The kilosecond variability of X-ray sources in nearby galaxies

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Abstract *Chandra* observations of 17 nearby galaxies were analyzed and 166 bright sources with X-ray counts > 100 were chosen for temporal analysis. Fractional root mean square (rms) variability amplitudes were estimated for light curves, binned at ~ 4 kilosecond (ks), with length ~ 40 ks. While there are nine ultra-luminous X-ray sources (ULXs) with unabsorbed luminosity (in the 0.3–8.0 keV band) $L > 10^{39}$ erg s^{-1} in the sample for which the fractional rms variability is constrained to be $< 10\%$, only two of them show variability. One of the variable ULXs exhibits a secular transition and has an ultra-soft spectrum with temperature ~ 0.3 keV while the other is a rapidly varying source in NGC 0628, which has previously been compared to the Galactic microquasar GRS 1915+105. These results seem to indicate that ULXs are typically not highly variable on ks timescales, except for some ultra-soft ones. Among the relatively low luminosity sources ($L \sim 10^{38}$ erg s^{-1}), we find five of them to be variable. Apart from an earlier known source in NGC 1569, we identify a source in NGC 2403 that exhibits persistent high amplitude fluctuations. In general, the variability of the sources does not seem to be correlated with hardness, which indicates that they may not be due to variations in any absorbing material, but instead could reflect instabilities in the inner accretion disk.

Key words: galaxies: general — X-rays: binaries

1 INTRODUCTION

The unprecedented angular resolution of *Chandra* allows for the detailed study of X-ray point sources in nearby galaxies. Most of these sources are expected to be X-ray binaries harboring neutron stars or black holes, similar to the ones found in our Galaxy. Some of these sources have an isotropic luminosity exceeding $> 10^{39}$ erg s^{-1} and are called Ultra-Luminous X-ray sources (ULXs). Since these sources emit radiation at a rate larger than the Eddington limit for a ten-solar mass black hole, they may be harboring black holes with mass $10\,M_\odot < M < 10^5\,M_\odot$ (Colbert & Mushotzky 1999; Makishima et al. 2000) where the upper limit is constrained by the argument that a more massive black hole would have settled into the nucleus due to dynamical friction (Kaaret et al. 2001). In this interpretation, these black holes have mass in the intermediate mass range between those of stellar mass black holes found in Galactic X-ray binaries and those associated with active galactic nuclei (AGN), and hence are called intermediate mass black holes (IMBHs). Alternatively, if these sources are powered by stellar mass black holes which are radiating at a super Eddington level (Begelman

2002; King 2008), this would imply that their accretion state is significantly different than that of AGN and X-ray binaries. The process by which such black holes are created (Taniguchi et al. 2000; Madau & Rees 2001; Portegies Zwart & McMillan 2002) and their environment which allows such sustained high accretion rates (King et al. 2001) are largely unknown and understanding them may lead to radical shifts in the present paradigms of stellar and binary evolution and the history of the Universe. For a review of their observational properties and implications see Miller et al. (2004); Miller (2005); Feng & Soria (2011).

While there have been several extensive analyses of individual ULXs (e.g., Feng & Kaaret 2005, 2006; Miller et al. 2004; Devi et al. 2008; Dewangan et al. 2005, 2006b; Agrawal & Misra 2006), it is also important to undertake systematic spectral and temporal analysis of ULXs and other lower luminosity sources to bring out any systematic differences between the two. Lower luminosity sources ($L_{\rm X} \sim 10^{38}$ erg s^{-1}) are expected to be similar to typical Galactic black hole systems. Galactic black hole systems show variability on short timescales of ~ 10 Hz (e.g., Nowak et al. 1999) and long term ($\sim$ months) variations which are usually associated with spectral state transitions (e.g., Zdziarski & Gierliński 2004; Remillard & McClintock 2006, for a review). In the "Hard" state, the spectrum is dominated by a power-law, often modeled to be thermal Comptonization, while in the "Soft "state, it is a thermal one arising from a multi-color disk. X-ray binaries show long term ($>$ days) variability from super-orbital modulations (Kotze & Charles 2012) and aperiodic behavior (Gilfanov & Arefiev 2005). On timescales of hours, Galactic black hole systems typically do not seem to show large, persistent variability, with the exceptions of the microquasar GRS 1915+105 (Mirabel & Rodríguez 1994) and the recently discovered source IGR J17091–3624 (Altamirano et al. 2011). Occasional flares or large amplitude variations on minute timescales have been reported for some systems like V4641 Sgr (Maitra & Bailyn 2006).

