ORIGIN OF THE X-RAY QUASI-PERIODIC OSCILLATIONS AND IDENTIFICATION OF A TRANSIENT ULTRALUMINOUS X-RAY SOURCE IN M82

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ABSTRACT

The starburst galaxy M82 contains two ultraluminous X-ray sources (ULXs), CXOM82 J095550.2+694047 (=X41.4+60) and CXOM82 J095551.1+694045 (=X42.3+59), which are unresolved by XMM-Newton. We revisited the two XMM-Newton observations of M82 and analyzed the surface brightness profiles using the known Chandra source positions. We show that the quasi-periodic oscillations (QPOs) detected with XMM-Newton originate from X41.4+60, the brightest X-ray source in M82. Correcting for the contributions of the unresolved sources, the QPO at a frequency of 55.8 ± 1.3 mHz on 2001 May 6 had a fractional rms amplitude of 32%, and the QPO at 112.9 ± 1.3 mHz on 2004 April 21 had an amplitude of 21%. The QPO frequency may possibly be correlated with the source flux, similar to the type C QPOs in XTE 1550–564 and GRS 1915+105, but at luminosities 2 orders of magnitude higher. X42.3+59, the second-brightest source in M82, displayed a strikingly high flux of 1.4 × 10^{–11} erg s^{-1} cm^{-2} s^{-1} in the 2–10 keV band on 2001 May 6. A 7 year light curve of X42.3+59 shows extreme variability over a factor of 1000; the source is not detected in several Chandra observations. This transient behavior suggests accretion from an unstable disk. If the companion star is massive, as might be expected in the young stellar environment, then the compact object would likely be an intermediate-mass black hole (IMBH).

Subject headings: accretion, accretion disks — black hole physics — X-rays: binaries — X-rays: galaxies — X-rays: individual (M82 X-1, CXOM82 J095550.2+694047, X41.4+60, CXOM82 J095551.1+694045, X42.3+59)

1. INTRODUCTION

ULXs are nonnuclear, pointlike X-ray sources in external galaxies with luminosities (assuming isotropic emission) above the Eddington limit for a 20 M_{\odot} black hole (3 × 10^{39} ergs s^{-1}). Their fast variability and high luminosities indicate that they may contain IMBHs (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001). However, if the emission is beamed (King et al. 2001; K{"o}rding et al. 2002), exceeds the Eddington limit (Watarai et al. 2001; Begelman 2002), or both (Poutanen et al. 2007), IMBHs are not required. Using ASCA, Ptak & Griffiths (1999) and Matsumoto & Tsuru (1999) found that the bright X-ray emission from the central region of the starburst galaxy M82 was highly variable on time-scales of hours to days, suggesting it arises from a compact object. The emission from the core of M82 was resolved with Chandra into several point sources, among which an extremely bright ULX, CXOM82 J095550.2+694047, was identified at a luminosity of 10^{40}–10^{41} ergs s^{-1} (Matsumoto et al. 2001; Kaaret et al. 2001). Following the convention of naming sources in M82 by their offset from α = 09^{h}51^{m}00^{s}, δ = +69^{\circ}54'00", (B1950.0), we refer to this source as X41.4+60 and use the same convention in referring to other X-ray and radio sources in M82. The source is highly variable, indicating that it is not a supernova or remnant, and not coincident with the dynamical center of M82, indicating that it is not an active galactic nucleus (AGN). If the radiation is isotropic and Eddington-limited, the source would be an IMBH candidate with a mass in excess of 500 M_{\odot}. The luminosity of X41.4+60 is too high to be explained by mechanically beamed emission from a stellar mass black hole (King & Dehnen 2005). An X-ray flare detected using the Rossi X-Ray Timing Explorer (RXTE) in 2005 February showed no strong radio emission in contemporaneous Very Large Array (VLA) observations, which ruled out the possibility that the source is relativistically beamed (Kaaret et al. 2006).

XMM-Newton cannot resolve the multiple point sources detected with Chandra in the central region of M82, but provides a superior collection area, allowing sensitive studies of timing properties. Strohmayer & Mushotzky (2003) analyzed a 27 ks XMM-Newton observation of the source obtained in 2001 and discovered quasi-periodic oscillations (QPOs) at a frequency of 54 mHz in the energy range 2–10 keV. The QPOs were confirmed in a 103 ks XMM-Newton observation in 2004; however, the frequency shifted to 114 mHz (Dewangan et al. 2006; Mucciarelli et al. 2006). The power spectral density (PSD) from the second observation also showed a low frequency break at 34 mHz. Mucciarelli et al. (2006) found that the QPOs changed frequency from 107 mHz to 120 mHz during the second observation, and discovered a plausible harmonic ratio of 1 : 2 : 3 for QPO frequencies with more data from RXTE. Due to the limited angular resolution of XMM-Newton (and RXTE), all of these analyses treated the emission as arising from a single point source, called M82 X-1.

