Variable Low-Mass X-ray Binaries in Early-Type Galaxies

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Abstract. As the *Chandra X-ray Observatory* mission matures, increasing numbers of nearby galaxies are being observed multiple times, sampling the variability of extragalactic X-ray binaries on timescales extending from seconds to years. We present results on luminous low-mass X-ray binaries from several early-type galaxies. We show that instantaneous LMXB luminosity functions of early-type galaxies do not significantly change between observations; a relatively low fraction of sources are strongly variable on $\lesssim$ 5yr timescales. We discuss the implications that a relatively small number of transient LMXBs are being discovered in early-type galaxies.

1. Introduction

The detailed study of Galactic X-ray binaries (XRBs) has placed strong constraints on theories of XRB evolution and accretion (see reviews of Tauris & van den Heuvel 2006; King 2006). These studies are limited by the ~ 300 active Galactic XRBs (Liu et al. 2006, 2007). Fewer XRBs have well determined distances and absorption column densities, or have high luminosities ($L_X \sim 10^{38-39}\,\mathrm{erg\,s^{-1}}$). The luminous systems are of interest as they likely contain neutron stars (NSs) or black holes (BHs) radiating near or above the Eddington limit: $L_{\rm Edd} \simeq 1.3 \times 10^{38} M_{\rm co}/M_{\odot}\,\mathrm{erg\,s^{-1}}$ for spherical accretion of hydrogen onto a compact object of mass $M_{\rm co}$.

Low-mass X-ray binaries (LMXBs) have companions of $\lesssim 1 M_{\odot}$ that are typically undergoing Roche-lobe overflow. If radiating near $L_{\rm Edd}$, the entire mass of the companion can be accreted in $\lesssim 10^8$ yr for accretion duty cycles of unity. This would imply that observed LMXBs formed recently. Alternatively, the duty cycle can be lower if the episodes of near Eddington accretion are transient, and observed LMXBs need not have formed recently. The transient behavior of LMXBs has been attributed to a disk instability first identified

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in cataclysmic variables (van Paradijs 1996). In short-period systems ($P_{\rm orb} \lesssim 12$ hr) where the companion is a main-sequence star, theory predicts most LMXBs are persistent (King 2006). An evolved companion, which is somewhat surprising at these periods, could explain the short-period transients with BHs (and some NSs) observed to have outbursts with timescales of $\sim$ 10s of days. In longer-period binaries, transient systems are expected, and should have longer outbursts due to their larger disks. One such source, GRS 1915+105, has been in outburst for 15 yr. Thus, the luminosity functions of entire populations of LMXBs depend on the mass spectrum of accretors, transient duty cycle, companion types (main-sequence, red giant, or white dwarf), and stellar age (e.g., Ivanova & Kalogera 2006, and Kalogera et al. 2008 in these proceedings).

With the launch of the *Chandra X-ray Observatory*, luminous XRBs in more distant galaxies are now routinely being studied (e.g., references in Fabbiano & White 2006). Extragalactic studies are complementary to Galactic studies. Large numbers of XRBs that share a relatively common distance and absorption column density are revealed; however, many binary properties (e.g., compact object mass, donor type, orbital period) cannot be directly observed. For the old stellar populations in early-type galaxies, the X-ray binaries are LMXBs. Although the studies of resolved LMXBs in early-type galaxies are typically limited to $L_X \gtrsim 10^{37}$–10^{38} erg s^{-1}, tens to hundreds of sources can be detected in a single galaxy. X-ray variability can help shed light on the nature of these luminous LMXBs.

As the *Chandra* mission matures, more early-type galaxies are being observed multiple times, revealing LMXB variability on timescales of seconds to years. We discuss some results from multi-epoch observations of NGC 4697, NGC 4365, and Centaurus A (Cen A) in this paper[1]. For both NGC 4697 (11 Mpc; Jordán et al. 2005) and NGC 4365 (20 Mpc; Tonry et al. 2001), four $\sim$ 40 ks ACIS-S observations were made $\sim$ 4 yr after initial $\sim$ 40 ks observations (Sarazin, Irwin, & Bregman 2000, 2001; Sivakoff, Sarazin, & Irwin 2003). Recently six $\sim$ 100 ks ACIS-I observations of Cen A (3.7 Mpc, averaging 5 distance indicators from § 6 in Ferrarese et al. 2007) were analyzed with shorter archival observations taken $\sim$ 4–7 yr earlier. In this paper, we focus on the variability between observations.

