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A 2 HOUR QUASI PERIOD IN AN ULTRALUMINOUS X-RAY SOURCE IN NGC 628

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ABSTRACT

Quasi-periodic oscillations and X-ray spectroscopy are powerful probes of black hole masses and accretion disks, and here we apply these diagnostics to an ultraluminous X-ray source (ULX) in the spiral galaxy NGC 628 (M74). This object was observed four times over 2 years with the *Chandra X-Ray Observatory* and *XMM-Newton*, with three long observations showing dramatic variability, distinguished by a series of outbursts with a quasi period of 4000–7000 s. This is unique behavior among ULXs and Galactic X-ray binaries because of the combination of its burstlike peaks and deep troughs, its long quasi periods, its high variation amplitudes of >90%, and its substantial variability between observations. The X-ray spectra is fitted by an absorbed accretion disk plus a power-law component, suggesting the ULX was in a spectral state analogous to the low/hard state or the very high state of Galactic black hole X-ray binaries. A black hole mass of $\sim(2\text{–}20) \times 10^3\ M_\odot$ is estimated from the f_b-$M_\bullet$ scaling relation found in the Galactic X-ray binaries and active galactic nuclei.

Subject headings: galaxies: individual (NGC 628) — X-rays: binaries

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs), found in many nearby galaxies by *Einstein*, by *ROSAT*, and recently by *Chandra* and *XMM*, are nonnuclear X-ray point sources with X-ray luminosities in the range of 10^{39}–10^{41} ergs s^{-1} (e.g., Colbert & Mushotzky 1999). If ULXs emit at the Eddington limit, such luminosities imply black holes (BHs) of masses 10–1000 $M_\odot$, or 100–10,000 $M_\odot$ if the sources emit at the 10% level of the Eddington luminosity. Such intermediate-mass black holes (IMBHs) can naturally explain the observed high luminosities and, if they exist, bridge the gap between stellar mass BHs ($\sim 10^1\ M_\odot$) and supermassive BHs (10^6–$10^9\ M_\odot$) in the center of galaxies. However, such IMBHs are not predicted to be the products of ordinary stellar evolution models, and it is still in debate whether they can form in dense stellar fields via runaway stellar collisions with seed BHs of a few hundred solar masses (e.g., Portegies Zwart & McMillan 2002). Alternatively, these sources can be stellar mass BHs, for which the formation is well established in theory and observation. Special mechanisms are required for these stellar mass BHs to emit at super-Eddington luminosities. Such a mechanism could be extreme relativistic beaming (e.g., Georganopoulos et al. 2002), mild geometric beaming (e.g., King et al. 2001), or the photon-bubble instability in a radiation pressure–dominated accretion disk, which leads to truly super-Eddington luminosities (Begelman 2002).

X-ray timing and spectral analyses have been widely used to study Galactic X-ray binaries. Combined with X-ray spectroscopy, rapid variability provides direct information on the compact object and the accretion disk, the site of X-ray emission. Most Galactic X-ray binaries show variability characterized as periodic variations, quasi-periodic oscillations (QPOs), and low-frequency noise on timescales from 10^{-4} s to years. They emit in well-defined spectral states, including the very high (VH) state, the high/soft state, the low/hard (LH) state, and the quiescent state (e.g., Lewin et al. 1995 and references therein). In comparison, ULXs are less variable on short timescales. Swartz et al. (2004) found in a recent *Chandra* survey that only 5%–15% of the ULXs showed significant variability during their *Chandra* exposures. In another *Chandra* survey, Roberts et al. (2004) detected only short-term flux variability in one of the two epochs for two out of the eight ULXs in their survey.