However, higher angular resolution observations made with Chandra show that M82 contains two ULX sources, CXOM82 J095550.2+694047 (X41.4+60) and CXOM82 J095551.1+694045 (X42.3+59), and several dimmer sources that contribute to the emission ascribed to M82 X-1. The second ULX, X42.3+59, has shown pronounced variability, appearing as the second brightest source in M82 on 1999 October 28 but being undetected on 2000 January 20 (Matsumoto et al. 2001; Kaaret et al. 2001). A Chandra observation in 2005 February revealed X42.3+59 in a bright state with strong variability, but the sensitivity was not adequate to confirm or reject the presence of QPOs.

It is of interest to determine which of the two ULXs is the source of the QPO detected with XMM-Newton. We revisited the two XMM-Newton observations of M82 (§ 2), corrected their astrometry using a Chandra observation (§ 2.1), resolved the source count rates of X41.4+60 and X42.3+59 from surface brightness fits (§ 2.2), and compared them with timing analysis.
TABLE 1

| Source No. | R.A. (J2000.0) | Decl. (J2000.0) | Name |
|------------|---------------|----------------|------|
| 1          | 09 55 54.68   | +69 41 01.1    | ...  |
| 2          | 09 55 52.31   | +69 40 54.1    | ...  |
| 3          | 09 55 51.48   | +69 40 36.0    | ...  |
| 4          | 09 55 51.05   | +69 40 45.3    | X42.3+59 |
| 5          | 09 55 50.17   | +69 40 46.7    | X41.4+60 |
| 6          | 09 55 51.05   | +69 40 45.3    | X42.3+59 |
| 7          | 09 55 50.17   | +69 40 46.7    | X41.4+60 |
| 8          | 09 55 46.61   | +69 40 41.1    | ...  |

Notes—The first column indicates the source index in Matsumoto et al. (2001). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. All positions are obtained from wavdetect and then shifted by matching source 7 to the position R.A. = 09°55′50″17′′, decl. = +69°40′46.7″ (Kaaaret et al. 2001).

done with various source regions to determine the PPO origin (§ 2.4). A 7 year light curve of X42.3+59 using all available XMM-Newton and Chandra archival data is presented in § 2.5. The results are discussed in § 3.

2. OBSERVATIONS AND DATA ANALYSIS

XMM-Newton observations of M82 made on 2001 May 6 (ObsID 01112290201) and 2004 April 21 (ObsID 0206080101) were used for image and timing analysis. The Chandra observation with the High-Resolution Camera (HRC) made on 1999 October 28 (ObsID 1411-1) was used to correct the astrometry of XMM-Newton images. All Chandra and XMM-Newton observations were used to produce the light curve of X42.3+59. We used SAS version 7.0.0 with up-to-date calibration files for Chandra images were found using edetect_chain in the 2–10 keV band. Point sources within 8″ of X41.4+60 were not used because the diffuse emission and the two unresolved bright ULXs could bias the XMM-Newton source detection. Positions for Chandra sources, shown in Table 1, were obtained using wavdetect and then corrected by shifting X41.4+60 to the position R.A. = 09°55′50″17′′, decl. = +69°40′46.7″ (Kaaaret et al. 2001). We note that none of our results depend on the absolute astrometry. We adopt the position of X41.4+60 from Kaaaret et al. (2001) as a reference in order to keep the source names consistent with those previously used in the literature. We found eight matched point sources between the MOS1 and HRC image for the first observation and seven for the second observation. All these sources were used to align the XMM-Newton MOS1 images to the HRC image.

2.2. Surface Brightness Fits

We use only XMM-Newton MOS1 images for the surface brightness fits. MOS2 images are not used because the MOS2 point-spread function (PSF) is not axisymmetric within a few arcseconds of the core. PN images are not suitable because its pixel size of 4″ slightly undersamples the core and is close to the angular distance between the two ULXs. M82 X-1 is a bright X-ray source, so the MOS1 images with 3 × 10^4 source photons in the 2–10 keV band for the first observation and 8 × 10^4 for the second provide adequate statistics.

