-disk model[3] (Kawaguchi 2003) to study the M82 X-1 energy spectrum. Kawaguchi (2003) has calculated slim-disk spectra under four different assumptions. In model 1, the local emission is assumed to be modified blackbody, and in model 2, Comptonization is taken into account. Gravitational redshift is included in model 3; and in model 4, which is our "best" model, transverse Doppler effects are additionally considered. In Figure 2, we compare the simulated model 4 spectrum with the power-law, disk blackbody, and *p*-free disk models. It is obvious that the simulated model 4 spectral shape is well represented by the *p*-free model, and its curvature is just between those of the power law and disk blackbody.

[3] This model is available at http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/models/slimdisk.html for use in XSPEC.

Comparing Figures 1 and 2, we can see that M82 X-1 and the simulated model 4 share similar spectral characteristics.

Next, we directly fit the M82 X-1 spectrum with our slim-disk model. We try all four models with assumptions as listed in Table 2. We tried models with the viscous parameter $\alpha = 0.001, 0.01, 0.1$, and 1, and found that $\alpha = 1$ gives the best fit. We also fit allowing α to be free, with little improvement of the fit. Thus, we show only the results with $\alpha = 1$ in Table 2. Fixing the distance to M82 at 2.7 Mpc (e.g., Rieke et al. 1980), there are then only two free parameters, M and $\dot{M}$. Kawaguchi's model calculates the face-on disk flux, so we assume the face-on geometry in the following.

As summarized in Table 2, we obtain $M = 19$–$32\ M_\odot$, $\dot{M} = (320$–$560)(L_{\rm Edd}/c^2)$ depending on the physical processes assumed. In the case of the standard optically thick accretion disk where the inner disk radius is 3 times the Schwarzschild radius, $\dot{M} = 17.5 L_{\rm Edd}/c^2$ gives the Eddington luminosity; so we can see that M82 X-1 has extremely high mass accretion rates and super-Eddington luminosities. However, since slim disks are radiation inefficient, the disk luminosity is not so large as being proportional to the mass accretion rates. Bolometric face-on flux $f_{\rm bol}$ is obtained as $\sim 3 \times 10^{-11}$ ergs s^{-1} cm^{-2} by numerically integrating the best-fit model spectra over the energy, which is weakly dependent on the assumptions. The bolometric disk luminosity is $L_{\rm bol} = 2\pi d^2 f_{\rm bol}$, where d is the distance (2.8 Mpc), and we obtain $L_{\rm bol} \approx 1.4 \times 10^{40}$ ergs s^{-1}. Hence, depending on the assumptions, our slim-disk model fits suggest that M82 X-1 is shining at 4–6 times the super-Eddington luminosity.

3. DISCUSSION

We have studied the M82 X-1 spectrum using archival *XMM-Newton* data of 105 ks exposure. We have applied the slim-disk spectral model of Kawaguchi (2003), and estimated the mass $M \approx 19$–$32\ M_{\odot}$ and the bolometric luminosity 4–6 times the Eddington luminosity. Since ULXs are, by definition, very luminous objects, it is rather straightforward that their accretion disks are in the slim-disk state, rather than the standard state. While standard accretion disks around $\gtrsim 20\ M_{\odot}$ black holes have characteristic temperatures $\lesssim 0.8$ keV (see § 1), slim disks can explain the observed high disk temperature (∼2.8 keV).

We briefly review why a slim disk can produce such a hard spectrum (see Kawaguchi 2003 for more details). (1) As the mass accretion rate increases, the innermost radius of the slim disk can be smaller than 3 times the Schwarzschild radius even in the Schwarzschild geometry (Watarai et al. 2000), which makes the innermost disk temperature higher. (2) The ratio of the electron scattering opacity to the absorption opacity increases with mass accretion rates. Thus, photons generated deeper in the disk, where the temperature is higher, can escape from the disk surface more easily, and the local spectral shape gets closer to modified blackbody, rather than the standard blackbody (e.g., Rybicki & Lightman 1979). (3) Furthermore, because of the small absorption, inverse Compton scattering (disk Comptonization) is enhanced to shift energies from electrons to emerging photons. Reason 1 increases the disk effective temperature, while reasons 2 and 3 increase the spectral hardening factor, which is the ratio of the local color temperature and the effective temperature.

On the basis of the slim-disk model fitting, we have found M82 X-1 is shining at 4–6 times the Eddington luminosity. Although the standard disk cannot exceed the Eddington limit, such a moderate super-Eddington luminosity is naturally explained in the slim-disk model (e.g., Abramowicz et al. 1988; Watarai et al. 2000). Also, a recent two-dimensional radiation-hydrodynamic numerical simulation reports that a slim disk is formed under supercritical accretion flow, and the disk luminosity can exceed the Eddington luminosity by several factors (Ohsuga et al. 2005).

We have estimated the black hole mass in M82 X-1 as ≈ 19–$32\ M_{\odot}$. Although we have not seen such a rather heavy stellar-mass black hole in our Galaxy, such black holes are not prohibited by stellar evolution theory (e.g., Fryer 1999). Actually, a universal luminosity function for X-ray binaries extends toward the highest luminosity of $\sim 10^{40}$ ergs s^{-1} without any break (Grimm et al. 2003), and it is likely that ULXs correspond to the highest luminosity X-ray binaries. This scenario agrees with the binary evolution synthesis model of ULXs by Rappaport et al. (2005), which strongly suggests ULXs are stellar-mass black hole binaries. Finally, detailed evolution models of stellar binaries show a very small generation rate of intermediate-mass black holes (Madhusudhan et al. 2006), which is also in favor of our stellar-mass ULX model.

In conclusion, we suggest that the brightest ULX M82 X-1 harbors a rather heavy but still stellar-mass black hole shining at several times the Eddington luminosity. The slim-disk model is reasonably successful in explaining the X-ray energy spectrum of M82 X-1 above ∼3 keV. The high disk luminosity and temperature, which are characteristics of the slim disk, are not specific to M82 X-1 but are also seen from some other ULXs. We propose that those ULXs having similar disk properties may also be interpreted in the framework of the slim-disk model with stellar black holes shining at super-Eddington luminosities.

Finally, we remark that the present data analysis of M82 X-1 was limited above ∼3 keV in order to avoid contamination from the soft starburst component, whereas the disk spectra from putative "intermediate-mass black holes" would be most prominent below ∼3 keV. Therefore, it will be interesting to apply our slim-disk scenario to other ULXs in which their disk spectra are clearly seen below 3 keV as well as above 3 keV. If the slim-disk model can explain the ULX energy spectra in the entire energy range, intermediate-mass black holes are not required to explain the X-ray energy spectra of ULXs.

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