Systematic spectral studies of a sample of sources have also been undertaken to uncover differences between ULXs and less luminous sources. Swartz et al. (2004) fitted the spectra of such a large sample with an absorbed power-law model and found no bimodal distribution for the spectral index. However, using a disk blackbody model, a bimodal distribution was revealed at least for sources with very high luminosity ($> 10^{40}$ erg s^{-1}) in the samples obtained from *XMM-Newton* (Winter et al. 2006) and *Chandra* (Devi et al. 2007). One set of high luminosity sources has temperatures of $kT \sim 0.1$ keV while the other one has systematically higher temperatures of $kT \sim 1$ keV. It is not clear whether they represent two kinds of sources or are two spectral states of a generic type. Such a bimodal distribution is not evident for low luminosity sources ($\sim 10^{38}$ erg s^{-1}). The hard sources are dominated by an optically thick Comptonized component while the soft ones are compatible with being emission from accretion disks around an IMBH accreting matter at ~ 0.1 times the Eddington limit (Devi et al. 2007). However, Gladstone et al. (2009) argue that detailed X-ray spectral analysis of bright sources does not favor an IMBH interpretation.

An important aspect of ULXs is that they are generally variable on a wide range of timescales. For a review of the time variability of X-ray sources in nearby galaxies see Fabbiano (2006). Nearly half of the X-ray sources in M31 (Kong et al. 2002), M82 (Chiang & Kong 2011), the Antennae galaxies (Zezas et al. 2006), NGC 6946 and NGC 4485/4495 (Fridriksson et al. 2008) are variable on timescales of weeks to months. ULXs seem to be more variable as 12 of 14 sources in the Antennae galaxies show long term variability. These cases of long term variability are sometimes associated with changes in the spectral state (Colbert & Mushotzky 1999; Kubota et al. 2001; Dewangan et al. 2004; Feng & Kaaret 2006, 2009; Gladstone & Roberts 2009; Kajava & Poutanen 2009; Dewangan et al. 2010). Although rapid variability (on ~ 100 s timescales) are difficult to detect in low count rate sources, quasi-periodic oscillations have been reported from the bright ULXs – M82 X-1 (Strohmayer & Mushotzky 2003; Dewangan et al. 2006a; Feng et al. 2010) at 54 and 114 mHz, Holmberg IX X-1 at 202 mHz (Dewangan et al. 2006b) and NGC 5408 X-1 at 20 mHz (Strohmayer et al. 2007; Strohmayer & Mushotzky 2009). These results provide strong evidence that the ULXs are not distant background AGN and the frequencies of oscillations suggest that they

Table 1 Properties of the Sample Galaxies

Galaxy	Distance (Mpc)	ObsID	T_{exp} (ks)	N (≥ 100)
NGC 0628	9.7	2058	46.16	5
NGC 0891	10.0	794	50.90	12
NGC 1291	8.9	795	39.16	6
NGC 1399	18.3	319	55.94	27
NGC 1569	2.2	782	96.75	11
NGC 2403	3.1	2014	35.59	2
NGC 3556	14.1	2025	59.36	14
NGC 3628	10.0	2039	57.96	9
NGC 4125	24.2	2071	64.23	6
NGC 4365	20.9	2015	40.42	3
NGC 4579	21.0	807	33.90	3
NGC 4631	7.6	797	59.21	6
NGC 4649	16.6	785	36.87	13
NGC 4697	11.8	784	39.25	8
NGC 5128	4.0	962	36.50	17
NGC 5775	26.7	2940	58.21	12
NGC 6946	5.5	1043	58.28	12

Notes: T_{exp}, exposure time in ks; N, number of point sources with net counts ≥ 100.

harbor IMBHs, although Middleton et al. (2011) also argue for a super-Eddington interpretation. Heil et al. (2009) studied the variability in the frequency range $10^{-3} - 1$ Hz for 16 ULXs using *XMM-Newton* observations. They found that while six sources show intrinsic variability, more interestingly they could constrain the variability of four sources to be significantly less than what is expected from black hole binaries and AGN. Like X-ray binaries, different spectral states of ULXs should be associated with different temporal behavior and this was shown to be the case for the bright ULX in NGC 1313, which was variable in the high flux state but not in the low one (Dewangan et al. 2010). A bright source in NGC 628 is known to have a rapid variability on short timescales of 1000 s (Krauss et al. 2005). This source is of particular interest because it could be an extragalactic example of the Galactic black hole system GRS 1915+105. Large amplitude variability on kilosecond (ks) timescales has also been reported from two X-ray sources in NGC 1569 (Heike et al. 2003).