MOS1 images for the 2–10 keV band were created in a 250″ × 250″ region around X41.4+60 and sampled on a 1″ × 1″ grid with events screened by FLAG equal to #XMMEA_EM and PATTERN between 0 and 12. The effective exposure for the MOS1 image is 30.0 ks for the first observation and 101.2 ks for the second. The PSF for MOS1 can be well described by a King function, and the King parameters are stored in the latest calibration file (e.g., XRT1_XPSF_0007.CCF for MOS1 by now). We used the command calview with an EXTENDED accuracy level to produce the on-axis King model PSF at 2 keV for MOS1. The King model parameters vary little with energy. Therefore, a monochromatic PSF at 2 keV provides an adequate description of the photon distribution for a 2–10 keV point-source image.

Six of the nine sources listed in Matsumoto et al. (2001) were used in the surface brightness fits. However, the source names in Matsumoto et al. (2001) do not retain the subarcsecond accuracy that is necessary for the fit. We thus used the positions obtained from wavdetect as mentioned in § 2.1 and listed in Table 1.

The two-dimensional surface brightness fits of the XMM-Newton MOS1 images were performed with the CIAO program Sherpa. The PSF is loaded with a size of 128″ × 128″ around the core. We use 6-functions to model the point sources and a constant to model the background. Point sources are fixed at positions quoted in Table 1 and allowed to shift together.

For the first XMM-Newton observation, only two point sources, X41.4+60 and X42.3+59, were considered in the fit. The model had five free parameters: the pattern shifts ΔX and ΔY, source amplitudes for the two ULXs (X41.4+60 and X42.3+59), and a background amplitude taken as constant across the whole field. We applied the CHI GEHRELS statistics in Sherpa because the situation for the second observation is slightly more complex, because the long exposure causes the diffuse emission and other dim sources in the central region to become significant. If we only model X41.4+60 and X42.3+59 plus a constant background, the χ^2/dof in the central 18″ region is 2230/1009. We thus added another four point sources to the model—i.e., sources 1, 2, 3, and 9 in Matsumoto et al. (2001). Sources 4, 6, and 8 are not added because source 8 was not bright in the second observation and sources 4 and 6 are too close to X42.3+59 (source 5). We then performed the fit with a model including six point sources and a constant background with nine free parameters. The six point sources were still set to move together as a whole pattern, and their best-fit position is only 0.3″ away from the Chandra position. In this observation, the count rate of X41.4+60 increased to 0.305 counts s^-1 while the X42.3+59 rate decreased to 0.064 counts s^-1. The background level is 1.6 × 10^{-6} counts s^{-1} arcsec^{-2}. In a 18″ radius circle, the model and data result in χ^2 = 948 with 1009 degrees of freedom (dof), indicating an adequate fit.

The situation for the second observation is slightly more complex, because the long exposure causes the diffuse emission and other dim sources in the central region to become significant. If we only model X41.4+60 and X42.3+59 plus a constant background, the χ^2/dof in the central 18″ region is 2230/1009. We thus added another four point sources to the model—i.e., sources 1, 2, 3, and 9 in Matsumoto et al. (2001). Sources 4, 6, and 8 are not added because source 8 was not bright in the second observation and sources 4 and 6 are too close to X42.3+59 (source 5). We then performed the fit with a model including six point sources and a constant background with nine free parameters. The six point sources were still set to move together as a whole pattern, and their best-fit position is only 0.3″ away from the Chandra position. In this observation, the count rate of X41.4+60 increased to 0.305 counts s^{-1} while the X42.3+59 rate decreased to 0.064 counts s^{-1}. The background level is 3.3 × 10^{-6} counts s^{-1} arcsec^{-2}. Modeling the extra four sources improved the fit significantly, resulting in χ^2/dof = 1453/1005. We checked the residual map and found that most residuals came from structure in the diffuse emission region, which is not included in our model.

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1 See § 3 and Fig. 2 in the XMM-Newton current calibration file release notes 167.
the fit is not formally adequate, we believe the resolved count rates are reliable because the emission from the ULXs is much stronger than the diffuse emission.

After checking all Chandra ACIS (Advanced CCD Imaging Spectrometer) observations, we found that the count rate in the 2–8 keV band of source 4 varied by a factor of 2, while source 6 appeared constant. We estimate that sources 4 and 6 contribute a systematic error to the count rate estimated for X42.3+59 of 5% in the first observation and 30% in the second.

Contour maps of the surface brightness (corrected with exposure map and mask) for the two observations are shown in Figure 1. From the contour maps we can clearly see that the count rate of X41.4+60 is slightly lower than X42.3+59 in the first observation and much higher than X42.3+59 in the second. This is consistent with the rates from the surface brightness model fits, which are listed in Table 2.