Periodic variations and quasi-periodic oscillations are powerful probes of the orbit motion and the BH–accretion disk interaction but have been detected only for a few ULXs so far. A ULX in IC 342 showed small-amplitude (5%) periodic variations on a timescale of 30–40 hr in a 155 hr *ASCA* observation (Sugiho et al. 2001). A ULX in the Circinus galaxy showed X-ray eclipses and a period of 7.5 hr, although it is possibly a foreground interloper in our Galaxy, given its proximity to the Galactic plane and the similarity to a long-period AM Her system (Bauer et al. 2001). A ULX in M51 showed ~70% variations in a smooth sinusoidal light curve with a period of 7620 ± 500 s in a 15 ks *Chandra* observation (Liu et al. 2002), while in another 27 ks observation, the luminosity dropped by a factor of 50 and there were too few counts to verify this periodicity. From *XMM* and *Rossi X-Ray Timing Explorer* observations of a ULX in M82, Strohmayer & Mushotzky (2003) discovered a narrow QPO of 54.4 ± 0.9 mHz (~18 s) with an rms amplitude of 8.4%, which suggests a geometrically thin accretion flow and argues against substantial beaming. Soria et al. (2004) found that the light curve of a ULX in NGC 5408 showed flares of amplitude of ~30% at a quasi period of a few hundred seconds, which they attributed to variability in the power-law component of the emission. A ULX in the colliding galaxy NGC 7714 showed medium-amplitude (~30%) periodic variations on a timescale of 2 hr in a 15 ks *XMM* observation when it was in a high/hard state with $L_X = 6.6 \times 10^{40}$ ergs s^{-1}, while such a period was not detected in an earlier *XMM* observation when it was in a low/soft state with $L_X = 4.4 \times 10^{40}$ ergs s^{-1} (Soria & Motch 2004).

A ULX in NGC 628 (M74), CXOU J013651.1+154547, was found to be extremely variable with unique quasi-periodic variation patterns in recent *Chandra* and *XMM* observations (Krauss et al. 2003). This source is located in a bubble nebula on a spiral arm of NGC 628, a face-on Sc spiral galaxy with a Galactic latitude of −45° at a distance of 9.7 Mpc; it is most likely in NGC 628, given the association with the nebula and absence of bright foreground objects or known active galactic nuclei (AGNs)/QSOs in the vicinity. In this Letter, we analyze two *Chandra* observations and two *XMM* observations available in the archive and report its spectral and timing properties

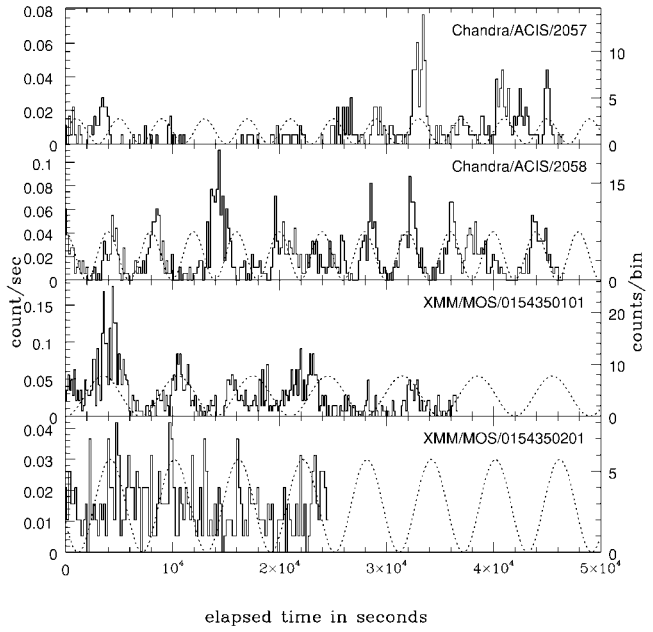


FIG. 1.—Light curves for CXOU J013651.1+154547 in four observations. Overplotted for comparison are sinusoidal curves with the periods of 4000/4000/7000/6000 s, respectively.