The main aim of this work is to study and quantify the variability of a sample of *Chandra* detected X-ray sources in nearby galaxies on the timescale of ~ 10 ks. Given the faintness of these sources and *Chandra's* sensitivity we expect to detect only large amplitude variations. On these timescales, such large variability may be due to spectral state transitions and this study will help us identify sources which have undergone such transitions. While such transitions may be rare events, a 'snapshot' study of a large enough sample may shed light on how often they occur on these timescales, i.e. the number of such sources may provide an idea of the duty cycle of such events. On the other hand, the large amplitude variability could reflect persistent aperiodic/periodic behavior of the source. Finally, the study may reveal differences between regular X-ray sources and ULXs in terms of their ks variability properties.

2 OBSERVATIONS AND DATA ANALYSIS

Devi et al. (2007) have analyzed thirty galaxies observed by *Chandra*. They selected those sources with counts > 60 and whose spectra were not contaminated by excessive diffuse emission and not affected by photon pile up. For the timing analysis, we have chosen 17 of these galaxies that have an exposure time roughly equal to or greater than 40 ks. In order to obtain reasonable statistics we have limited our analysis to sources having net counts > 100. The names of these galaxies, the distances to them, the *Chandra* observation IDs and the number of sources used in this analysis are listed in Table 1. A total of 166 sources was chosen for temporal analysis.

The estimation of the unabsorbed luminosity of a source, in general, can depend on the specific spectral model used. Hence, Devi et al. (2007) fitted each source with two models, an absorbed power-law and an absorbed disk blackbody, and have tabulated the best fit spectral parameters. For some sources, one of the models provides a significantly better fit (with a C_{stat} difference greater than 2) and the unabsorbed luminosity of the source can then be estimated using the better fitting model. However, for extreme soft spectra which give the best photon index $\Gamma > 4$, we choose the disk blackbody representation, irrespective of the spectral fitting statistics. For cases when both spectral models provide similar fits to the data, we conservatively choose the lower of the unabsorbed luminosities estimated from the models. Throughout this work, unless otherwise specified, we have used the above criterion to estimate the unabsorbed luminosity of the sources.

For each source, background subtracted light curves were generated with a time bin size of $4\,\mathrm{ks}$ by using the CIAO tool dmextract. Following Vaughan et al. (2003), we calculate the fractional root mean square (rms) variability amplitude F_{var} of the light curves. The normalized variance of a light curve, x_i, is

$$\sigma_N^2 = \frac{1}{(N-1)\bar{x}^2} \sum_{i=1}^{N} (x_i - \bar{x})^2, \tag{1}$$

where N is the number of points in the light curve and $\bar{x}$ is the mean. A fraction of the variance is due to measurement errors and hence it is convenient to define normalized excess variance as

$$\sigma_{\mathrm{NXS}}^2 = \sigma_N^2 - \bar{\sigma}_{\mathrm{err}}^2, \tag{2}$$

where $\bar{\sigma}_{\mathrm{err}}^2 = \frac{1}{N\bar{x}^2} \sum_{i=1}^{N} \sigma_{\mathrm{err},i}^2$ is the normalized mean square error. Finally the fractional amplitude is defined as $F_{\mathrm{var}} = \sqrt{\sigma_{\mathrm{NXS}}^2}$. Using simulations, Vaughan et al. (2003) have estimated the error for σ_{NXS}^2 to be

$$\mathrm{err}(\sigma_{\mathrm{NXS}}^2)^2 = \left(\sqrt{\frac{2}{N}} \sigma_{\mathrm{err}}^2 \right)^2 + \left(\sqrt{\frac{\sigma_{\mathrm{err}}^2}{N}} 2F_{\mathrm{var}} \right)^2. \tag{3}$$

At the n-sigma level, a source is considered to be variable only if $\sigma_{\mathrm{NXS}}^2 > n\,\mathrm{err}(\sigma_{\mathrm{NXS}}^2)$. For such variable sources, the n-σ upper and lower limits on F_{var} can be estimated to be $F_{\mathrm{var},u} = \sqrt{\sigma_{\mathrm{NXS}}^2 + n\,\mathrm{err}(\sigma_{\mathrm{NXS}}^2)}$ and $F_{\mathrm{var},l} = \sqrt{\sigma_{\mathrm{NXS}}^2 - n\,\mathrm{err}(\sigma_{\mathrm{NXS}}^2)}$ respectively. For non-variable sources, $F_{\mathrm{var},u}$ provides an upper limit on any variability that may be hidden in the measurement errors.