2. LMXB Luminosity Functions in NGC 4697 and NGC 4365

For NGC 4697 and NGC 4365, we performed standard reduction and flare removal. We used CIAO WAVDETECT to detect sources (158 in NGC 4697; 322 in NGC 4365) in the combined 185 ks (NGC 4697) and 194 ks (NGC 4365) observations. For each observation, we determined the count rates from PSF-scaled source regions and local backgrounds. We converted count rates to luminosities assuming a 9.1keV bremsstrahlung spectrum and correcting for vignetting, the PSF, and QE degradation. We display the cumulative instantaneous luminosity function of each observation in Figure 1. We find no evidence for changes in the instantaneous luminosity functions over < 4.6 yr. Thus, variability on such timescales will not affect interpretations of luminosity functions from single observations.

The relatively constant luminosity function could result from either sources that are not strongly variable, or sources that are strongly variable, but whose average luminosity function is relatively constant. To address this, we determined the fraction of sources that are strongly variable between any two observations (*left* of Figure 2) or over the entire set of observations. We classify a source as strongly variable if χ^2 testing against a constant luminosity indicates the probability a source is variable is $> 95.4\%$ (i.e, $> 2\sigma$). For example,

[1]Multi-epoch observations of NGC 3397 are discussed by Brassington et al. (2008) in these proceedings.

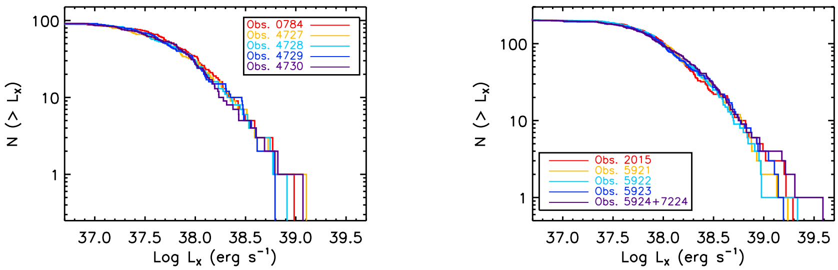

Figure 1. Cumulative, instantaneous luminosity functions from five observations of NGC 4697 (*left*) and NGC 4365 (*right*). These functions do not vary strongly over 4.6 yr.

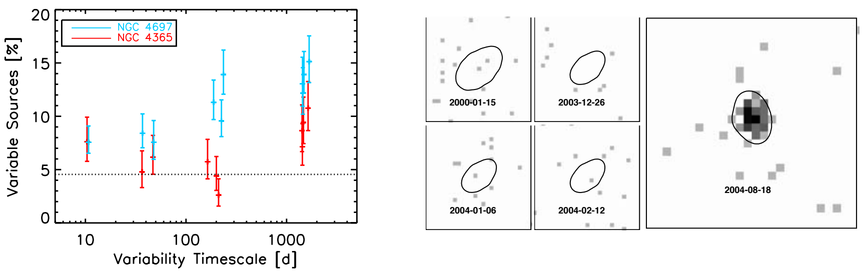

Figure 2. (*Left*) The fraction of sources in NGC 4697 and NGC 4365, that are strongly variable between any two observations as a function of the timescale between the observations. Strongly variable LMXBs are not common. (*Right*) A transient source in NGC 4697 with 87 counts in the last observation, but only 5 in all of the previous observations.

we require $\chi^2 > 4$ when comparing any two observations. We only test sources whose average luminosity over all five observation is more than 3σ above zero in calculating the fractions. There are 124 and 232 such sources in NGC 4697 and NGC 4365; however, the number of these sources in a given observation is smaller due to varying field-of-views. The fraction of strongly variable sources between any two observations ranges from $\sim$ 3–15%, but is roughly consistent with 8%. The variable fraction considering all five observations is $\approx 16 \pm 4\%$ for NGC 4697 and $\approx 13 \pm 3\%$ for NGC 4365. Strongly variable LMXBs are not common.

3. Transient LMXBs

Most of the sources in NGC 4697 and NGC 4365 are persistent over 4.6 yr timescales. This leads to two potential interpretations: the majority of observed sources are persistent LMXBs or are transients sources with outbursts that last $\gg$ 5 yr.

