BLACK HOLE MASS OF THE ULTRALUMINOUS X-RAY SOURCE M82 X–1
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ABSTRACT

We report first clear evidence for the simultaneous presence of a low frequency break and a QPO in the power spectrum of a well known ultraluminous X-ray source (ULX) in M82 using long XMM-Newton observations. The break occurs at a frequency of $34.2^{+5}_{-3}$ mHz. The QPO has a centroid at $\nu_{QPO} = 114.3 \pm 1.5$ mHz, a coherence $Q \equiv \nu_{QPO}/\Delta \nu_{FWHM} \simeq 3.5$ and an amplitude (rms) of 19% in the $2 - 10$ keV band. The power spectrum is approximately flat below the break frequency and then falls off as a power law with the QPO on top of it. This form of the power spectrum is characteristic of the Galactic X-ray binaries (XRBs) in their high or intermediate states. M82 X-1 was likely in an intermediate state during the observation. The EPIC PN spectrum is well described by a model comprising of an absorbed power-law ($\Gamma \sim 2$) and an iron line at $\sim 6.6$ keV with a width $\sigma \sim 0.2$ keV and an equivalent width of $\sim 180$ eV. Using the well established correlations between the power and energy spectral parameters for XRBs, we estimate a black hole mass in the range of $\sim 50 - 260 M_\odot$ for the ULX M82 X-1. An additional uncertainty of about a factor of 2 in the black hole mass is possible due to the uncertainty in the calibration of the photon index and QPO frequency relation.

Subject headings: accretion, accretion disks — stars: individual (M82 X-1) — X-rays: stars

1. INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are extranuclear point X-ray sources with luminosities exceeding $\sim 10^{39}$ erg s$^{-1}$. These objects were first discovered with Einstein observations (Fabbiano 1989). Later they were detected in large numbers by ROSAT (Colbert & Mushotzky 1999; Roberts & Warwick 2000; Colbert &Ptak 2002) and recently with Chandra and XMM-Newton (e.g., Swartz et al. 2004) from many galaxies. The nature of ULXs continues to be an enigma, since their adopted isotropic high energy output surpasses the Eddington limit of even the most massive stellar mass black holes (BHs), sometimes by large factors.

Several models have been proposed to explain the high luminosities of ULXs. The most popular is the “intermediate mass black hole (IMBH)” with masses $M_{BH} \simeq 10^2 - 10^4 M_\odot$ (e.g., Colbert & Mushotzky 1999, hereafter CM99) bridging the gap between stellar mass BHs in X-ray binaries (XRBs) and super-massive BHs in active galactic nuclei. XRBs with anisotropic emission (King et al. 2001), beamed XRBs with relativistic jets directly pointing towards us i.e., scaled down versions of blazars (Mirabel & Rodriguez 1999), and XRBs with super-Eddington accretion rates (Begelman 2002). Several observations suggest that ULXs may be similar or scaled up versions of the Galactic the X-ray binaries (XRBs). Discovery of orbital modulations from several ULXs (Bauer et al. 2001; Sugihara et al. 2001) implies binary nature. Recent Chandra and XMM-Newton observations of ULXs show soft X-ray excess emission which has been interpreted as the emission from accretion disks with temperatures in the range of $\sim 100 - 500$ eV (see Shrader & Titarchuk 2003 and references therein). Observations of spectral transitions between low/hard and high/soft state from two ULXs in IC 342 (Kubota et al. 2001) further demonstrate their similarity with the XRBs. There are also observations of high/soft to low/hard spectral variability from some ULXs (e.g., Dewangan et al. 2004; Soria & Motch 2004), consistent with a variable power-law and a steady soft X-ray excess component. The recent observation of a break at a frequency of $\sim 28$ mHz in the power density spectrum (PDS) of the ULX NGC 4559 X-7 suggests a mass of a few thousands solar masses (Cropper et al. 2004). Another ULX in NGC 5408 has a break at $\sim 2.5$ mHz in its PDS, suggesting a mass of $\sim 100 M_\odot$ (Soria et al. 2004).

The enigmatic nature of ULXs can be understood by determining their BH masses. The most reliable method is to measure the mass function through the secondary mass and the orbital parameters such as velocities, period, orbit size etc., which can be measured only if the secondary is optically identified. There are two cases of optical identification (Kuntz et al. 2005; Liu et al. 2004), however, the orbital parameters of a ULX binary system is yet to be measured. Good progress can still be made by establishing a direct physical connection between ULXs and XRBs. This can be done by comparing the characteristic time scales such as that associated with the low frequency quasi-periodic oscillations (QPOs). However, this comparison is ambiguous without the information about a low frequency break, the shape of the PDS and energy spectrum.