To measure the variability of the sources in a similar range of timescales, we bin all the data in $\sim 4\,\mathrm{ks}$ time bins and take the length of the light curves to be $\sim 40\,\mathrm{ks}$, i.e. $N \sim 10$. For NGC 1569, the long exposure time of $\sim 90\,\mathrm{ks}$ allowed us to obtain two light curves of $\sim 40\,\mathrm{ks}$. The fractional variability was averaged over the two light curves for this case. Using a $\sim 4\,\mathrm{ks}$ time bin, for most sources we place a 2-σ upper limit on $F_{\mathrm{var}} < 0.4$. Choosing a smaller time bin would result in a large number of sources having upper limits of $F_{\mathrm{var}} \sim 0.8$, which does not represent a constraint. A larger time bin would not allow for many sources to have at least ten data points.

3 RESULTS

Of the 166 sources, variability was detected above the 3-σ level for five sources and above the 2-σ level for eight sources. One of these highly variable sources is a foreground star CXOU J013647.4 +154745 (Soria et al. 2004). We have not included this source for further analysis. We are left with a total of 165 X-ray point sources, out of which seven are highly variable sources with F_{var} ranging from $0.16 - 1.16$. Their spectral parameters for the absorbed power-law and disk blackbody models are tabulated in Table 2. If all the 165 sources were not variable, one may expect by chance to get ~four sources to show variability at a 2-σ level. Hence, although we present the results of the two sources that are variable at levels less than 3-σ, we caution that some of them may be spurious. For
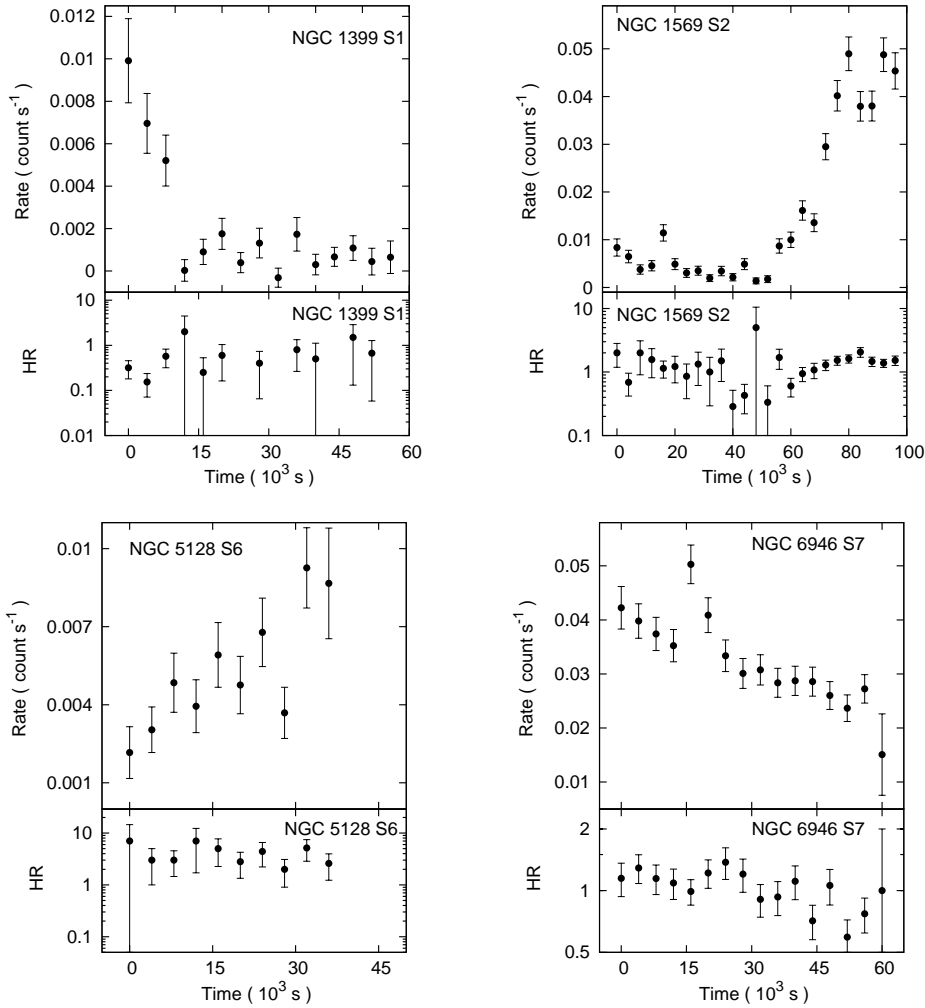
Fig. 1 The light curves and the HR (i.e. ratio of counts in the energy band $1-8$ to those in the $0.3-1\,\mathrm{keV}$ band) for the four sources that show secular transitions or flares. The spectral properties of these sources are tabulated in Table 2. The source in NGC 5128 does not show such variability in other observations and hence for this source, flares/transitions are not persistent.