Among the strongly variable LMXBs, we identify several sources as transient candidates. We do this by grouping each variable source into two luminosity states. Transient candidates

Table 1. Breakdown of Luminous ($L_X > 8 \times 10^{38}$ ergs^{-1}) LMXBs

Galaxy	Transient Srcs. [Number]	Persistent Src. [Number]	Foreground/Background Srcs. [Number]	Max Baseline [yr]
NGC 1399	0	21	3	3.3
M87	0	16	1	5.6
NGC 4697	1[a]	4	1	4.6
NGC 4365	1[b]	9	1	4.6
Total	2	50	6	∼4.4

[a]Supersoft ULX of unknown origin; [b]Candidate BH-LMXB in a globular cluster.

are sources where the luminosity of the fainter (quiescent) state is less than 3σ above zero and the luminosity of the brighter (outburst) state is more than 3σ above zero and occurs over consecutive observations. There are eleven transient candidates in NGC 4697 and twelve transient candidates in NGC 4365, most of which either turn on or turn off. For each galaxy, we estimate the average outburst timescale assuming all sources in a galaxy are transients undergoing long-duration outbursts and we detected the beginning or end of that outburst in all of our transient candidates. We estimate relatively consistent outburst timescales of ~ 100 yr in NGC 4697 and ~ 180 yr in NGC 4365; however, we note that either assumption could be violated. The presence of persistent NS-LMXBs cannot be ruled out at the $\gtrsim 10^{37}$ erg s^{-1} luminosities we probe. Only four transient candidates had an outburst luminosity more than ten times the limit on the quiescent luminosity (at $> 3\sigma$ confidence), and are considered clear transient sources (e.g., the clear transient in NGC 4697 is displayed in the *right* of Figure 2).

To mitigate these uncertainties, one can only consider the brightest LMXB candidates ($L_X > 8 \times 10^{38}$ erg s^{-1}). Such sources will not be weakly varying LMXBs near the detections limits and would be super-Eddington for a typical NS-LMXB. Although multiple NS-LMXBs in extragalactic GCs (Sivakoff et al. 2007a; Kundu, Maccarone, & Zepf 2007) could be more luminous, multiple NSs near the Eddington limit would be required. In Irwin (2006), the lack of transient sources among luminous LMXBs was used to imply outburst timescales of $\gtrsim 50$ yr. In Table 1, we summarize the data for these galaxies, adding NGC 4697 and NGC 4365. Averaging all galaxies together, we estimate outburst timescales of ~ 200 yr for the brightest LMXBs.

4. Discussion

Multi-epoch observations of LMXBs in early-type galaxies have revealed long-term variable LMXBs; however, they are a minority ($\sim$ 10–15%) and do not strongly affect the luminosity functions of LMXBs. Most LMXBs are persistent over ~ 5 yr timescales, implying either a prevalence of inherently persistent sources or that the sources are transient on longer timescales. We argue that having all sources undergo outbursts with timescales of $\sim$ 100–200 yr is consistent with our observations. This is particularly true for the most luminous LMXBs. A picture is emerging where these sources are analogs of GRS 1915+105, i.e., long-period binaries with an evolved companion. Recent modeling of GRS 1915+105 (Wynn et al. 2008, in these proceedings) is also consistent with an outburst timescale of ~ 100 yr.

To estimate the duty cycle, one needs both an outburst duration and a recurrence timescale. For ~ 100 yr outbursts, the recurrence timescale will be beyond the reach of direct measurements, requiring alternative estimates of the recurrence timescale. One estimate of ~ 1500 yr comes from the crustal heating recurrence timescale for the Galactic NS-LMXB

KS 1731−260 (Rutledge et al. 2002). This would imply a duty cycle of $\sim 10\%$. Comparing the number of active and quiescent LMXBs in Galactic GCs (Heinke et al. 2003) yields a similar duty cycle of $\sim 12\%$. Such duty cycles also have support from the theoretical side. The duty cycle of GRS 1915+105 is estimated to be $\sim 4\%$ (Wynn et al. 2008, in these proceedings) and duty cycles of $\sim 10\%$ are required to fit the luminosity functions of early-type galaxies (Kalogera et al. 2008, in these proceedings). This suggests a healthy outlook for future probes of the duty cycle by both observations and theory.

An outstanding issue is the lack of shorter-term transients, like those of Galactic short-period transient LMXBs, detected in early-type galaxies. Only NGC 4365 has three transients whose outburst timescales could be on the order of years or less; however, the observations are too shallow to confirm their transient nature. In the more nearby Cen A, there are two clear, luminous transients, but no luminous persistent sources (Sivakoff et al. 2007b). One source is a recurring transient with outbursts that last $\lesssim 2$ yr, while the single outburst of the other has lasted > 70 d. Unless the latter source proves to have a much longer duration outburst, the rates and types of luminous transients in Cen A may be anomalous compared to other early-type galaxies. Before asserting that shorter timescale transient binaries do not exist in large numbers in early-type galaxies, more work needs to be spent on understanding whether the observational strategies employed were sufficient to detect such transients. Future cadence times between observations and lengths of individual observations may need adjustment.

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