M82 X-1 is one of the brightest ULX (CXO M82 J095550.2+604017, source 7 in Matsumoto et al. 2001) that is well suited to determine the shape of the PDS. Chandra High Resolution Camera observations showed that the source is unresolved and off-nuclear (Matsumoto...
et al. 2001). The ULX has no optically bright counterpart (Karret et al. 2001). Recently, Strohmayer & Mushotzky (2003), hereafter SM03, discovered a QPO from M82 X-1 at a frequency of 54 mHz based on 27 ks XMM-Newton observation. They also found QPOs in the 50 – 100 mHz frequency range in the RXTE data. Fiorito & Titarchuk (2004), hereafter FT04 apply a new method to determine the BH mass of M82 X-1. The method uses the index-QPO low-frequency correlation that has been recently established in Galactic BH candidates GRS 1915+105, XTE J1550-564, 4U 1630-47, and others (Titarchuk & Fiorito 2004, hereafter TF04). Using scaling arguments and the correlation derived from the consideration of Galactic BHs, they conclude that M82 X-1 is an intermediate mass BH with a mass of the order of $1000 M_\odot$. Here, we revisit the BH mass estimation in M82 X-1 using new data on the power spectrum and energy spectra in M82 X-1.

2. Observation and Data Reduction

XMM-Newton observed M82 on 2001 May 5 for 30 ks and again on 2004 April 21 for 103 ks. The first observation let to the discovery of a 54 mHz QPO from the ULX (SM03). Here we consider the EPIC data from the second observation only. The EPIC PN and MOS cameras were operated in the full frame mode using the medium filter. We used the SAS version 6.1 and the most recent updated calibration data base to process and filter the event data. Examination of the background rate above 10 keV showed that the observation is completely swamped by the particle background after an elapsed time of 71.5 ks and was excluded from the rest of the analysis.

In the central regions of M82, Chandra revealed diffuse emission and several point sources, M82 X-1 being the brightest among them (Matsumoto et al. 2001). The diffuse emission is evident in the EPIC images but the point sources are not resolved. Following SM03, we extracted PN and MOS events using a 18″ circular region around the bright point source whose position is consistent with the Chandra position of M82 X-1. Above 2 keV, the diffuse emission contributes only < 10% to the point source inside the 18″ circular region. At the faintest flux level of M82 X-1, nearby point sources contribute ≤ 30% to the 0.5 – 10 keV X-ray emission in the 18″ region (Matsumoto et al. 2001; SM03).

3. Analysis & Results

3.1. The power spectrum

For temporal analysis, we combined the PN and MOS data and used the continuous exposure of 70.2 ks during which both the PN and MOS cameras operated simultaneously. We calculated a power density spectrum (PDS) using the background corrected PN+MOS light curves sample at 0.5 s. Figure 1 (left) shows the 2 – 10 keV PDS of M82 X-1 rebinned by a factor of 1024 yielding a frequency resolution of 7.8 mHz. The PDS continuum is approximately flat at low frequencies below ~ 30 mHz and then falls of approximately following a power law up to ~ 200 mHz where the white noise arising from the poisson errors starts to dominate the PDS. There is a prominent QPO with its peak frequency near 114 mHz.

We fitted the PDS with two models: (i) a broad Lorentzian for the continuum and a narrow Lorentzian for the QPO, and (ii) a broken power law (BPL) for the continuum and a Lorentzian (L) for the QPO. We also used a constant to account for the poisson noise. Both models provided statistically acceptable fits, giving a minimum $\chi^2$ of 128.6 for 121 degrees of freedom (dof) and 127.9 for 120 dof for double Lorentzian and BPL+L model, respectively. The errors on the best-fit PDS model parameters, quoted below, are at 1σ level.