2.3. Flux from X41.4+60

Because XMM-Newton is unable to resolve X41.4+60 from other point sources and the diffuse emission in M82, one needs great caution to make energy spectral analysis with XMM-Newton data. So far the only energy spectrum of X41.4+60, which is neither contaminated by X42.3+59 nor strongly affected by pile-up, is from Kaaret et al. (2006) with an off-axis Chandra ACIS observation. In that observation, X41.4+60 presented a featureless power-law spectrum with a photon index of 1.67.

We adopt a power-law spectral index of 1.7 (Kaaret et al. 2006) with an absorption column density of 3 × 10^{22} cm^{-2}, and use PIMMS to estimate the unabsorbed source flux in the 2–10 keV range according to the resolved count rates (with a factor of 0.7, because PIMMS accepts the counting rate in a 15″ region, which contains around 70% of a 2–10 keV PSF), which gives 8.5 × 10^{-12} ergs cm^{-2} s^{-1} for the first observation and 1.0 × 10^{-11} ergs cm^{-2} s^{-1} for the second. The corresponding luminosity is 1.3 × 10^{40} and 1.7 × 10^{40} ergs s^{-1} at a distance of 3.63 Mpc (Freedman et al. 1994), respectively, for the first and second observation. The flux is not very sensitive to the photon index, varying only by 10% as the photon index varies between 1.5 and 2.3, but a decrease of the column density to 1 × 10^{22} cm^{-2} will bring down the unabsorbed flux by 25%.

2.4. Timing Analysis

All PN and MOS data were used for the timing analysis in order to increase the signal-to-noise ratio. We applied FLAG equal to #XMMEA_EP and PATTERN between 0 and 4 to select PN events, and FLAG equal to #XMMEA_EW and PATTERN between 0 and 12 for MOS events.

We examined the timing gaps in the data and background flares before binning events into light curves. CCD timing gaps are stored in the good time interval (GTI) extension of the events file for each CCD chip. GTIs to exclude background flares and only to exclude CCD timing gaps.
Every continuous piece of the light curve longer than 512 s was divided into segments of 512 s each. Individual PSDs were calculated with a 1024 point fast Fourier transform (FFT) for each 512 s segment. All PSDs were normalized to rms (van der Klis 1989) and averaged to a final one, which corresponds to an effective exposure of 20.5 ks for the first observation and 50.7 ks for the second. The PSD was rebinned linearly at \( \nu \leq \nu_b \) by a factor of \( \delta_1 \) and logarithmically at \( \nu > \nu_b \) by a factor of \( \delta_2 \). We set \( \nu_b = 0.1 \) Hz, \( \delta_1 = 3 \), and \( \delta_2 = 1.2 \) for the first observation and \( \nu_b = 0.16 \) Hz, \( \delta_1 = 5 \), and \( \delta_2 = 1.2 \) for the second.

Three regions defined in Figure 2 were used to extract events: an 18" radius circle centered on X41.4+60 divided into two half-circles by a line perpendicular to the line connecting X41.4+60 and X42.3+59. Region A is the half-circle on the side without X42.3+59 and region B is the half-circle containing X42.3+59. PSDs for regions A+B, A, and B are presented in Figure 3 for the first observation and in Figure 4 for the second.

We fit the PSDs for the first observation with a power-law plus Lorentzian model; the former component is to model the continuum and the latter is for the QPO. For the second observation, the continuum component is modeled by an exponentially cut off power-law model. The best-fit parameters—including the power-law slope \( \alpha \), cutoff frequency \( \nu_{\text{cut}} \), Lorentz centroid \( \nu_L \), and full width at half-maximum (FWHM) \( \nu_1 \), as well as the fractional rms amplitude (rms/mean) of the QPO component—are listed in Table 3 with 1 \( \sigma \) errors for each region and observation. We note that the QPO is not detected in region B for the first observation. We fixed the power-law index to \(-1.5\) to model the continuum and evaluated a 2 \( \sigma \) upper limit of the QPO rms by integrating the powers in the 30–70 mHz frequency region.

Given the resolved source count rates from the surface brightness fits, X41.4+60 contributes 41%, 67%, and 30% of 2–10 keV photons, respectively, for region A+B, A, and B for the first observation, and 84%, 94%, and 76%, respectively, for the second. Assuming that the QPO comes from one of the ULXs, the required rms for a particular source is obtained by normalizing the measured rms to the photon fraction in each region. The calculated values are shown in columns (8) and (9) in Table 3. Column (8) shows consistent rms values from the different regions for each observation. Thus, the assumption that X41.4+60 produces the QPOs gives consistent results regardless of the region chosen to measure the QPO strength. Conversely, column (9) shows that if X42.3+59 is assumed to produce the QPOs, then widely differing rms values are found from the different regions. Thus, we conclude that the QPOs originate from X41.4+60.
The source count rate or flux in two Chandra observations has been reported in the literature. These are Chandra observation 10 (see Table 4) with ACIS (Kaaret et al. 2006), and observation 3 with HRC (Matsumoto et al. 2001).