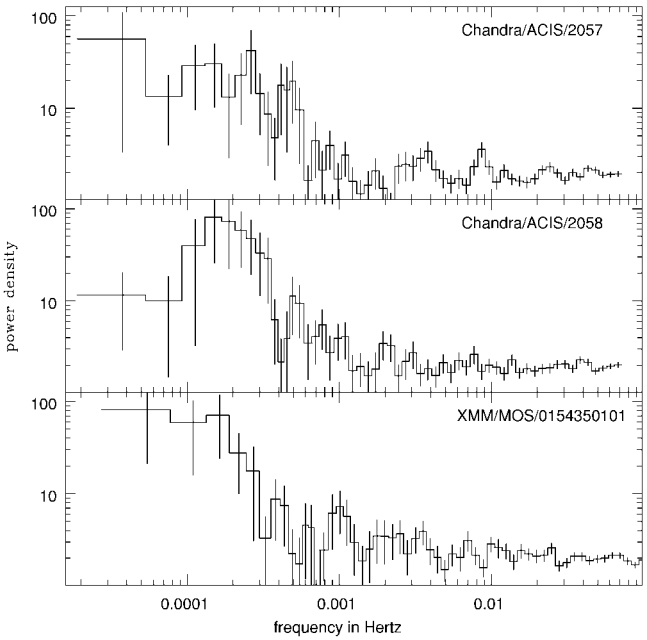


FIG. 2.—PDSs calculated with the Fourier transform for CXOU J013651.1+154547 in the first three observations. A broad peak around (1–4) × 10^{-4} Hz is clearly present in the second *Chandra* observation, which can be interpreted as a QPO.

in § 2. A discussion on the QPOs and the BH mass is presented in § 3.

2. DATA ANALYSIS AND RESULTS

There are four X-ray observations in the archive for the ULX, including two *Chandra* ACIS observations, on 2001 June 19 (observation ID [ObsID] 2057, 46.3 ks) and 2001 October 19 (ObsID 2058, 46.3 ks), and two *XMM* EPIC observations, on 2002 February 2 (ObsID 0154350101, 36.9 ks) and 2003 January 7 (ObsID 0154350201, 24.9 ks). To extract spectra and event lists for the ULX, we used CIAO 2.3 and CALDB 2.20 for the *Chandra* data and SAS 6.0.0 for the *XMM* data.

The event lists for the ULXs were extracted from the observations for timing analysis. For *Chandra* observations, we used the 3 σ source region enclosing 95% of the source photons computed by WAVDETECT. In two *XMM* EPIC observations, the ULX fell into the chip gap on the pn, so only MOS observations were used for analysis. The events were extracted from a source circle of 25″.6 enclosing ~90% of the source photons, within which no other point sources are detected in two *Chandra* observations. To estimate the background photon counts in the source regions, we extracted the events in a nearby region similar in shape but offset from any point sources. It was found that the background counts are less than 3% of the total counts for *Chandra* observations and 34% (30%) for the first (second) *XMM* observation. The light curves for the four observations are shown in Figure 1.

Some distinct features of the light curves are immediately obvious in Figure 1. The burstlike peaks and deep troughs alternate quasi-periodically in the first three observations; the signal is too weak to see such features in the fourth observation. The changes in fluxes are violent on timescales of hours. In ObsID 2057, there was a period of 5 ks without any photons detected, preceded by a decrease in count rates and followed by an increase that leads to a large burst. The average count rate is 7.5 (20.6) ACIS counts ks^{-1} for the first (second) *Chandra* observation and 27.1 (15.0) MOS counts ks^{-1} for the third (fourth) *XMM* observation. The standard deviations from the average count rates are 11.2/19.8/28.3/12.8 counts ks^{-1}, respectively, indicating variation amplitudes of 90% or higher.

To study the quasi periodicity for the ULX, the power-density spectra (PDSs) were calculated with XRONOS 5.19 (Fig. 2) for the first three observations. The PDS for ObsID 2057 shows a peak indicative of a QPO around $f \sim 2.5 \times 10^{-4}$ Hz, which appears as a hump in an otherwise declining power law ($f^{-\alpha}$ with $\alpha \sim 1$). This PDS resembles that of a Galactic BH binary in its VH state or steep power-law state as described by McClintock & Remillard (2005). However, because of the large errors and low resolution at low frequencies, this PDS also could be viewed as a flat-top spectrum at low frequencies that breaks into a declining power law with $\alpha \sim 1.5$ around $f_b \sim 2.5 \times 10^{-4}$ Hz, thus resembling that of a BH binary in its LH state or the *hard* state (McClintock & Remillard 2005). The PDS for ObsID 2058 shows a significant broad peak that is more clearly interpreted as a QPO within the frequency range of (1–4) × 10^{-4} Hz. The PDS for the first *XMM* observation is similar to that of a BH binary in its LH state, with a break frequency (i.e., QPO frequency) around $f \sim 1.5 \times 10^{-4}$ Hz and a declining power law with $\alpha \sim 1.2$.