The double Lorentzian model resulted in a QPO centroid frequency $\nu_{QPO} = 114.6 \pm 1.5$ mHz, a width $\nu_{FWMH} = 31.3^{+2.5}_{-2.3}$ mHz, an amplitude $A_{QPO} = 0.037 \pm 0.0024$ and the broad Lorentzian centroid $\nu_0 = 11.4^{+4.2}_{-4.4}$ mHz, a width $\nu_{FWMH} = 60.2^{+7.5}_{-6.3}$ mHz and an amplitude $A = 0.038 \pm 0.0034$. The BPL+L model resulted in a QPO centroid frequency $\nu_{QPO} = 114.3 \pm 1.5$ mHz, a width $\nu_{FWMH} = 32.7^{+2.9}_{-2.6}$ mHz, an amplitude $A_{QPO} = 0.038 \pm 0.0024$, and the broken power-law indices of $\Gamma_1 = 0.11^{+0.10}_{-0.09}$ before the break frequency $\nu_b = 34.2^{+5.5}_{-2.9}$ mHz and $\Gamma_2 = 2.32^{+0.56}_{-0.38}$ after the break frequency, and an amplitude $A_{BPL} = 0.36 \pm 0.03$ at a reference frequency of 10 mHz. The total integrated power (0.001 – 1 Hz) and the QPO power expressed as $rms/mean$ are 23% and 19%, respectively. The use of a broken power law is an improvement ($\Delta \chi^2 = -24.8$ for two additional parameters) over a simple power law at a statistical significance level of > 99.99% based on the maximum likelihood ratio test. Thus the break in the continuum of the power spectrum is real. The best-fit BPL+L model is shown in Fig. 1 (left) as a thick line.

To make a comparison we have also calculated PDS of a Galactic XRB XTE J1550-564 using the RXTE observation of 10 September 1998. XTE J1550-564 shows a large range in its low frequency QPO centroid ($\nu_{QPO} \sim 0.08 – 18$ Hz; Sobczak et al. 2000a). Our choice of the particular RXTE observation relies on the fact that XTE J1550-564 showed a power-law photon index of $\Gamma \sim 2$ on 10 September 1999 (Sobczak et al. 2000b), which is very similar to the 3 – 10 keV photon index of M82 X-1 (see below). Fig. 1 (right) shows the PDS of XTE J1550-564 calculated from the PCA light curve sampled at 0.125 s which was obtained from the RXTE public data archive. We used to a model comprising of a broken power law and two Lorentzian to fit the PDS. This model resulted in a statistical acceptable fit (minimum $\chi^2 = 94.2$ for 118 dof). The broken power law has the best-fit parameters: $\Gamma_1 = 0.03 \pm 0.006$ before the break frequency $\nu_b = 0.27 \pm 0.007$ Hz, $\Gamma_2 = 0.89 \pm 0.01$ after the break and an amplitude $A_{BPL} = 0.026 \pm 0.0005$ at a reference frequency of 10 mHz. The two QPOs have centroid frequencies $\nu_{QPO} = 1.034 \pm 0.004$ and 2.055 $\pm 0.016$ Hz, widths $\nu_{FWMH} = 0.125 \pm 0.010$ and 0.39 $\pm 0.05$ Hz and amplitudes $A_{QPO} = 0.026 \pm 0.0005$ and 0.0046 $\pm 0.0003$ for the fundamental and first harmonic, respectively. The total integrated power (0.01 – 4 Hz) and the QPO (fundamental) power expressed as $rms/mean$ are 23% and 16%, respectively.

3.2. The energy spectrum

We extracted PN and MOS spectra using a 18″ circular region centered at the position of M82 X-1. We also extracted PN and MOS background spectra using nearby circular regions free of sources. We created appropriate response files using the SAS tasks rmfgen and
Fig. 1.— Power density spectra of the ULX M82 X-1 and a Galactic XRB XTE J1550-564 having very similar power-law photon indices ($\Gamma \sim 2.0$). Left: Power spectrum of M82 X-1 derived from the EPIC PN and MOS data above 2 keV. The white noise level expected ($\sim 1.4$) from the poisson errors has not been subtracted. The frequency resolution is 7.8 mHz. The best-fitting model comprising of a broken power law and a Lorentzian is shown as a thick line. Right: Power spectrum of the Galactic XRB XTE J1550-564 derived from the RXTE observations of 1998 September 10. The best-fit model consisting of a broken power law and two Lorentzian is shown as a thick line.

Fig. 2.— (a) Ratio of EPIC PN data and the best-fit absorbed power-law model showing the iron Kα line. (b) The PN spectrum and the best-fit absorbed power law and a Gaussian line model (upper panel) and their ratio (lower panel).