For ACIS observations, we calculated the pile-up fraction following the definitions in the Chandra ABC Guide to Pileup, where $f_i$ is the fraction of good events lost due to grade or energy migration, $f_s$ is the fraction of single events over all detected events, $f_c$ is the fraction of count rate lost, and $\alpha$ is the probability that a piled event is retained as a good grade.

Two ACIS observations, 11 and 12, suffer only mild pile-up, with $f_i < 10\%$. X42.3+59 has the same count rate in these two observations. Observation 12 is about 1 day later than observation 11, and has an exposure of only 1/4 of observation 11. We assume the source stayed in the same state for both observations and use observation 11 to constrain the spectral parameters. The energy spectrum is created from a 1″ source region binned for a minimum count of 100 per bin. We subtracted a background estimated using a nearby diffuse emission region free of point sources and then fitted with a pile-up-corrected, absorbed power-law model in the energy range of 0.3–8 keV using Sherpa. Best-fit parameters include an absorption column density $N_H = (3.45 \pm 0.11) \times 10^{22}$ cm$^{-2}$ and a power-law index $\Gamma = 1.49 \pm 0.06$, with $\chi^2 = 129$ for 101 dof. The pile-up model indicates a pile-up fraction $f_c = 1.2\%$ with $\alpha = 0.28$, which is consistent with the estimate from the count rate. The best-fit model predicts an unabsorbed source flux of $6.0 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in 2–10 keV.

Five ACIS observations (4, 6, 7, 8, and 9) suffer from severe pile-up. These observations have a pile-up fraction $f_i > 20\%$ and thus are not suitable for spectral analysis. The count rates are measured from a $2 \times 2$ pixel array in 0.3–8 keV and then corrected by $f_c$, which is estimated from a $3 \times 3$ pixel island in the full band assuming $\alpha = 0.5$. The background level, measured from observation 11, is only about 2% of the source flux for these observations and thus negligible.

The source was not detected in five observations: three with HRC (5, 13, and 14) and two with ACIS (1 and 2). For the HRC observations, the upper limit of the count rate is calculated from a 1″ source region. For the ACIS observations, it is adopted from the brightest pixel around the source region. We note that there is strong diffuse emission around X42.3+59; thus, our upper limits are conservative and likely an overestimate.

All count rates (with a factor of 0.7 for XMM-Newton observations) are converted to 2–10 keV unabsorbed flux with PIMMS, given $N_H = 3 \times 10^{22}$ cm$^{-2}$ and a power-law photon index $\Gamma = 1.5$. The flux estimates from the XMM-Newton data include the systematic uncertainty caused by the very nearby sources 4 and 6 as mentioned above. The complete light curve with all the available XMM-Newton and Chandra data is presented in Figure 5. It is clear that X42.3+59 is highly variable. The source exhibited an unabsorbed flux of $1.4 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ and a corresponding luminosity of $2.2 \times 10^{40}$ erg s$^{-1}$ in the first XMM-Newton observation, reaching its brightest state that has ever been observed.

### 3. DISCUSSION

#### 3.1. Origin of the QPO

We present solid evidence that the QPOs from M82 originate from the brightest source, X41.4+60, rather than the second-brightest source, X42.3+59. The angular resolution of

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2 See http://asc.harvard.edu/ciao/download/doc/pileup_.abc.ps.
**TABLE 3**

**BEST-FIT PSD PARAMETERS FOR LIGHT CURVES EXTRACTED FROM DIFFERENT SOURCE REGIONS IN THE 2–10 keV RANGE**

| Region (1) | $\alpha$ (2) | $\nu_{\text{col}}$ (mHz) (3) | $\nu_L$ (mHz) (4) | $w_L$ (mHz) (5) | $\chi^2$/dof (6) | $\text{rms}_{\text{QPO}}$ (%) (7) | $\text{rms}_{41.1}$ (%) (8) | $\text{rms}_{42.2}$ (%) (9) |
|------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A+B        | $-1.6 \pm 0.6$ | $52 \pm 3$      | $29 \pm 9$      | $21/25$         | $12.1 \pm 0.8$  | $30 \pm 2$      | $20.5 \pm 1.4$  |                  |
| A          | $-1.2 \pm 0.5$ | $55.8 \pm 1.3$  | $19 \pm 4$      | $26/25$         | $21.6 \pm 0.8$  | $32.2 \pm 1.2$  | $65 \pm 2$      |                  |
| B          | $-1.5$ fixed  | ...             | ...             | ...             | $<11$           | $<37$           | $<16$           |                  |

