

# The remarkable stability of probable black hole low-mass X-ray binaries in nearby galaxies

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## ABSTRACT

The most luminous X-ray sources in nearby elliptical galaxies are likely black hole low-mass X-ray binaries (BHLMXBs). In the Milky Way, such systems are always transient, and with the exception of GRS 1915+105 have burst durations on the order of weeks or months. However, the low duty cycle of short-duration outburst BHLMXBs makes it improbable that any one source would be caught in an outburst during a single snapshot observation. Long-duration outburst BHLMXBs, although much rarer, would be detectable in a series of snapshot observations separated by several years. Our analysis of multi-epoch *Chandra* observations of the giant elliptical galaxies NGC 1399 and M87 separated by 3.3 and 5.3 yr, respectively, finds that all 37 luminous ( $>8 \times 10^{38} \text{ erg s}^{-1}$ ) X-ray sources that were present in the first epoch observations were still in outburst in all of the following observations. Many of these probable long-duration outburst BHLMXBs reside within globular clusters of the galaxies. Conversely, no definitive short-duration outburst BHLMXBs were detected in any of the observations. This places an upper limit on the ratio of short-to-long-duration outbursters that is slightly lower, but consistent with what is seen in the Milky Way. The fact that none of the luminous sources turned off between the first and last epochs places a 95 per cent lower limit of 50 yr on the mean burst duration of the long-duration outburst sources. The most likely scenario for the origin of these sources is that they are long-period ( $>30 \text{ d}$ ) black hole binaries with a red giant donor, much like GRS 1915+105. However, unlike GRS 1915+105, most of the sources show only modest variability from epoch to epoch.

**Key words:** binaries: close – galaxies: elliptical and lenticular, cD – X-rays: binaries – X-rays: galaxies.

## 1 INTRODUCTION

The time variability of accreting neutron star (NS) or black hole X-ray binaries has long been used as a valuable diagnostic for understanding the accretion process on to compact objects. One important distinction between NS and black hole accretors in binary systems is the fraction of each type of binary that exhibits transient behaviour. While a significant number of Galactic NS X-ray binaries are persistent X-ray emitters, there are only three known persistent luminous sources among black hole binaries, and all three have young, massive donor stars (high-mass X-ray binaries). Of the 15 confirmed Galactic black hole X-ray binaries with low-mass donor stars, all exhibit transient behaviour. These sources spend most of their time in quiescence, but periodically burst to near-Eddington X-ray luminosities for weeks or months time-scales (e.g. McClintock & Remillard 2006), although the unusual black hole

low-mass X-ray binary (BHLMXB) GRS 1915+105 has been in continuous outburst since its discovery in 1992 (Castro-Tirado, Brandt & Lund 1992).

The transient behaviour of BHLMXBs is believed to be understood in terms of instabilities in the accretion disc that trigger sporadic episodes of near-Eddington accretion as matter that has accumulated in the disc since the previous outburst empties. This instability is suppressed and the source will appear as persistent if the temperature of the entire accretion disc is held above the hydrogen ionization temperature,  $T_{\text{H}} \sim 6500 \text{ K}$ . This can be accomplished, for example, by irradiation of the disc by the central X-ray source (e.g. van Paradijs 1996), particularly in the case of a NS accretor. Irradiation can also result from the ultraviolet ionizing flux from a young massive donor star – this most likely accounts for the persistent nature of the three high-mass black hole X-ray binaries mentioned above. The lack of a hard surface of a black hole is believed to greatly diminish irradiation of the disc by the central source (King, Kolb & Szuszkiewicz 1997) making it far more difficult for the accretion disc of a black hole with a low-mass companion to

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remain above  $T_H$  than it is for a NS binary with a similar sized disc. Larger discs are also harder to keep entirely above  $T_H$ , implying that all long-period binaries should be transient. King et al. (1997) have deduced that all BHLMXBs with orbital periods greater than two days should be transient sources, in accordance with the sparse Galactic BHLMXBs data.

Given the limited number of BHLMXBs in the Milky Way, nearby galaxies provide an opportunity to increase greatly the statistics of BHLMXBs, as well as uncover modes of accretion that are too rare to have been seen in the meager Galactic population. Although the much larger distances to extragalactic BHLMXBs preclude the determination of basic quantities like those obtained for their Galactic counterparts such as the mass function or orbital period of the binary, the fact that the distances to the BHLMXBs' host galaxies are reasonably well-constrained allows for a more accurate determination of the X-ray luminosities of the sources. This is particularly useful for identifying which sources have X-ray luminosities exceeding the Eddington limit of a NS, indicating that their accretors are black holes instead.

With the maturation of the *Chandra* mission, probing the long-term temporal behaviour of probable BHLMXBs in nearby galaxies is now possible as multiple epoch observations of galaxies separated by several years become available. For studies of BHLMXBs, elliptical galaxies are better suited than spiral galaxies. Aside from the fact that elliptical galaxies are generally larger and have more globular clusters [where low-mass X-ray binaries (LMXBs) preferentially form; Sarazin et al. 2003; Verbunt & Lewin 2004] than spiral galaxies, the old stellar populations of elliptical galaxies harbour only LMXBs, rather than a mixture of high- and low-mass X-ray binaries as is the case for spiral galaxies. Given the difficulty in distinguishing between high- and low-mass X-ray binaries with limited X-ray photon statistics, elliptical galaxies provide a much cleaner sample of just LMXBs.

Although short-duration outburst BHLMXBs far outnumber long-duration outburst BHLMXBs in the Milky Way, it is not clear which population will actually be detected in relatively short *Chandra* observations of nearby galaxies. Typical short-duration outbursts are luminous for only a month or so every  $\sim 10$  yr, so any one source is not expected to be in outburst at any given time. On the other hand, if a long-duration BHLMXB is in its 'on' state, it is likely to be detected in a series of *Chandra* observations spanning several years. The relative number of each type of source in the galaxy will determine which population is predominantly detected.

In this study, we investigate the temporal behaviour of BHLMXBs in two of the nearest and largest elliptical galaxies, NGC 1399 and M87, on 3–5 yr time-scales. Both galaxies are at the centres of clusters of galaxies (Fornax and Virgo, respectively) and are observed to harbour numerous high X-ray flux sources that are most likely BHLMXBs. While a similar total number of BHLMXBs might be obtained from a larger number of smaller elliptical galaxies, observations of smaller galaxies suffer more from contamination from serendipitous high X-ray flux foreground/background sources at a given flux level, making it difficult to establish which sources are BHLMXBs and which are unrelated to the galaxy. As we show below, NGC 1399 and M87 each contain enough high-flux sources that the amount of contamination from serendipitous sources is small.