most of these sources, F_{var} is not well constrained because it is typically $F_{\mathrm{var}} < 0.4$. However, for 11 sources we do obtain upper limits on $F_{\mathrm{var}} < 0.1$.

The analysis is only sensitive to large amplitude variations $F_{\mathrm{var}} \gtrsim 0.4$. Such large variations are expected to be due to secular (i.e one-time) transitions between flux levels. This is indeed true for four of the sources with detected variability. The light curves for these are shown in Figure 1, where it can be seen that the variability is due to secular transition behavior. The hardness ratio (HR), defined as the ratio of the counts in the $1-8\,\mathrm{keV}$ band to those in the $0.3-1\,\mathrm{keV}$ band, does not show such a significant variation (Fig. 1). Thus, the large amplitude variations of flux in these sources are not necessarily accompanied by significant changes in spectral shape. This implies that the variability of these sources is not due to variable absorption as reported for a source in NGC 4472 (Maccarone et al. 2007). The large flux variation for the source in NGC 1569 (S2 in Table 2) has been reported

Table 2 Spectral Properties of Variable Sources

Galaxy	Source No.	R.A. (h m s)	Decl. (° ′ ″)	$(n_{\rm H})_{\rm pow}$ $(10^{22}\,{\rm cm}^{-2})$	Γ	$\log(L)_{\rm pow}$ (erg s^{-1})	$(n_{\rm H})_{\rm dbb}$ $(10^{22}\,{\rm cm}^{-2})$	$kT_{\rm in}$ (keV)	$\log(L)_{\rm dbb}$ (erg s^{-1})	$F_{\rm var}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NGC 1399	S1	3 38 31.73	−35 30 58.65	$0.01^{+0.16}_{-0.01}$	$2.5^{+1.7}_{-0.6}$	$38.5^{+0.5}_{-0.1}$	$0.00^{+0.06}_{-0.00}$	$0.25^{+0.06}_{-0.06}$	$38.82^{+0.26}_{-0.02}$	$1.16^{+0.12}_{-0.12}$
NGC 1569	S2	4 30 48.14	+64 50 50.57	$0.51^{+0.06}_{-0.06}$	$4.0^{+0.3}_{-0.2}$	$38.7^{+0.2}_{-0.2}$	$0.19^{+0.02}_{-0.03}$	$0.41^{+0.04}_{-0.03}$	$38.13^{+0.04}_{-0.05}$	$0.76^{+0.03}_{-0.04}$
NGC 1569	S3	4 30 48.62	+64 50 58.59	$0.24^{+0.06}_{-0.05}$	$1.6^{+0.2}_{-0.1}$	$37.72^{+0.03}_{-0.02}$	$0.10^{+0.04}_{-0.05}$	$1.68^{+0.30}_{-0.19}$	$37.96^{+0.04}_{-0.04}$	$0.64^{+0.04}_{-0.05}$
NGC 2403	S4	7 37 11.63	+65 33 45.52	$0.63^{+0.26}_{-0.18}$	$2.3^{+0.4}_{-0.3}$	$38.4^{+0.2}_{-0.1}$	$0.28^{+0.16}_{-0.14}$	$1.09^{+0.23}_{-0.15}$	$38.40^{+0.05}_{-0.05}$	$0.35^{+0.05}_{-0.06}$
NGC 0628	S5	1 36 51.06	+15 45 46.86	$0.03^{+0.05}_{-0.03}$	$1.9^{+0.2}_{-0.1}$	$39.22^{+0.04}_{-0.02}$	$0.00^{+0.00}_{-0.00}$	$0.89^{+0.08}_{-0.11}$	$39.42^{+0.02}_{-0.04}$	$0.25^{+0.03}_{-0.04}$
NGC 5128	S6	13 25 27.52	−43 02 14.78	$0.02^{+0.08}_{-0.02}$	$1.7^{+0.4}_{-0.3}$	$38.0^{+0.06}_{-0.04}$	$0.00^{+0.10}_{-0.00}$	$1.12^{+0.37}_{-0.23}$	$38.20^{+0.08}_{-0.05}$	$0.36^{+0.08}_{-0.09}$
NGC 6946	S7	20 35 0.13	+60 09 07.97	$0.61^{+0.06}_{-0.05}$	$5.1^{+0.3}_{-0.3}$	$40.4^{+0.2}_{-0.2}$	$0.22^{+0.03}_{-0.03}$	$0.32^{+0.02}_{-0.03}$	$39.46^{+0.08}_{-0.06}$	$0.16^{+0.02}_{-0.04}$