A wavelet technique (e.g., Torrence & Compo 1998; Hughes et al. 1998) is used to search for the quasi periods for the QPOs and has certain advantages over the Fourier approach. The conventional Fourier transform may not work well to reveal quasi-periodic signals at low frequencies, because the power associated with the data's window can appear at low frequencies, and nonperiodic outbursts will spread power across the spectrum. In comparison, the wavelet analysis studies the behavior of the signal on different timescales as a function of time and preserves the temporal locality of the signal. The global power spectra calculated from summing up the power spectra at all times are shown in the period space to facilitate the search (Fig. 3). To assess the significance of a quasi period in the global power spectrum of a signal, its power is compared

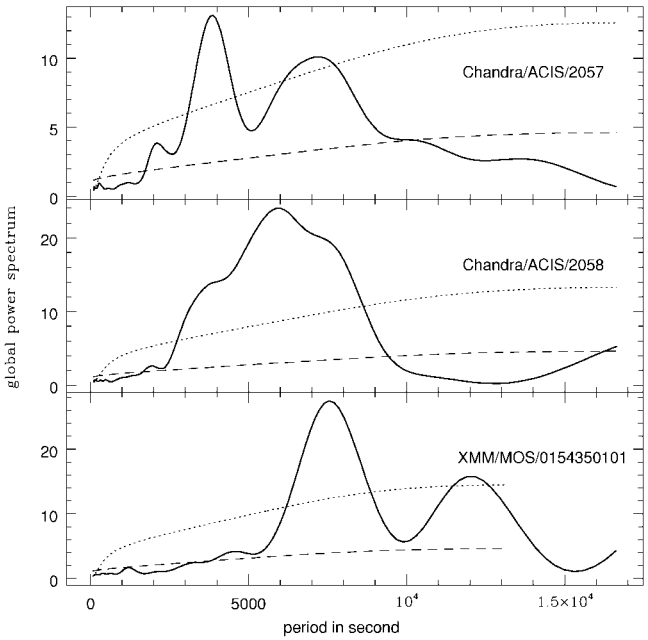


FIG. 3.—Global power spectra calculated with a wavelet technique for CXOU J013651.1+154547. The dotted (dashed) line indicates the significance level at which the power of a (quasi) periodic signal is above 99% of the random realizations of a red (white) noise process. Above the 99% significance level of a red noise process are quasi periods at ~4000 and ~7000 s in the first observation, quasi periods at ~4000, ~6000, and ~7000 s blended together in the second observation, and quasi periods at ~7000 and ~12,000 s in the third observation. The 7 ks quasi period can be seen in all three observations.

to the distribution of the power spectra of both white and red noise random processes at that timescale (Torrence & Compo 1998). Three quasi periods at ~4, ~6, and ~7 ks are found in the first three observations above the 99% significance level; i.e., the powers at the quasi periods are higher than 99% of the red noise random processes. The quasi period at ~7 ks (i.e., 2 hr) was present in all three observations.

The spectra for the first three observations were fitted with three models: the power-law model (i.e., wabs+powerlaw), the multicolor disk model (i.e., wabs+diskbb), and the disk plus power-law model (i.e., wabs+diskbb+powerlaw) using XSPEC 11.2.0; no spectrum was fitted for the fourth observation owing to problems with the observational data file. The spectra were binned to a minimum of 15 photons per bin and fitted in the 0.3–8 keV band (Table 1). The best model for both *Chandra* observations is the disk plus power-law model. Despite the flux change by a factor of ~3, the two spectra are strikingly similar, with similar model parameters (i.e., the same disk temperature of ~0.2 keV and the same power-law photon index of ~1.5) and similar fractional fluxes from the disk component ($\sim\frac{1}{4}$) and the power-law component ($\sim\frac{3}{4}$). The spectral decomposition suggests the ULX might be in a spectral state analogous to the LH state of Galactic BH binaries or the VH state, given the presence of low-frequency QPOs and the power-law photon index up to ~2.2 allowed by the fitting errors. The power-law models are also acceptable for two *Chandra* observations, with a similar best-fit column density and photon index (~2.2). Three emission lines in two *Chandra* observations were detected at ~2 σ significance levels, and the details will be studied in a future work. For the combined MOS spectrum in the third observation, the disk plus power-law model is unphysical since the power-law component increases with photon energy ($\Gamma \sim -2.5$); the power-law model is acceptable and has the same model parameters as in two *Chandra* observations within the errors.