This paper is organized in the following manner. The method of distinguishing NS from black hole LMXBs is described in Section 2, and the *Chandra* observations and data analysis are outlined in Section 3. The long-term variability of the luminosities and spectral properties of the sources are discussed in Section 4. Limits on the burst durations of the BHLMXBs are calculated in Section 5,

and possible origins for the luminous LMXBs are discussed in Section 6. Finally, our conclusions and future work are summarized in Section 7.

## 2 NEUTRON STAR OR BLACK HOLE LMXB?

Definitively distinguishing between an extragalactic NS and a black hole LMXB is not a trivial task, as the distance of extragalactic LMXBs precludes the determination of the mass function for the system. The low X-ray count rates and limited temporal coverage generally make it difficult to identify Type I X-ray bursts that are found exclusively in Galactic NSLMXBs. Progress has been made in distinguishing NSLMXBs from BHLMXBs in M31 by Trudolyubov, Borozdin & Priedhorsky (2001) and Barnard, Kolb & Osborne (2005) from their X-ray spectra and the presence or absence of a break in the power density spectra of their light curves. However, this method is not feasible with current X-ray instrumentation for sources at the distance of NGC 1399 or M87.

The presence of a break in the X-ray luminosity function (XLF) of LMXBs in nearby elliptical galaxies might provide a method for identifying at least a fraction of the BHLMXB population. First identified in the elliptical galaxy NGC 4697 (Sarazin, Irwin & Bregman 2000), a break in the XLF at  $L_X = 3\text{--}5 \times 10^{38} \text{ erg s}^{-1}$  was confirmed in the co-added XLF of many galaxies analysed by Gilfanov (2004) and Kim & Fabbiano (2004). The popular interpretation of this XLF feature is that it represents a division between NSLMXB and BHLMXB populations, given that the location of the break is located intriguingly close to the Eddington limit of a heavy ( $2\text{--}3 M_\odot$ ) NS (or a  $1.4 M_\odot$  NS with a He or C/O donor). The XLF break has also been interpreted as an effect of aging of the LMXB population, for which higher mass transfer (more X-ray luminous) systems consume their mass supply sooner and cease being X-ray emitters (Wu 2001). Regardless of the interpretation of the XLF break, it seems likely that the sources well above the break (e.g.  $>8 \times 10^{38} \text{ erg s}^{-1}$ ) are considerably easier to explain in terms of BHLMXBs emitting at or near their Eddington limits rather than a population of NSLMXBs emitting at several times (or more) of their Eddington limit. While super-Eddington emission from Galactic NSLMXBs has been observed, such high mass transfer rates rarely last more than a few hundred seconds (Type I bursts), and have never been seen to persist for an extended period of time.

Since sources at or below the break in the XLF could be either NSLMXBs or BHLMXBs, little can be said about the nature of the accretor. However, for sources well above the break, we make the assumption that they are  $4\text{--}20 M_\odot$  black holes accreting near their Eddington limit.

## 3 OBSERVATIONS AND DATA REDUCTION

The *Chandra* data for NGC 1399 and M87 were obtained from the *Chandra* online archive. There were nine and 48 observations covering a time-span of 3.35 and 5.30 yr for NGC 1399 and M87, respectively. Many of the observations were of limited use (i.e. too short an exposure, grating observations, data were taken in 1/8th array mode, the target was far off-axis) for determining the flux of the point sources, but were inspected nonetheless to search for very luminous transients. Of the more suitable observations, several were grouped together over a few day time-span, which we have counted as a single epoch. For M87, there were a total of six independent epochs, while for NGC 1399 there were two independent epochs.

The data for each observation were processed in a uniform manner following the *Chandra* data reduction threads using CIAO v3.3.

Times of high background were removed from the data, and all images created were corrected for exposure and vignetting. Point sources were identified using WAVDETECT in CIAO on the 0.3–6.0 keV band image. For both NGC 1399 and M87, the first epoch observations (Observation IDs 00319 and 00352, respectively) were taken with the ACIS-S array. Therefore, for these and all following observations, we only consider X-ray sources that fall within the field of view of the S3 chip of the first epoch observation. For both galaxies, the S3 chip field of view corresponds well to the  $D_{25}$  contour of the galaxy.

The source lists were culled to remove sources that were detected at less than  $3\sigma$ . For each source a local background was determined from a circular annular region around each source with an inner radius that was set to 1.5 times the semimajor axis of the source extraction region and an outer radius chosen such that the area of the background annulus was five times the area of the source’s extraction region. Care was taken to exclude neighbouring sources from the background annuli of each source in crowded regions.

Exposure-corrected counts rates were determined for each source in all epochs. To convert the X-ray count rate to an energy flux, we performed spectral fitting within XSPEC on each source according to the significance of its detection. If a source was detected at  $>5\sigma$  significance, the spectrum of the source was fit with a simple power law absorbed by the Galactic hydrogen column density (Dickey & Lockman 1990) toward the target galaxy. In general, more sophisticated spectral models were not justified by the data owing to the low X-ray count rates of an individual source. The slope of the power law was free to vary. If a source was detected at less than  $5\sigma$  significance, the best-fitting power-law model for that source from a neighbouring epoch was assumed. Otherwise, a power law of  $\Gamma = 1.56$  was assumed, a value found to be representative of the sum of many LMXB spectra in early-type galaxies and the bulge of M31 (Irwin, Athey & Bregman 2003). With these best-fitting models, fluxes were converted to 0.3–10 keV luminosities assuming distances of 20.0 and 16.1 Mpc for NGC 1399 and M87, respectively (Tonry et al. 2001). All X-ray luminosities quoted are in the 0.3–10 keV band unless otherwise noted.

M87 exhibits considerable small-scale structure in its hot interstellar medium, most notably knots in the well-known jet emanating from the nucleus of the galaxy. Such small-scale structure can be distinguished from LMXBs by the soft X-ray spectrum of the knots compared to the much harder spectrum expected from X-ray binaries, and these knots were subsequently removed from consideration.