**Notes.**—Col. (1): Regions from which the light curves are extracted; see Fig. 2 for details. Col. (2): Exponent of the power law (first observation) or the exponentially cut off power law (second observation). Col. (3): Cutoff frequency of the exponentially cut off power law (only for second observation). Col. (4): Centroid of the Lorentzian. Col. (5): Full width at half-maximum of the Lorentzian. Col. (6): $\chi^2$ and degrees of freedom. Col. (7): Fractional rms amplitude of the QPO (=the Lorentzian) Col. (8): Required rms if the QPO originates from X41.4+60. Col. (9): Required rms if the QPO originates from X42.3+59. All errors are at the 1σ level.

**TABLE 4**

**Chandra Observations of M82**

| Index (1) | MJD (2) | ObsID (3) | Instrument (4) | Exposure (ks) (5) |
|-----------|---------|-----------|-----------------|-----------------|
| 1         | 51,441.7 | 361       | ACIS-1          | 33.3            |
| 2         | 51,442.0 | 1302      | ACIS-1          | 15.5            |
| 3         | 51,479.4 | 1411-1    | HRC-1           | 36.3            |
| 4         | 51,542.1 | 378       | ACIS-1          | 4.1             |
| 5         | 51,563.7 | 1411-2    | HRC-1           | 17.8            |
| 6         | 51,614.9 | 379       | ACIS-1          | 8.9             |
| 7         | 51,671.9 | 380-1     | ACIS-1          | 3.9             |
| 8         | 51,707.6 | 380-2     | ACIS-1          | 1.2             |
| 9         | 52,443.9 | 2913      | ACIS-S          | 18.0            |
| 10        | 53,406.3 | 6097      | ACIS-S          | 52.8            |
| 11        | 53,599.5 | 5644      | ACIS-S          | 68.1            |
| 12        | 53,600.8 | 6361      | ACIS-S          | 17.5            |
| 13        | 54,109.7 | 8189      | HRC-S           | 61.3            |
| 14        | 54,112.6 | 8505      | HRC-S           | 83.2            |

**Notes.**—ObsIDs 380 and 1411 consist of two individual observations. The MJD indicates the mean time of each observation.

**XMM-Newton** is not adequate to cleanly resolve the two sources, but is adequate, with surface brightness fitting using the known source positions, to determine the count rate from each source. Using these count rates and the QPO amplitudes calculated from three different extraction regions, we find that the assumption that X41.4+60 produces the QPOs gives consistent results. Conversely, if X42.3+59 is taken as the source of the QPOs, then the QPO rms amplitude values calculated from different extraction regions differ at a significance level of at least 20σ.

The origin of the broken power-law feature in the PSD continuum, first reported by Dewangan et al. (2006) and Mucciarelli et al. (2006) in the second XMM-Newton observation, has not yet been determined. The same feature is confirmed in our analysis (although we fit this noise component with an exponentially cut off power law). The integrated powers for the continuum in the 2–80 mHz range are 14%, 5%, 16%, and 11% ± 5%, respectively, for regions A+B, A, and B. Assuming that only one of the sources produces the continuum noise, we require an rms amplitude of 17% ± 5%, 17% ± 6%, and 14% ± 7% from X41.4+60, or 87% ± 25%, 267% ± 100%, and 46% ± 21% from X42.3+59, to produce the detected continuum noise in regions A+B, A, and B, respectively. Because the errors are large, we cannot completely rule out X42.3+59 as the origin of the continuum noise. However, it appears that X41.4+60 is more likely to be the origin of the continuum power.

### 3.2. X41.4+60

It is of interest to use the detected QPO frequencies to attempt to constrain the mass of the compact object in X41.4+60. Provided the QPO frequency is limited by the Keplerian frequency at the innermost stable circular orbit around a Schwarzschild black hole, the compact object mass of X41.4+60 is constrained to be less than $3 \times 10^8 M_\odot$ according to the maximum QPO frequency of 190 mHz that has been reported in Kaaret et al. (2006). This clearly rules out X41.4+60 being a supermassive black hole.