For ObsID 2058, two separate spectra for the high- and low-flux states, 2058-H and 2058-L, are extracted from the time intervals above and below 20 counts ks^{-1}, a sensible but non-unique division point. The two spectra sample the photons in the bursts and troughs, respectively, and are fitted with the three models as above. Both the power-law model and the disk plus power-law model are acceptable for these two spectra; in both models, the parameters (column density, photon index, and disk temperature) for the high-flux spectrum are the same as those for the low-flux spectrum. Such a similarity between these two spectra is expected only if the QPOs are present in both the disk component and the power-law component of the X-ray emission. In accordance to this implication, the QPOs with similar variation amplitudes are seen in the light curves of low-energy photons (<1 keV, dominated by the disk component) and high-energy photons (>1 keV, dominated by the power-law component).

3. DISCUSSION

QPOs are seen in the X-ray observations for CXOU J013651.1+154547, one of the four ULXs with possible QPOs. The quasi periodicity is directly visible in the light curves, and it is present in observations spanning 2 yr with flux changes of a factor of 3. This is verified by the timing analysis with two different techniques, which have revealed significant QPOs as peaks and/or breaks in the PDSs. Quasi periods of ~4–7 ks

TABLE 1
SPECTRAL FITS FOR CXOU J013651.1+154547

Spectrum	Model	$N_{\rm H}$ (10^{20} cm^{-2})	Γ	$kT_{\rm in}$ (keV)	χ^2_ν/dof	Probability (%)	$L_{\rm X}$(0.3–8) (10^{38} ergs s^{-1})	$L_{\rm diskbb}$(0.3–8) (10^{38} ergs s^{-1})	$L_{\rm pl}$(0.3–8) (10^{38} ergs s^{-1})
ACIS2057	wabs(pl)	6.4 ± 4.6	2.4 ± 0.3	...	0.87/50	73.4	3.8	...	3.8
	wabs(diskbb)	0.0 ± 100	...	0.46 ± 0.03	1.12/50	26.5	2.8	2.8	...
	wabs(pl+diskbb)	8.8 ± 10.4	1.5 ± 0.7	0.21 ± 0.08	0.81/48	82.7	4.5	1.3	3.2
ACIS2058	wabs(pl)	6.2 ± 2.2	2.2 ± 0.1	...	1.10/109	22.3	11.6	...	11.6
	wabs(diskbb)	0 ± 100	...	0.64 ± 0.03	1.53/109	0	8.4	8.4	...
	wabs(pl+diskbb)	7.2 ± 4.6	1.4 ± 0.4	0.24 ± 0.05	1.04/107	36.4	13.4	3.3	10.1
2058-H	wabs(pl)	15.8 ± 3.2	2.1 ± 0.2	...	0.92/86	67.6	21.4	...	21.4
	wabs(diskbb)	2.9 ± 1.7	...	0.93 ± 0.09	1.11/86	22.7	17.8	17.8	...
	wabs(diskbb+pl)	28.7 ± 13.8	1.8 ± 0.3	0.16 ± 0.03	0.88/84	78	23.4	3.3	20.1
2058-L	wabs(pl)	9.6 ± 4.4	2.3 ± 0.3	...	1.21/43	16.7	3.8	...	3.8
	wabs(diskbb)	0 ± 5.3	...	0.74 ± 0.10	1.44/43	3.0	3.2	3.2	...
	wabs(pl+diskbb)	9.1 ± 9.1	1.7 ± 0.9	0.25 ± 0.13	1.22/41	15.1	4.2	0.9	3.2
0154350101	wabs(pl)	14.3 ± 8.9	2.1 ± 0.4	...	1.01/35	45.7	4.6	...	4.6
	wabs(diskbb)	0 ± 11.3	...	0.91 ± 0.17	1.00/35	46.7	3.9	3.9	...
	wabs(diskbb+pl)	0 ± 100	−2.5 ± 100	0.86 ± 0.39	1.06/33	38.1	5.3	3.8	1.5