For NGC 1399, the first epoch observation was taken when the focal plane temperature of ACIS was  $-110^\circ\text{C}$ , for which the calibration is less secure than the second epoch observation taken when the focal plane temperature of ACIS was  $-120^\circ\text{C}$ . Furthermore, the first observation was taken with a backside-illuminated chip, while the second observation was taken with frontside-illuminated chips. To demonstrate that the cross-calibration between the two observing set-ups is not affecting our results, we have extracted spectra of the hot gas plus unresolved LMXBs within 15 arcsec of the centre of NGC 1399 from both observations. This emission is not expected to vary between the two observations. The spectra were fit within XSPEC with a variable abundance thermal (VAPEC) model for the hot gas and a  $\Gamma = 1.56$  power-law model for the unresolved LMXB emission (which comprises only a small fraction of the diffuse emission). The temperature, elemental abundances, and normalization of the VAPEC model as well as the normalization of the power-law model were allowed to vary for each data set. It was found that the values of all the free parameters as well as the model flux were consistent within

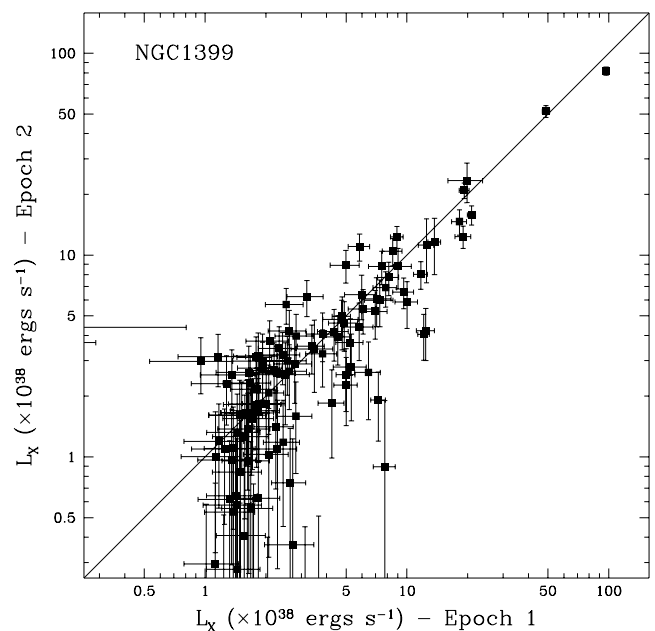
the uncertainties between the two observations, indicating that the cross-calibration between the two observations must be sufficiently good as to not affect the main results of the paper.

#### 4 LUMINOSITY AND SPECTRAL VARIABILITY

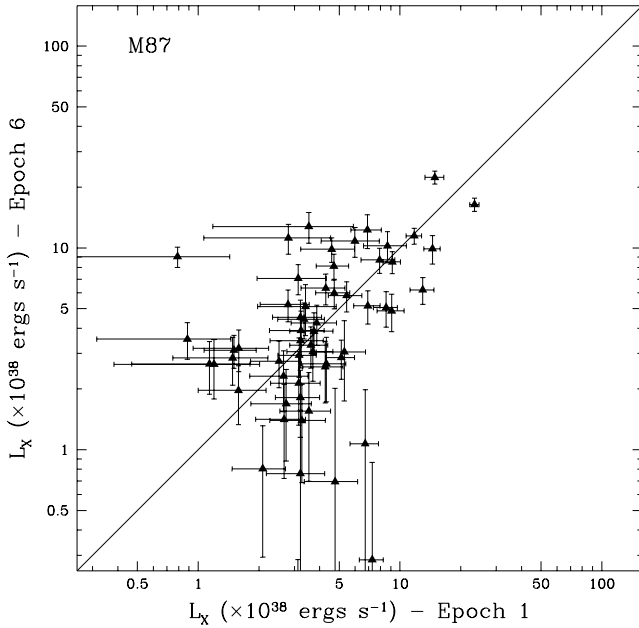
Figs 1 and 2 illustrate how the 0.3–10 keV luminosity for each source in NGC 1399 and M87 changed between the first epoch observations (Observation IDs 00319 and 00352) and the last epoch observations (Observation IDs 04172 and 07212). In this plot, transient sources appear near the  $x$ - and  $y$ -axes, and have very large error bars (since this is a log–log plot). Remarkably, all sources that had a luminosity of at least  $8 \times 10^{38} \text{ erg s}^{-1}$  in the first epoch were detected in the last epoch, as well as all epochs in between. There was not a single case where a short-term transient source was detected with a luminosity exceeding  $8 \times 10^{38} \text{ erg s}^{-1}$  in any of the epochs.

There were a handful of fainter sources that were detected in only one epoch. However, given how close these sources were to the detection limit (most were detected at  $<5\sigma$  significance), it is unclear whether these sources are transient or just somewhat variable. This is particularly true for the sources in NGC 1399, since the last epoch observation was shorter and observed with a less sensitive instrument than the first epoch observation. Observations of less distant early-type galaxies such as NGC 5128 (Kraft et al. 2001) are more suitable for determining the transient nature of lower luminosity sources.

We estimated the number of serendipitous high X-ray flux foreground/background objects that would appear to have luminosities exceeding  $8 \times 10^{38} \text{ erg s}^{-1}$  in order to remove them statistically from the sample. For NGC 1399 and M87,  $8 \times 10^{38} \text{ erg s}^{-1}$  corresponds to a flux of  $1.7 \times 10^{-14}$  and  $2.6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ , respectively. After converting to 0.5–2.0 keV fluxes, we used the log  $N$  versus log  $S_X$  relation derived by Hasinger et al. (1998) from



**Figure 1.** X-ray luminosity–luminosity plot for the sources detected in the two epochs of NGC 1399. The error bars represent  $1\sigma$  uncertainties. The solid line represents no change in luminosity between epochs. The apparent overabundance of fainter sources detected in the first epoch but not the second epoch is a result of differences in exposure time and instrument sensitivity.