The centroid of low-frequency QPOs in Galactic black holes varies in a large range, e.g., $10^{-2}$ to 10 Hz for GRS 1915+105 (Morgan et al. 1997). Therefore, it is difficult to derive the

![Fig. 5.—7 year light curve of X42.3+59 observed with XMM-Newton MOS, Chandra ACIS, or Chandra HRC. The left axis indicates the 2–10 keV unabsorbed flux, and the right axis is the corresponding luminosity at a distance of 3.63 Mpc.](image-url)
compact object mass by simply scaling the QPO frequency to mass between ULXs and Galactic black holes. One must instead determine whether the QPO frequency correlates with another observable, such as the luminosity or spectral state, which would enable one to correct for the intrinsic frequency variations.

The X41.4+60 QPO in the second XMM-Newton observation is analogous to the “type C” QPO as defined by Remillard et al. (2002): appearing with a flat-top PSD and high amplitude. The QPO in the first XMM-Newton observation is also of type C, which has a high amplitude. A positive correlation between the QPO frequency and disk/power-law flux has been found for type C QPOs in some stellar mass black hole binaries, such as XTE J1550−564 and GRS 1915+105 (Sobczak et al. 2000a; Reig et al. 2000; Remillard & McClintock 2006). We note that GRO J1655−40 displayed a negative correlation between the QPO frequency and the power-law flux (Sobczak et al. 2000a). However, those QPOs have relatively small amplitudes, and factors are likely not of type C (Remillard et al. 1999). We obtained timing and spectral data for two Galactic sources: XTE J550−564 from Sobczak et al. (2000a, 2000b) and GRS 1915+105 from Vignarca et al. (2003). For XTE J550−564, we consider only QPOs with amplitudes >13% to include only type C QPOs. The QPO frequency versus 2−10 keV luminosity is presented in Figure 6. For comparison, we plotted the data for X41.4+60. We include an uncertainty of 25% on the XMM-Newton luminosities for X41.4+60 to account for uncertainties in the conversion from XMM-Newton count rates to luminosities due to the lack of knowledge of the spectrum. The two observations weakly suggest a similar positive correlation between the QPO frequency and the source flux (power-law flux). However, due to the significant uncertainty in the luminosities extracted from the XMM-Newton data and the fact that there are only two data points, any conclusions must be regarded as tentative. We also plotted one data point for the ULX NGC 5408 X-1, which is the second ULX found to produce QPOs, in this case near 20 mHz (Strohmayer et al. 2007). The QPOs detected from NGC 5408 X-1 are also of type C.

GRS 1915+105 is slightly more massive than XTE J1550−564, and its luminosity at a given QPO frequency is slightly higher than XTE J1550−564. If the frequency versus luminosity pattern does indeed scale with the mass of the compact object, then the data in Figure 6 would indicate that X41.4+60 and NGC 5408 X-1 are IMBHs. Although the sample of QPO detections for the ULXs is not large enough to derive the black hole mass accurately, we can see in Figure 6 that the pattern for X41.4+60 is shifted by a factor of 100−500 in luminosity relative to that of the Galactic black holes, indicating a black hole mass of around $10^3 M_{\odot}$. More observations of both ULXs are required to check if the QPO frequency robustly follows a correlation with luminosity similar to that seen from Galactic stellar mass black hole X-ray binaries.

Correlations between the QPO and the power-law photon index have been observed in several Galactic black holes (Sobczak et al. 2000a; Vignarca et al. 2003). Titarchuk & Fiorito (2004) have suggested that the QPO frequency scales inversely with the mass of the compact object at a fixed power-law photon index. Unfortunately, it is difficult to accurately measure the photon index for X41.4+60 or X42.3+59 with XMM-Newton due to the large overlap between their PSFs. This prevents us from making a quantitative comparison with the relations seen for stellar mass black hole X-ray binaries. It would be of interest to conduct simultaneous XMM-Newton and Chandra observations in order to derive timing information from XMM-Newton simultaneously with spectral information from Chandra, in order to study the QPO frequency versus spectral index correlation for X41.4+60. A combined spectral/timing analysis of the behavior of X41.4+60 would likely provide the most robust estimate of compact object mass. The same observations could also greatly improve the uncertainty in luminosity and thus provide a test of the putative QPO frequency versus luminosity correlation discussed above.