**arfgen.** The spectra were grouped to a minimum of 20 counts per spectral channel and analyzed with XSPEC 11.3. The errors on the best-fit spectral parameters are quoted at a 90% confidence level. An absorbed power law (PL) model fitted to the PN data showed strong soft excess emission below $\sim 3$ keV due to the presence of the diffuse soft X-ray emission in the source extraction region. We ignored the data below 3 keV and performed the spectral fitting of the PN and MOS data separately. A simple power-law model poorly describes both the PN and MOS data. We show the ratio of the PN data and the best-fitting absorbed power-law model in Figure 2(a). A prominent iron Kα line at $\sim 6.6$ keV is evident. Addition of a Gaussian line (GL) to the power-law model improved the fit significantly ($\Delta \chi^2 = -71.7$ for three additional parameters) and resulted in a good fit (minimum $\chi^2 = 898.9$ for 944 dof. The Gaussian line has a centroid energy $E_{\text{line}} = 6.61^{+0.07}_{-0.08}$ keV, a width $\sigma = 278^{+161}_{-115}$ eV, a line flux $f_{\text{line}} = 1.9^{+0.7}_{-0.6} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ and an equivalent width of $\sim 180$ eV. The best-fit photon index is $2.00^{+0.07}_{-0.07}$ and the the absorption column is $N_H = 2.5^{+0.6}_{-0.6} \times 10^{22}$ cm$^{-2}$. The observed 2 – 10 keV flux is $9.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and the corresponding luminosity is $1.7 \times 10^{40}$ erg s$^{-1}$ assuming a distance of 3.9 Mpc (Sakai & Madore 1999). In Figure 2(b), we show the best-fit PL+GL model to the EPIC PN data. The PL+GL model fitted to the MOS data resulted in slightly flatter power-law ($\Gamma_X = 1.80^{+0.11}_{-0.09}$), an absorption column $N_H = 1.8^{+0.7}_{-0.3} \times 10^{22}$ cm$^{-2}$ and a weaker iron line, $EW \sim 94$ eV.

4. DISCUSSION

Based on long XMM-Newton observation, we show clear evidence for the simultaneous presence of a low frequency break at $\nu_b = 33.5^{+6.7}_{-3.0}$ mHz and a QPO with centroid frequency $\nu_{QPO} = 113.2 \pm 1.5$ mHz in the power spectrum of M82 X-1. The QPO frequency is similar to that found from the RXTE observation of 1997 July 21, while it is about a factor of two larger than that found in the first XMM-Newton observation of 2001 May and an RXTE observation of 1997 February 24 (SM03). Thus
the QPO frequency of M82 X-1 is variable.

The M82 X-1 PDS is flat below the break frequency and then falls off as a power law with a prominent QPO on top of it. This form of the PDS is characteristic of Galactic X-ray binaries in their high/soft state or intermediate state (e.g., McClintock & Remillard 2003; Cui et al. 1999; see also Fig. 1 for a comparison). PDSs of many Galactic XRBs display low frequency QPOs in the frequency range of \( \sim 0.05 - 30 \) Hz (Remillard et al. 2002). The QPO frequency is strongly correlated with the break frequency (Wijnands & van der Klis 1999). The break frequency is always lower than the QPO frequency by at least a factor of three (see, Wijnands & van der Klis 1999). M82 X-1 also follows the correlation as its QPO frequency is about a factor three larger than the break frequency. Thus the PDS of the ULX is very similar to the XRBs PDSs in their high/soft or transition state.

Since characteristic time scales of accretion powered sources scale with BH mass, the similarity of the PDSs of M82 X-1 and XRBs provides a chance to determine the ratio of their BH masses. However, as stated above, the Galactic XRBs show a large range in their low frequency QPO and break frequencies. Therefore, the frequency scaling factor between any two power spectra of two XRBs will lead to incorrect determination of the ratio of their BH masses. Fortunately, the PDS features (break and QPO frequencies) are well correlated with the energy spectral parameters. Sobczak et al. (2000a) found strong positive correlation between the QPO frequency and the disk flux for the XRBs XTE J1550-564 and GRO J1655-40. A similar relation was also found for the variable 1 - 15 Hz QPOs in GRS 1915+105 (Markwardt, Swank & Taam 1999) and the 20 - 30 Hz QPOs in XTE J1748-288 (Revnivtsev, Trudolyubov & Borozdin 2000). The low frequency QPOs are related to the flux of the power-law energy spectral component. The variable frequency QPOs in XTE J1550-564 and GRO J1655-40 appear only when the power law contributes more than 20% of the 2 - 10 keV flux (Sobczak et al. 2000a and references therein). GRS 1915+105 also shows similar behavior (Muno et al. 1999). The power-law index is well correlated with centroid of the low frequency QPOs in GRS 1915+105 (Vignarca et al. 2003) and XTE J1550+564 (Sobczak et al. 2000a, 2000b). The photon index increases with the QPO frequency until it saturates. The frequency scaling factor between the low frequency QPOs of two XRBs with similar power-law photon indices can be used to determine the ratio of their BH masses (TF04; FT04). Thus it is crucial to determine the shape of X-ray spectrum and detect both the QPO and the low frequency break in order to make sure that the detected QPO lies at low frequencies after the break frequency and on top of a PDS power-law continuum.