**Figure 2.** Same as Fig. 1 but for the first and sixth epoch observations of M87.

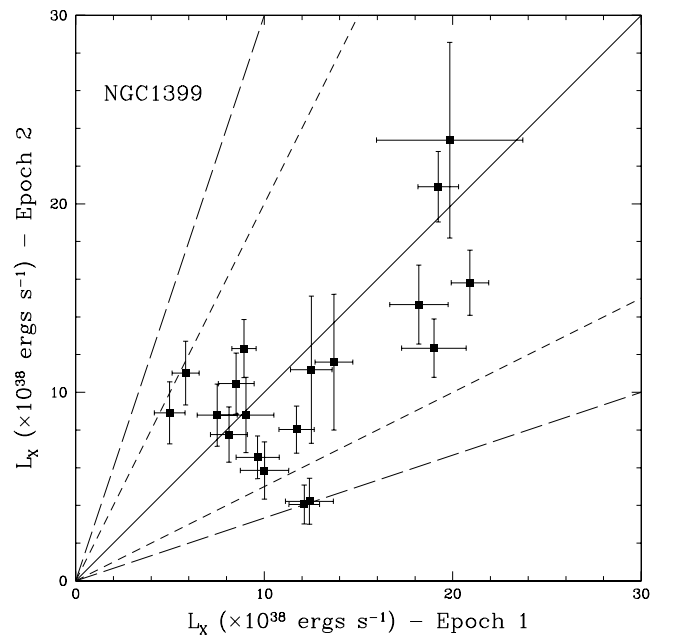
many *ROSAT* High Resolution Imager (HRI) observations of isolated, non-extended X-ray sources to estimate that there are three and two background/foreground sources expected to be in the *Chandra* S3 fields of view of NGC 1399 and M87, respectively, above this flux level. One luminous source in M87 has an optical counterpart that is not a globular cluster (Jordán et al. 2004), and is most likely a background AGN and has already been removed from the sample, leaving one unidentified foreground/background source in M87 at this flux level.

For the purpose of identifying BHLMBXBs among the luminous sources in NGC 1399, we define them as having an X-ray luminosity of at least  $8 \times 10^{38} \text{ erg s}^{-1}$  in one epoch and at least  $5 \times 10^{38} \text{ erg s}^{-1}$  in the other epoch. Two additional sources that just missed this cut were added, since both sources were detected at low significance in one of the shallow interim observations and have estimated luminosities of  $\sim 8 \times 10^{38} \text{ erg s}^{-1}$  in that observation. This requires the X-ray luminosity to be above the Eddington limit of a heavy NS in both epochs, and well above the Eddington limit in at least one of the epochs. This was done to eliminate potential NSLMBXBs that happened to flare to super-Eddington luminosities in one of the epochs. It also assumes that a NSLMBXB is highly unlikely to be super-Eddington in both epochs. While this definition has eliminated potential BHLMBXBs from our sample (those that dipped well below the Eddington limit of a NS in one epoch), we wish to be conservative in the assignment of which sources are long-duration outburst BHLMBXBs in order to have a clean sample as possible. For M87, for which six epochs are available, we require the source to exceed  $8 \times 10^{38} \text{ erg s}^{-1}$  in at least two epochs, and remain above  $5 \times 10^{38} \text{ erg s}^{-1}$  in two of the four remaining epochs (while remaining detectable in all epochs). With this definition, we find 21 and 16 potential long-duration outburst BHLMBXBs in NGC 1399 and M87, respectively. Statistically, subtracting the expected number of foreground/background sources for each galaxy gives 18 and 15 sources, respectively.

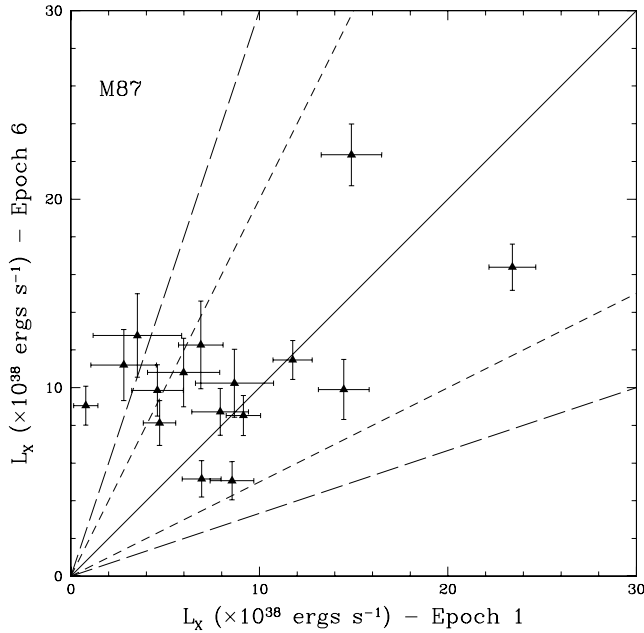
For the 37 sources in both galaxies combined, a total of 14 sources fell within the field of view of *Hubble Space Telescope* (*HST*) observations (Angelini, Loewenstein & Mushotzky 2001; Jordán et al.

2004). Of these 14 sources, 11 of them reside within globular clusters of these galaxies, two resided in the field, and one was ambiguous. The fraction of luminous sources in globular clusters (85 per cent) is larger than the fraction of all sources found in globular clusters of 63 per cent (84/132 sources), but the sample size of BHLMBXBs is too small to draw any definitive conclusions about whether globular clusters preferentially harbour more luminous X-ray sources. A few of these globular cluster LMBXBs have X-ray luminosities exceeding  $2 \times 10^{39} \text{ erg s}^{-1}$ . These sources are of particular interest, since no black hole has ever been found in a Milky Way globular cluster. Yet it appears quite difficult to explain them in terms of highly super-Eddington ( $> 10$  times) NS binaries, especially given their steady emission on a 3–5 yr time-span. While it might be argued that these globular clusters contain multiple X-ray sources like the Galactic globular cluster M15 (White & Angelini 2001), it is statistically highly unlikely that the luminous sources in the globular clusters of NGC 1399 are composites of lower luminosity LMBXBs. Previous studies have shown that the probability of a globular cluster harbouring an X-ray source with  $L_X > \text{few} \times 10^{37} \text{ erg s}^{-1}$  is only about 4 per cent (e.g. Kundu, Maccarone & Zepf 2002; Sarazin et al. 2003). The fraction of globular clusters that harbour a  $L_X > 5 \times 10^{38} \text{ erg s}^{-1}$  source is well under 1 per cent. The probability of a globular cluster harbouring four or more such luminous sources is vanishingly small.

The  $L_X - L_X$  relations for just the long-duration outburst BHLMBXB candidates are shown in linear space in Figs 3 and 4. The dotted and dashed lines indicate a change of luminosity by a factor of 2 and 3, respectively. The luminous sources in NGC 1399 and M87 were quite steady between the two epochs. For NGC 1399, 19 (21) of the 21 sources varied by less than a factor of 2 (3) between the first and last epochs, and for M87, 12 (13) of the 16 sources varied by less than a factor of 2 (3). Over all six epochs of M87, seven (11) of the 16 sources varied by less than a factor of 2 (3).