are found from the observations, most evident with a wavelet decomposition technique. In both *Chandra* observations, the X-ray spectra are best fitted with a multicolor disk plus a power-law component with similar parameters, in which the disk components ($T_{\rm in} \sim 0.2$ keV) dominate the soft band and contribute ~25% of the total flux, while the power-law components dominate the hard band and contribute ~75% of the total flux. This spectral shape, combined with the presence of low-frequency QPOs, suggests the ULX was in a spectral state analogous to the LH state or the VH state of Galactic BH binaries.

While QPOs of $\sim 10^3$ s occasionally occur in GRS 195+105 (e.g., Greiner et al. 1996), the QPO for CXOU J013651.1+154547 is unique among ULXs and Galactic BH binaries for the combination of its burstlike peaks and deep troughs, its long quasi periods, and its extreme variability. The light curves of CXOU J013651.1+154547 exhibit substantial variability from quasi period to quasi period. Within a quasi period of about 2 hr, the troughs are usually 10%–20% of the average flux or lower, and the peaks are up to 5 times the average flux, reaching $\sim 5 \times 10^{39}$ ergs s^{-1}. In comparison, QPOs for other ULXs and Galactic X-ray binaries usually have smooth (sometimes sinusoidal) quasi-periodic patterns and rms amplitudes of a few percent reaching up to 30% only in rare occasions. The QPOs are present in both the accretion disk component and the power-law component. As a comparison, the QPOs for a ULX in NGC 5408 with a quasi period of a few hundred seconds are significant only in the hard power-law component (Soria et al. 2004).

The BH mass can be estimated with the f_b-$M_\bullet$ scaling relation if the QPOs originate from the accretion disk, as for Galactic X-ray binaries. The scaling relation between the QPO frequency and the BH mass has been found to exist in Galactic BH X-ray binaries and AGNs, albeit with large uncertainties in the calibration (e.g., Belloni & Hasinger 1990; Markowitz et al. 2003). The PDS for CXOU J013651.1+154547 is comparable to that of Cygnus X-1 (~10 $M_\odot$), which at low frequencies exhibits a flat top that breaks at f_{b1} of 0.04–0.4 Hz into a declining power law with slope ~ -1 that breaks again at f_{b2} of a few hertz into a steeper power law with slope ~ -2. If the observed QPO frequency $\sim 2 \times 10^{-4}$ Hz corresponds to f_{b1}, as suggested by the PDS shape, the BH mass is estimated as $\sim (2\text{–}20) \times 10^3\ M_\odot$. The BH mass would be $\sim 10^5\ M_\odot$ if the QPO frequency corresponds to f_{b2}, as is possible owing to the uncertainties in the PDSs of these short observations. The above mass estimates are not conclusive, since the low-frequency QPOs occur at different locations of the accretion disk for different accretion rates; thus, their frequencies are not determined only by the BH mass. This mass estimate is different from the mass estimated from its luminosities ($\leq 100\ M_\odot$) if the system emits isotropically at above 10% of the Eddington limit, as indicated by the emission state possibly analogous to the VH state in Galactic BH binaries.

More convincing and stringent mass estimates can be made with high-frequency QPOs, especially the 3 : 2 twin-peak QPOs that appear as kilohertz QPOs in Galactic X-ray binaries. This 3 : 2 twin-peak QPO is thought to occur at a specific resonance radius in the inner region of the accretion disk that is fixed in terms of the gravitational radius of the BH. Thus, its frequency is expected to scale with the BH mass. Abramowicz et al. (2004) advanced a stringent scaling relation $f = 2.8/M_\bullet$ kHz for such QPOs, which is verified in three microquasars and the central BH of our Galaxy, Sgr A*. If the 3 : 2 twin-peak QPO is to occur in the NGC 628 ULX, we expect a frequency of ~0.3 Hz, given the BH mass of $\sim 10^4\ M_\odot$ as inferred from the observed low-frequency QPOs. However, to verify such a QPO would require a lengthy observation and the object would need to be brighter than usual.

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