Notes: (1) Host galaxy name; (2) Source Name; (3) Right Ascension; (4) Declination; (5) $(n_{\rm H})_{\rm pow}$, equivalent hydrogen column density for the power-law model; (6) Γ, photon power-law index; (7) $L_{\rm pow}$, power-law X-ray luminosity in the energy range: 0.3–8.0 keV; (8) $(n_{\rm H})_{\rm dbb}$ $(10^{22}\,{\rm cm}^{-2})$, equivalent hydrogen column density for the disk black body model; (9) $kT_{\rm in}$, the inner disk temperature; (10) $L_{\rm dbb}$, disk black body X-ray luminosity in the energy range: 0.3–8.0 keV; (11) $F_{\rm var}$, fractional rms amplitude. The error quoted on $F_{\rm var}$ is 1-σ. The first five sources are variable at greater than 3-σ level while the rest are at greater than 2-σ level.

earlier by Heike et al. (2003). The source is well fitted by disk blackbody emission with bolometric luminosity varying from 10^{37} erg s^{-1} to 5×10^{37} erg s^{-1}, suggestive of it being a stellar mass black hole system (Heike et al. 2003).

A source in NGC 2403 (S4) showed secular transition behavior in the *Chandra* observation analyzed in the sample (Obs ID 2014). However, for three other *Chandra* observations, it showed persistent large amplitude variability. The light curves and HR for the four observations are shown in Figure 2. The luminosity of this source is $L \sim 10^{38}$ erg s^{-1} (S4 in Table 2). Two other sources exhibit aperiodic variability with large amplitudes and their light curves are shown in Figure 3. The source in NGC 1569 (like the one in NGC 2403) has a relatively low luminosity of $L \sim 10^{38}$ erg s^{-1} (S3 in Table 2) and its variable nature has been noted earlier by Heike et al. (2003). The other source which is in NGC 0628 (S5 in Table 2) has a luminosity $L > 10^{39}$ erg s^{-1} and is unique in the sample. It shows large amplitude variations on a timescale as short as ≤ 1000 s. This source (also called M74 X-1) has been extensively studied by Krauss et al. (2005) using both *Chandra* and *XMM Newton* data. They have compared the variability of the source as being similar to that of the Galactic X-ray binary system GRS 1915+105. Here we point out the rarity of such sources, since only one such object was found in our sample, which may be quantified as one object per 17 galaxies.

The high amplitude variability of the four sources shown in Figure 1 may be due to rare transitions/flares. In that case, other observations of these sources may not show such variability. The source S6 in NGC 5128 does not show variability ($F_{\rm var} \lesssim 0.2$) in seven other *Chandra* observations (IDs 2978, 3965, 7797, 7798, 8489, 8490 and 10722). Unfortunately, there are no additional *Chandra* observations of NGC 1569 (with an exposure time > 30 ks) to confirm the nature of the sources S3 or S2.