**Figure 3.** X-ray luminosity–luminosity plot for the candidate long-duration outburst BHLMBXB in NGC 1399 in linear space. The two most luminous sources above  $3 \times 10^{39} \text{ erg s}^{-1}$  have been omitted from the plot. The dotted and dashed lines represent variability of factors of 2 and 3, respectively, between epochs.

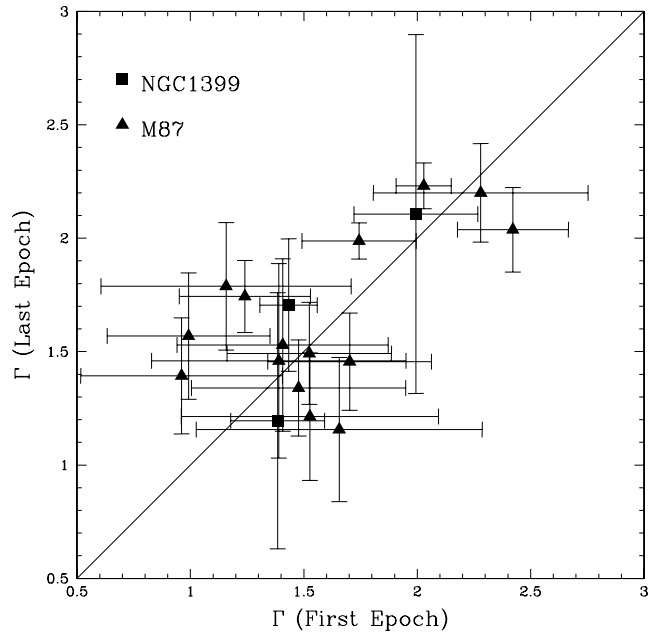


**Figure 4.** Same as Fig. 3 but for the first and sixth epoch observations of M87.

We also note that in a 89-ksec *ROSAT* HRI observation of NGC 1399 taken 1996 July 7, the three most luminous sources detected with *Chandra* are visible. Although the spatial resolution of the *ROSAT* HRI did not resolve two of the sources from their close neighbours, these two sources are so luminous that they must be responsible for a majority of the observed flux, indicating that all three sources were ‘on’ for at least 7 yr.

Sivakoff, Sarazin & Jordán (2005) detected rapid X-ray flares in three X-ray sources in the elliptical galaxy NGC 4697, one of which reached a peak luminosity of  $6 \times 10^{39}$  erg s<sup>-1</sup> for a duration of 70 s. We searched for such variability within each individual observation of NGC 1399 and M87. While in most instances the count rates were too low to make any strong statements, the vast majority of the sources did not show any evidence for significant (>2) variability on ~0.5-d time-scales.

The two sources more luminous than  $3 \times 10^{39}$  erg s<sup>-1</sup> deserve special mention. In general, sources more luminous than  $2\text{--}3 \times 10^{39}$  erg s<sup>-1</sup> are lacking from elliptical galaxies (Irwin, Bregman & Athey 2004), in contrast to spiral galaxies which are known to sometimes harbour large numbers of ‘ultraluminous’ X-ray sources, or ULXs. Whether ULXs result from accretion on to intermediate-mass black holes or beamed emission from stellar-mass black holes is the subject of much debate. This debate is avoided for sources in elliptical galaxies, which (except for a small handful of special sources) do not contain sources more luminous than the Eddington luminosity of a 15–20 M<sub>⊙</sub> black hole. However, one such source that might be classified as a ULX resides in a globular cluster of NGC 1399 and has an X-ray luminosity of  $5 \times 10^{39}$  erg s<sup>-1</sup> (Angelini et al. 2001). Another very luminous ( $10^{40}$  erg s<sup>-1</sup>) source in the upper right corner of Fig. 1 is located outside the  $D_{25}$  contour of NGC 1399 at a distance of 4.6 arcmin (27 kpc) from the centre of the galaxy. It therefore has an increased chance of being an unrelated high-flux foreground/background object rather than a LMXB, although there is presently no means of verifying this without follow-up optical imaging and spectroscopy of the optical counterpart. At any rate, the luminosity of these two sources changed very little between the two epochs.



**Figure 5.** Best-fitting power-law indices of the spectra of the luminous BLMXBs in NGC 1399 and M87. Error bars represent 90 per cent uncertainties on one free parameter. Only sources for which  $\Gamma$  could be constrained to better than  $\pm 1$  are plotted.

Fig. 5 shows how the spectra of the more luminous sources varied between the first and last epochs. Only sources for which  $\Gamma$  could be constrained to better than  $\pm 1$  are shown. Much like the luminosities of the sources, there was little variability in the spectral properties, with the power-law slopes of nearly all the sources consistent within the uncertainties between the two epochs. The simultaneous lack of luminosity and spectral variability argue against state transitions of any of the sources, as is commonly seen in Galactic LMXBs.

## 5 THE AVERAGE BURST DURATION

The fact that any one source remained in outburst during all the epochs does not itself put strong constraints on the burst duration beyond that of the elapsed time between the first and last observations. However, NGC 1399 and M87 contain such a large number of long-duration outburst BLMXBs that the burst duration must be considerably longer if none of the sources turned off between the first and last epochs. We can start with a simple approximation of the lower limit of this burst duration by first assuming that all the sources have the same burst duration. If this burst duration is denoted  $t_{\text{burst}}$  and the time between the first and last observations is denoted  $\Delta t$  then the probability that any one source is still in outburst  $\Delta t$  yr later is  $(t_{\text{burst}} - \Delta t)/t_{\text{burst}}$ , and the probability that  $n$  sources are still in outburst  $\Delta t$  yr later is  $[(t_{\text{burst}} - \Delta t)/t_{\text{burst}}]^n$ . Requiring that this quantity is equal to 0.05 sets the 95 per cent lower limit on  $t_{\text{burst}}$ .

For NGC 1399,  $\Delta t = 3.35$  yr and  $n = 18$ . This implies  $t_{\text{burst}} = 21.9$  yr at the 95 per cent confidence level. For M87,  $\Delta t = 5.30$  yr and  $n = 15$ , yielding a lower limit of 29.3 yr. Combining sources in both galaxies gives a burst duration of at least 48.9 yr.