The long XMM-Newton observation of M82 X-1 has yielded all 3 pieces of information required to determine its BH mass. The photon index of the 3 - 12 keV power law is \( 2.0 \pm 0.1 \) as determined from the high signal-to-noise PN data. Galactic XRBs show a range of power-law photon indices from \( \Gamma \sim 1.6 \) in their low/hard state to \( \Gamma \sim 2.5 \) in their high/soft state. Thus M82 X-1 is likely in a state intermediate to the high and low states. Sobczak et al. (2000a) studied spectral behavior of XTE J1550-564 during its 1998-1999 outburst using 209 pointed observations with RXTE. They used a model consisting of multicolor disk blackbody and a power law to fit the spectra and found that the spectra gradually steepen from \( \Gamma \sim 1.5 \) to \( \sim 2.9 \) for XTE J1550-564. The low frequency QPO is also found to vary from 0.08 - 13 Hz. At a power-law photon index of 1.91 (2.12), XTE J1550-564 shows a low frequency QPO at 0.81 Hz (1.6 Hz) (Sobczak et al. 2000a; 2000b). Noting that the BH mass scales inversely proportion to the QPO frequency and the BH mass of XTE J1550-564 is about 10\( M_\odot \) (Titarchuk & Shrader 2002, Shrader & Titarchuk 2003), we can determine the BH mass of the ULX as \( M_{BH} (ULX) \sim \nu_{QPO}(XTE J1550-564)/\nu_{QPO}(ULX) \times M_{BH} (XTE J1550-564) \sim 70 - 150 M_\odot \). Another Galactic XRB GRS 1915+105 shows a low frequency QPO with its centroid at 0.642 \( \pm 0.004 \) Hz (1.609 \( \pm 0.007 \) Hz) when its power-law photon index is 1.88 \( \pm 0.04 \) (2.16 \( \pm 0.04 \)) (Vignarca et al. 2003). Noting that that the BH mass of GRS 1915+105 is 14 \( \pm 4 M_\odot \) estimated dynamically from the IR spectroscopic observation of its companion star (Greiner et al. 2001), the BH mass for M82 X-1 is \( M_{BH} (ULX) \sim 50 - 260 M_\odot \). It is worth noting that the QPO frequencies and photon indices for M82 X-1 , XTE J1550-564 and GRS 1915+105 correspond to a region of steep dependence in the \( \Gamma - \nu_{QPO} \) relation (see FT04), it is likely that the uncertainty in the calibration of the \( \Gamma - \nu_{QPO} \) relation may introduce an additional factor of two uncertainty in the determination of the BH mass of M 82 X-1. Thus, the true BH mass of M 82 X-1 is most likely in the range of 25 - 500 \( M_\odot \), this is at least a factor of 2 lower than the previous estimate by FT04 which can be explained by the differences in the values of the QPO lower frequencies for M82 X-1 in our paper and those in FT04.

M82 X-1 is one of the brightest ULXs. During the second XMM-Newton observation, its 2 - 10 keV observed luminosity was \( 1.7 \times 10^{40} \) erg s\(^{-1}\) (SM03), while it was a factor of \( \sim 2 \) brighter in the first XMM-Newton observation. Based on the first XMM-Newton observation, SM03 quoted a bolometric luminosity of \( (4 - 5) \times 10^{40} \) ergs s\(^{-1}\), equivalent to the Eddington luminosity for a BH mass in the range of 300 - 400 \( M_\odot \). Given the uncertainty in the contamination by nearby X-ray sources, M82 X-1 was well within the Eddington limit during both the XMM-Newton observations.

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