Figure 4 shows the fractional rms variability amplitude, $F_{\rm var}$ versus the unabsorbed X-ray luminosity. For the seven sources with detected variability, the triangles represent sources whose spectra are better modeled as a power-law, while the circles are for those with spectra better modeled as a disk blackbody. The three sources marked with crosses exhibit aperiodic fluctuations (Fig. 2 and Fig. 3) in contrast to the other variable sources which exhibit secular transitions/flares (Fig. 1). One of the ULXs has an ultra-soft spectrum with disk blackbody temperature ~ 0.3 keV. The other is the rapidly varying source in NGC 0628. For non-variable sources, the upper limits are plotted in the figure. For 11 sources the upper limits are constrained to be less than 0.1 and these are represented by solid lines, and nine of them have luminosities in excess of $L > 10^{39}$ erg s^{-1}. Therefore, it seems
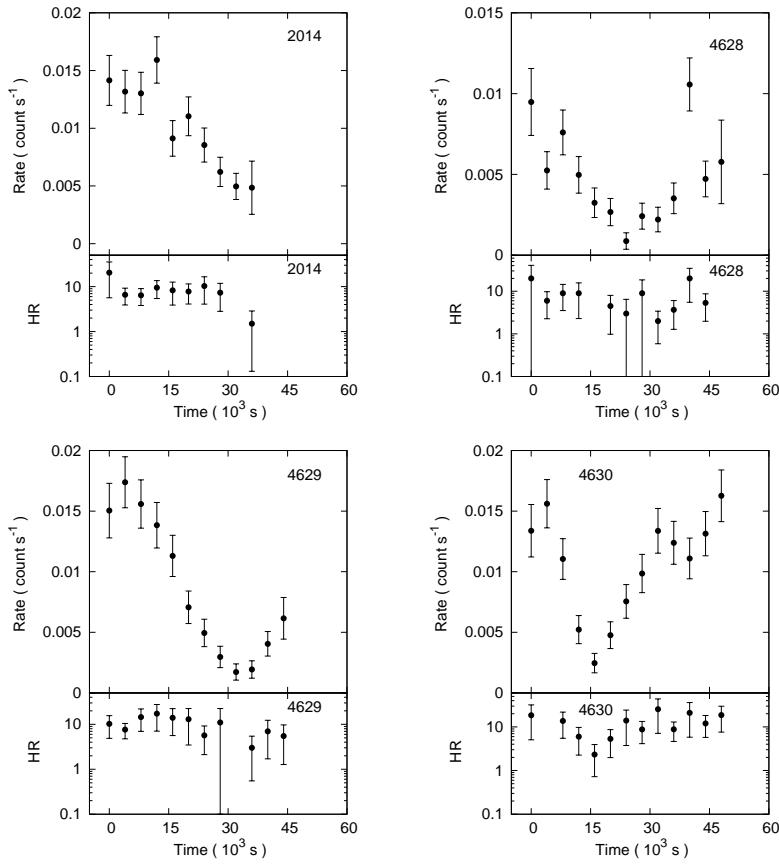
Fig. 2 The light curves and the HR (i.e. ratio of counts in the energy band $1 - 8$ to those in the $0.3 - 1$ keV band) for a source in NGC 2403, S4. The panels are for four *Chandra* observations and are labeled by their observation ID numbers. This source shows persistent flare like variability.
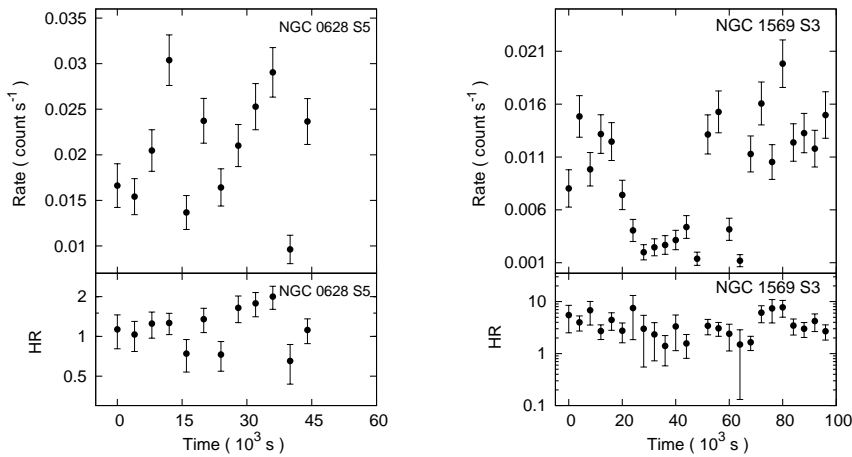