Alternatively, we relaxed the requirement that all the sources have the same burst duration, and assumed that the burst duration distribution could be described by a Gaussian with a width of 10 per cent of the Gaussian mean. From this distribution, we randomly selected 33  $t_{\text{burst}}$  values and calculated the probability that 18 sources

remained on for 3.35 yr and that 15 sources remained on for 5.30 yr. The mean of the distribution was varied until the probability was 0.05. This was repeated for Gaussians with a width of 25 per cent and 50 per cent of the outburst mean. The Gaussian mean that lead to a probability of 0.05 was 49.7, 52.6 and 71.6 yr for distributions with widths of 10, 25 and 50 per cent of the mean, respectively. Unless the width of the distribution of outburst times is quite large (i.e. 50 per cent of the mean burst duration), the derived lower limit on the mean burst duration is not sensitive to the width, and gives a lower limit of about 50 yr. If the duty cycle for outbursts were on the order of a few per cent as is the case for Galactic short-duration outburst BHLMBs, such outbursts would repeat on the order of 1000 yr.

## 6 THE ORIGIN OF THE LONG-DURATION OUTBURST BHLMBs IN ELLIPTICAL GALAXIES

Given the transient nature of Galactic BHLMBs, the pre-*Chandra* assumption was that at least some of the brightest LMBs in elliptical galaxies would be observed to flash on and off on month time-scales. While an earlier *Chandra* study of NGC 1399 noted that many of these luminous sources were still in outburst several years later (Loewenstein, Angelini & Mushotzky 2005), our work is the first to point out that *all* the brightest (and therefore probable BH) LMBs present in the first epoch observations of NGC 1399 as well as M87 were still in outburst 3–5 yr later. Next, we investigate under what conditions and with what kind of donor star most readily explains this luminous, long-duration outburst population of BHLMBs.

### 6.1 Main-sequence donor binary systems

For systems for which Roche lobe overflow (and hence mass transfer) from the donor star to the BH occurs when the donor star is on the main sequence, mass transfer is driven by angular momentum losses from gravitational radiation and magnetic braking. Depending on which prescription for magnetic braking is assumed, Ivanova & Kalogera (2006; hereafter IK06) concluded that main-sequence donor systems can be either persistent or transient systems. They demonstrate that such systems are persistent X-ray emitters if magnetic braking angular momentum losses dominate gravitational radiation losses, if the mass of the black hole is less than  $10 M_{\odot}$ , and if the donor star has a mass exceeding  $0.3 M_{\odot}$ . However, they also demonstrate that such persistent systems have mass transfer rates that are only 1–25 per cent of the Eddington rate, and would therefore only be capable of producing X-ray luminosities on the order of  $10^{38}$  erg s<sup>-1</sup> or less, an order of magnitude below the observed X-ray luminosities. Even if  $10^{39}$  erg s<sup>-1</sup> could be achieved, the required mass accretion rate that would be required to power such a large luminosity is  $\approx 2 \times 10^{-7} M_{\odot}$  yr<sup>-1</sup> (assuming 10 per cent accretion efficiency), implying active lifetimes of less than 5 million yr before the mass of the entire low-mass donor star is consumed. Such a short active lifetime would imply that a continuous replenishment of these sources would be needed. As we discuss below, such a continuous supply would only be possible within globular clusters and would not explain sources in the field.

Transient sources with main-sequence donors also fail to explain the length of the observed burst duration. A source will only be in outburst until the mass that has accumulated in the disc is drained and consumed by the BH. King (2006) summarizes how the decay constant for an outburst is approximately  $\tau \simeq 40 R_{11}^{5/4}$  d, where  $R_{11}$  is the radius of the orbit in units of  $10^{11}$  cm. Since main-sequence

stars around a black hole will only fill their Roche lobe if the binary period is less than 1–2 d, this implies that burst durations for main-sequence donor systems will be less than a year. The rather small size of accretion discs in main-sequence donor binaries will be drained in too short a time frame to explain the long-duration outburst sources seen in NGC 1399 and M87.

### 6.2 Long-period red giant donor binary systems

Given the short outburst decay time predicted for binaries with 1–2 d periods, binaries with periods on the order of 30 d or more might provide a means of explaining decades-long X-ray outbursts. For longer period binaries, the donor star will fill its Roche lobe and initiate mass transfer only after it has begun to ascend the giant branch. Thus, mass transfer is driven by the evolution of the donor rather than from angular momentum losses from magnetic braking or gravitational radiation. The large size of the accretion disc in long period binaries ensures that it is practically impossible for irradiation to keep the entire disc above the hydrogen ionization temperature, the condition for persistent emission. Indeed, King et al. (1997) and King (2000) have shown that all BH binaries with orbital periods in excess of a few days will be transient. If the accretion disc is a sizable fraction of the orbit, the drainage time of the disc can be several decades or more, leading to periods of extended outburst. This is believed to be the case for GRS 1915+105 (V1487 Aql), the only Galactic BHLMB that resembles the sources in NGC 1399 and M87. GRS 1915+105 has been in outburst since its discovery in 1992 (Castro-Tirado et al. 1992), has an orbital period of 33.5 d (Greiner, Cuby & McCaughrean 2001) and an orbital separation of  $7.5 \times 10^{12}$  cm. Based on the size of its accretion disc and assumed mass transfer rate of the donor star, Vilhu (2002) and Truss & Done (2006) have estimated that the time for the disc of GRS 1915+105 to empty is probably on the order of 20–40 yr, indicating that the end of the outburst of GRS 1915+105 might be in sight. This estimate is comparable to the lower limit we derived on the burst duration of luminous sources in NGC 1399 and M87 of 50 yr, with likely recurrence times of hundreds if not thousands of years. Long-period red giant binaries are therefore a viable option for explaining the nature of these sources.

In the Milky Way, there is no known LMB in a globular cluster with a period of more than a day, and three have periods less than an hour (Podsiadlowski, Rappaport & Pfahl 2002). Yet the long burst duration of BHLMBs in globular clusters of NGC 1399 and M87 suggests that long-period LMBs can exist in such an environment. Kalogera, King & Rasio (2004) demonstrate that black hole binaries with the required orbital periods can be created in globular clusters via exchange interactions. On the other hand, binaries created by tidal capture are likely to lead to much shorter orbital periods. The lack of a confirmed long-period LMB in the Milky Way globular cluster system is not necessarily an argument against this interpretation of what the luminous sources are. The fact that our Galaxy lacks a ULX or a  $10^{39}$  erg s<sup>-1</sup> X-ray source within its globular cluster system is a clear indicator that the Milky Way should not necessarily be used as a template for what should or should not exist in other galaxies.