The low-frequency break (from slope 0 to −1) in the PSD is tightly correlated with the QPO frequency (Wijnands & van der Klis 1999). We note that the 34 mHz break frequency found in M82 X-1 (plausibly from X41.4+60) and the 133 mHz QPO frequency are consistent with this correlation. The break frequency in the PSD has been thought to be correlated with the mass of the compact object (e.g., Markowitz et al. 2003). Comparing to Cygnus X-1, which has a low-frequency break varying between 0.02 and 0.4 Hz (Belloni & Hasinger 1990; Nowak et al. 1999), the compact object mass of X41.4+60 would be constrained to be between 6 and 120 $M_{\odot}$, assuming a mass of 10 $M_{\odot}$ for Cygnus X-1 (Herrero et al. 1995). We note that the estimated mass is lower than that inferred from isotropic emission under the Eddington limit, or the QPO frequency-luminosity correlation discussed above. Again, we emphasize the importance of obtaining multiple observations simultaneously with Chandra and XMM-Newton in order to study the correlations between spectral and timing properties, which could lead to a robust estimate of the compact object mass.

3.3. X42.3+59

The 7 year light curve of X42.3+59 (see Fig. 5) shows that the ULX is highly variable. The peak luminosity implies the compact object mass is at least 200 $M_{\odot}$, assuming isotropic emission. The ratio of the maximum to minimum observed flux is at least 1000.

The huge variability of X42.3+59 could be a natural consequence of a relativistic jet aimed along our line of sight—a
so-called microblazar. X42.3+59 is coincident with the radio source 42.21+59.0 (Muxlow et al. 1994). However, the radio counterpart presents a thermal spectrum instead of a synchrotron spectrum (Muxlow et al. 1994; McDonald et al. 2002), shows little if any variability on long timescales (Kronberg et al. 2000), and has a spatial extent of 4.9 pc (McDonald et al. 2002). These results indicate that X42.3+59 is not relativistic jet emission.

Kalogera et al. (2004) suggested an observational test to distinguish whether ULXs are stellar mass objects with beamed emission or IMBHs. The former are likely to arise as thermal timescale mass transfer binaries, in which the high mass accretion rates lead to thick accretion disks causing geometrically beamed emission. Thermal timescale mass transfer generally produces stable disks and persistent X-ray emission. X-ray binaries are transient when the disk temperature at the outer edge is below the hydrogen ionization temperature. This requires an average mass transfer rate below a critical value. As first shown by King et al. (1996), this implies that the black hole mass must be above a minimum set by the companion star mass and the orbital period. Transient behavior with a massive companion star likely requires an IMBH.

Unfortunately, the nature of the X42.3+59 binary is unknown. Identification of the spectral type of the companion star and measurement of the orbital period, together with the knowledge that the system is an X-ray transient, could be used to place direct constraints on the mass of the compact object. X42.3+59 is thought to be associated with an H ii region (Muxlow et al. 1994) that is full of young, hot stars. Simulations (Figs. 1 and 2 in Kalogera et al. 2004) show that if the companion was initially a 10–20 $M_\odot$ star, then transient behavior, such as that observed, likely requires an IMBH.

From the light curve in Figure 5, it seems that X42.3+59 has just completed an outburst that lasted about 6 years. This outburst duration is longer than that typically seen from Galactic soft X-ray transients, but could be similar to the current outburst of the transient GRS 1915+105. Given an accretion rate ($\dot{M}$) and donor mass ($M_2$), and according to equation (2) of Kalogera et al. (2004), an IMBH ($>20 M_\odot$) is required for a transient system if the binary period is less than a threshold value

$$P_{\text{trans}} \approx 2.4 \text{yr} \left(\frac{M}{10^{-4} M_\odot} \text{yr}^{-1}\right)^{1/4} \left(\frac{M_2}{10 M_\odot}\right)^{1/7}. \quad (1)$$

The average accretion rate $\dot{M}$ can be estimated from the outburst luminosity $L_{\text{out}}$ assuming an outburst duty cycle $d$ and an accretion power efficiency $\epsilon$ as $\dot{M} = dL_{\text{out}}/(\epsilon c^2)$. We can thus rewrite the equation above as

$$P_{\text{trans}} \approx 6.8 \text{ days} \left[\frac{dL_{\text{out}}}{(10^{46} \text{ ergs s}^{-1})}\right]^{1/4} \left(\frac{M_2}{10 M_\odot}\right)^{1/7}. \quad (2)$$

From Figure 5, the outburst luminosity of X42.3+59 is about $10^{46}$ ergs s$^{-1}$. Assuming $d = 0.1$ and $\epsilon = 0.1$, then $\dot{M} \approx 1.8 \times 10^{-7} M_\odot$ yr$^{-1}$. If the companion mass $M_2 \geq 1 M_\odot$, then the threshold period for transient behavior for a black hole mass larger than $20 M_\odot$ is 6.8 days. The threshold period depends very weakly on the companion mass. Measurement of the orbital period of X42.3+59 should enable us to place a lower bound on the compact object mass.

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