Fig. 3 The light curves and the HR (i.e. ratio of counts in the energy band $1 - 8$ to those in the $0.3 - 1$ keV band) for two sources that show rapid aperiodic variability. The spectral properties of these sources are tabulated in Table 2. The source in NGC 0628 is a ULX and its aperiodic variability makes it unique in the sample.
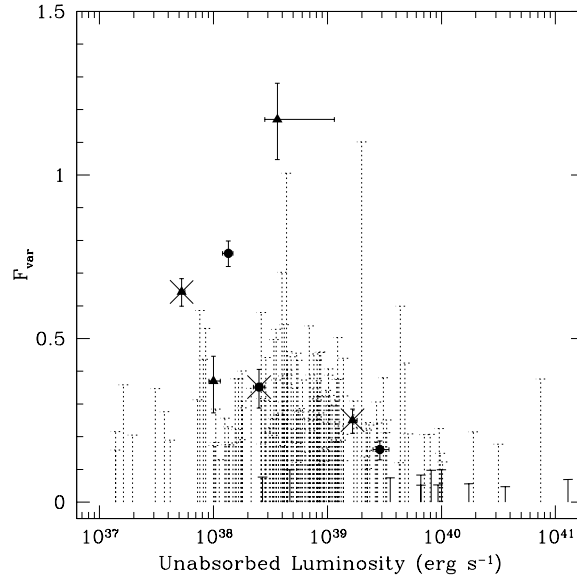
Fig. 4 Fractional rms variability amplitude ($F_{\rm var}$) versus the unabsorbed X-ray luminosity. The circles (triangles) indicate sources which are better fitted with a disk blackbody (power-law) spectral model. The sources marked with a star show rapid aperiodic variability. For 11 sources the 2-σ upper limits are constrained to be less than 0.1 and these are represented by solid lines. Note that 9 of these 11 non-variable sources are ULXs (i.e. $L_{\rm X} > 10^{39}$ erg s^{-1}).

that ultra-luminous X-ray sources are typically not highly variable in these ks timescales except for some ultra-soft ones.

4 DISCUSSION

Of the 165 (not including foreground star) sources in 17 nearby galaxies, seven of them were found to be highly variable on ks timescales. In general, their variability is not strongly correlated with the HR, which indicates that the variability is not due to varying absorption, but rather is likely to represent some structural changes in the accretion process.

In the sample, we find that while there are two ULXs which are variable ($F_{\rm var} > 0.2$), there are also nine ULXs for which we can constrain the variability $F_{\rm var} < 0.1$. One of the variable ULXs is ultra-soft with blackbody temperature ~ 0.3 keV. For such sources, a spectrum in the *Chandra* energy range of $0.3 - 8.0$ keV is essentially an exponentially decreasing function. Relatively small fluctuations in an intrinsic spectral parameter may lead to large flux variation in this spectral regime. Thus it seems that ULXs are not highly variable on ks timescales. A notable exception is the bright source in NGC 0628 whose variability is unique in the sample.

For four of the seven variable sources (i.e. $\sim 3\%$ of the sample), the variability seems to have a secular nature, perhaps representing state transitions. At least one of them is not variable in seven other *Chandra* observations, which implies that the variability has a secular nature and is not persistent. The analysis is based on a single "snapshot" observation with duration ~ 40 ks. If one hypothesizes that all sources undergo such transitions, the detection of such a variability in $\sim 3\%$ of the sources implies that on average the duty cycle of such transitions is $\sim 40000/0.03 \sim 1.3 \times 10^6$ s, representing a transition every ~ 15 d. A similar analysis for ULXs, where there is one source

showing a secular variability in a total of nine sources, would not imply there is a transition every $\sim 40000/0.1 \sim 4 \times 10^6$ s ~ 5 d. However, since the sample considered here is neither uniform nor complete, such quantitative statistical inference may not be reliable. Nevertheless, since spectral state transitions for Galactic sources typically occur much less frequently, it is more likely that these sources represent a special class of systems where transitions occurring on ks timescales happen frequently. Further, state transitions in Galactic sources are associated with spectral changes, but the HR does not significantly change during these transitions. Thus, it seems that these transitions are different from the state transitions observed in Galactic sources.

For three of the variable sources, the large amplitude fluctuations are persistent. Among Galactic X-ray binaries, GRS 1915+105 and the recently discovered IGR J17091–3624 (Altamirano et al. 2011; Pahari et al. 2012) show such persistent variability on these timescales. Two of these sources, unlike GRS 1915+105 but perhaps similar to IGR J17091–3624, have a relatively low luminosity of $\sim 10^{38}$ erg s^{-1}. A source in NGC 2403 shows large amplitude variability in all four *Chandra* observations. It is possible that the variability is quasi-periodic on a ~ 10 ks timescale, but the data are not sufficient to make concrete statements. Thus, we establish that there are X-ray sources in nearby galaxies, with modest luminosities of $L \sim 10^{38}$ erg s^{-1}, that exhibit persistent high amplitude variability on ks timescales.

It is premature to identify any specific accretion disk instability model to explain these cases of large amplitude variability. Indeed, the variability of the Galactic source GRS 1915+105 is still not clearly understood. Nevertheless, with the increased number of sources, detailed studies like flux resolved spectral analysis and time-lag analysis may shed light on the reasons for their variable nature.

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