### 6.3 White dwarf donors in ultracompact binary systems

Another alternative is that the donor stars are white dwarfs in a very tight, ultracompact (UC) binary system with the BH. Such systems have orbital periods on the order of minutes, and mass transfer is

dominated by angular momentum losses from gravitational radiation. The most X-ray luminous LMXB in a Galactic globular cluster (4U 1820–30 in NGC 6624) with  $L_X \sim 5 \times 10^{37} \text{ erg s}^{-1}$  is a persistent UC (NS) system with an orbital period of only 11.4 min (Stella, Priedhorsky & White 1987). Recently, Bildsten & Deloye (2004) have postulated that extragalactic LMXBs with luminosities in the range  $6 \times 10^{37} < L_X < 5 \times 10^{38} \text{ erg s}^{-1}$  are best explained by UC systems with He or C/O donors and NS accretors. Such a scenario not only correctly predicts the slope of the LMXB XLF in galaxies in this luminosity range, but also provides a means for explaining the number of millisecond radio pulsars in Galactic globular clusters (assuming UC binaries are the precursors to millisecond radio pulsars).

UC binaries with NS accretors are unlikely to produce X-ray luminosities exceeding  $8 \times 10^{38} \text{ erg s}^{-1}$ . Such super-Eddington accretion rates would be very difficult to maintain on several year time-scales as the *Chandra* data imply. However, UC binaries with black holes could achieve such high X-ray luminosities. IK06 have concluded that black hole UC systems are transient if the mass of the white dwarf is less than  $\sim 0.035 M_\odot$  and persistent if it is above this value. Transient systems will be unable to produce decade long outbursts owing to the small size of its accretion disc, as discussed above. Persistent systems are expected to have active X-ray lifetimes of  $\simeq 20 \times 10^6 \text{ yr}$  (IK06) although at the high mass accretion rate needed to fuel a  $10^{39} \text{ erg s}^{-1}$  source, the white dwarf donor would be consumed in less than a few million yr. This would imply that either we are observing them at a special point in their evolution, or systems of this nature are formed continuously over the age of the galaxy in order to replenish sources that have consumed all the mass of the donor.

Globular clusters would be an obvious site for the frequent ongoing creation of UC black hole systems. However, there are two problems with this explanation for the origin of the luminous X-ray sources within elliptical galaxies. First, it does not explain why luminous X-ray sources occur in the field where ongoing UC binary creation would not be expected. While it has been suggested that most if not all field LMXBs actually formed within globular clusters and were later ejected into the field (White, Sarazin & Kulkarni 2002), current observational evidence does not support this claim. Irwin (2005) has shown that the relation between the number (or total X-ray luminosity) of LMXBs and the number of globular clusters in early-type galaxies is flatter than if there were a one-to-one correspondence between the two quantities, indicative of a truly field-born population. Also, Kim et al. (2005) have found that the field LMXBs in six elliptical galaxies (including NGC 1399 and M87) follow the optical light of the galaxies rather than the flatter globular cluster distribution. They also find that field LMXBs are not preferentially located near globular clusters as might be expected if LMXBs regularly escaped from their globular cluster birthplace. Secondly, as IK06 point out, black holes in globular clusters have a strong tendency to dynamically separate from the rest of the cluster, as well as eject each other from the cluster until only one (at most) black hole remains (e.g. Kulkarni, Hut & McMillan 1993; Sigurdsson & Hernquist 1993). Therefore, although globular clusters might be efficient at creating one black hole UC system, they are not capable of replenishing the population of X-ray active black hole UC systems.

In summary, we conclude that long-period black hole binaries with red giant donor stars are the most likely candidates for explaining the luminous long-duration outburst X-ray sources in elliptical galaxies. The Galactic BHLMXB GRS 1915+105 appears to be the closest analogue to these sources that our Galaxy contains.

#### 6.4 Where are the short-period binaries in elliptical galaxies?

We have argued that the most luminous X-ray sources in NGC 1399 and M87 are long-period red giant binaries much like GRS 1915+105. However, in the Milky Way, the long burst duration of GRS 1915+105 is unique, as GRS 1915+105 is outnumbered by shorter burst duration BHLMXBs by a count of 14 to 1. One may ask why these short burst duration systems are not seen in the *Chandra* data. The most likely answer is that sources like the more typical Galactic BHLMXBs spend such a small fraction of the time above  $8 \times 10^{38} \text{ erg s}^{-1}$  that short (<2 d) *Chandra* observations separated by a year or more are unlikely to have caught such a flaring BHLMXB near its peak. If we assume that the duty cycle of short-duration outburst BHLMXBs is about 1 per cent (an outburst lasting approximately one month every 10 yr), then the odds that  $n$  such sources are quiescent at any given time is  $(0.99)^n$ . Setting this equal to 0.05 gives a 95 per cent upper limit on the number of short-duration outburst BHLMXBs of about 300 in both galaxies combined. This is not an unreasonable number considering that NGC 1399 and M87 are significantly larger and harbour many more globular clusters than the Milky Way. Given the 33 long-duration outburst BHLMXBs identified in this study, an upper limit of the short-to-long-duration outburst BHLMXB ratio of 9 is found. This is slightly lower than, although consistent with, the ratio of 14 to 1 found among BHLMXBs in the Milky Way. Furthermore, inspection of the burst profiles of Galactic BHLMXBs such as 4U 1543–47 or XTE J1859+226 (McClintock & Remillard 2006) shows that Galactic BHLMXBs do not always peak at X-ray luminosities exceeding  $8 \times 10^{38} \text{ erg s}^{-1}$  – the criterion we used to identify BHLMXBs in NGC 1399 and M87 in the first place – so the short-to-long-duration outburst ratio in NGC 1399 and M87 might be somewhat higher. It is also possible that the *Chandra* observations have caught a few short-duration outbursts on their way up or down from their peaks when their X-ray luminosities were below  $8 \times 10^{38} \text{ erg s}^{-1}$ . As mentioned above, there were fainter sources that were detected in one observation but not others.

#### 6.5 The remarkably steady emission of elliptical galaxy BHLMXBs

The X-ray emission from the luminous sources in NGC 1399 and M87 is quite steady. Of all the sources that reached  $8 \times 10^{38} \text{ erg s}^{-1}$  in at least one of the observations, only one source showed variability of more than a factor of 5. This contrasts strongly with GRS 1915+105, which exhibits flux changes of nearly a factor of 10 on <100 d time-scales (Truss & Wynn 2004). As GRS 1915+105 is presently unique among Galactic LMXBs as far as its burst duration, we unfortunately have little else to use as a comparison to the luminous sources in NGC 1399 and M87. Interestingly, LMXBs occurring in globular clusters of M31 are highly variable too (Trudolyubov & Priedhorsky 2004), although only one of these sources had a peak X-ray luminosity above  $8 \times 10^{38} \text{ erg s}^{-1}$ , and this source varied by only a factor of 2. The one source in our sample that did show large variability (CXOU J123054.9+122438) steadily increased in luminosity from 0.8 to 3 to  $25 \times 10^{38} \text{ erg s}^{-1}$  from 2000 July to 2002 July to 2005 January before levelling off to  $\sim 10^{39} \text{ erg s}^{-1}$  from 2005 March to 2005 November (the last epoch). Thus, the 2000 July observation might have just caught the turn-on of this source.

Multiple-epoch *Chandra* observations also exist for several spiral galaxies that harbour luminous X-ray sources, such as M51 and the Antennae galaxies. While these galaxies host ULXs with X-ray luminosities far exceeding any LMXB in an elliptical galaxy, they

also contain X-ray sources in the range of those sources considered here in NGC 1399 and M87. It is unlikely, though, that as a group these  $\sim 10^{39}$  erg s $^{-1}$  sources in spiral galaxies have much in common with the luminous sources in NGC 1399 and M87 other than the magnitude of their luminosities. It is unclear whether the  $\sim 10^{39}$  erg s $^{-1}$  sources in spiral galaxies are intermediate-mass black holes emitting at a lower fraction of their Eddington limit than ULXs, or if they are stellar-mass black holes emitting near their Eddington limit. At any rate, it is likely that most of them have massive, young donor stars unlike the NGC 1399 and M87 sources. Another difference is their variability on  $\sim 3$  yr time-scales. Of the nine sources in M51 in this luminosity range, six showed variability of at least a factor of 2, and a few showed  $>10$  variability (Dewangan et al. 2005). The same is true of several  $\sim 10^{39}$  erg s $^{-1}$  sources in the Antennae (Fabbiano et al. 2003). This contrasts with the sources in NGC 1399 and M87, for which only  $\sim 30$  per cent show variability of a factor of 2 or more, and only 3 per cent show variability greater than a factor of 5.

## 7 CONCLUSIONS AND FUTURE WORK

In this paper, we have discussed the remarkably steady nature of the most luminous X-ray sources in NGC 1399 and M87. All the luminous X-ray sources present in the first epoch *Chandra* observations of these two galaxies were still present in the last epoch observations 3–5 yr later (as well as in observations in between). The high mass transfer rates required to generate the high X-ray luminosities rule out persistent emission unless these types of sources are replenished frequently. This is unlikely to occur, especially in the field. Given that these sources must therefore be transient, their long ( $>50$  yr) outburst duration strongly argues that they must have very large accretion discs with a radius of at least  $10^{13}$  cm, a condition met only if the orbital period is on the order of 30 d or more (such as in GRS 1915+105). This requires the donor star to be a red giant in order for it to have filled its Roche lobe. IK06 predicted that the brightest LMXBs within elliptical galaxies would be primarily long-period binaries with red giant donors if the standard magnetic breaking description for approximating angular momentum losses is assumed, but also predicted that shorter period main-sequence donors would dominate if a weaker magnetic breaking description were assumed. Our work here indicates that the standard magnetic breaking description appears to describe more accurately angular momentum losses in BHLMXBs with main-sequence donors.

Given the long outburst times of GRS 1915+105 and the sources discussed here, it is likely that their recurrence times are quite long, on the order of 1000 yr. This would imply that there could be a reservoir of many inactive long-period BHLMXBs in the Milky Way for which an outburst has not been recorded in the relatively short 40 yr history of X-ray astronomy. The presence of BHLMXBs similar to GRS 1915+105 in other galaxies indicates that GRS 1915+105 is not necessarily such an unusual or unique object, and that the true ratio of short-to-long-period binary LMXBs might be considerably smaller than currently believed.

It still might be possible that persistent black hole UC binaries are responsible for the luminous sources in globular clusters, if not in the field. Future monitoring of NGC 1399 and M87 will address this issue. If the luminous sources in globular clusters are persistent UC systems in their active (few  $\times 10^6$  yr) phase, no sources are likely to turn off (or on) on a time-scale as short as a decade. On the other hand, if the globular cluster sources are long-period binaries in a decades-long outburst, at least a few of these sources are expected to turn off, and new sources turn on, on time-scales on the order of

a decade. The brightening of source CXOU J123054.9+122438 in M87 would argue for the long-period binary explanation, especially in light of the fact that the source resides within a globular cluster. Revisiting NGC 1399 and M87 in a few years might prove to be quite illuminating in further constraining the burst duration of these enigmatic sources, and in particular CXOU J123054.9+122438. Observations of NGC 1399 and M87 taken 10 yr after the first epoch observations will yield 95 per cent lower limits of over 100 yr for the burst duration should none of the 33 long-duration BHLMXBs be observed to turn off.

Finally, we note that caution must be used in searching for transient LMXBs in smaller galaxies for which contamination from background AGN is more of a concern. Unless an X-ray source can be positively identified as residing inside a globular cluster of the galaxy, doubt will remain as to whether the source is a LMXB or an AGN. To illustrate this, we inspected *Chandra* observations of eight clusters of galaxies chosen at random which were observed more than once with observations separated by at least a year. In two of the fields (A1413 and A1795), there appeared a high-flux ( $3\text{--}16 \times 10^{-14}$  erg s $^{-1}$  cm $^{-2}$ ) point source in one observation that was absent in the other observation, corresponding to a flux change of at least a factor of 100. No optical counterpart was evident for either source. These sources must be AGN, or less likely foreground Milky Way stars. Given the relative ease at which we found such bright but wildly variable X-ray sources that are clearly not LMXBs but not obviously background AGN illustrates the confusion that could arise if such a source happened to fall in the field of view of an observation of an elliptical galaxy and was mistaken for a LMXB in that galaxy. The large number of bright LMXBs in galaxies such as NGC 1399 and M87 statistically guard against such an event.

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