LOW MASS X-RAY BINARIES AND GLOBULAR CLUSTERS IN EARLY-TYPE GALAXIES

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ABSTRACT

Chandra observations have allowed the detection of a large number of low mass X-ray binaries (LMXBs) in early-type galaxies. Comparisons to catalogs of globular clusters (GCs) from Hubble Space Telescope observations have shown that a high fraction of the LMXBs in early-type galaxies are associated with GCs. The fraction of LMXBs associated with globular clusters increases along the Hubble sequence from spiral bulges to S0s to Es to cDs. On the other hand, the fraction of globular clusters which contain X-ray sources appears to be roughly constant (∼4% for $L_X \gtrsim 10^{38}$ ergs/s, ∼10% for $L_X \gtrsim 10^{37}$ ergs/s). There is a strong tendency for the X-ray sources to be associated with the optically more luminous GCs. There is a trend for the X-ray sources to be found preferentially in redder, more metal-rich GCs, which is independent of optical luminosity correlation. The relative role of formation of LMXBs in GCs and in situ formation in the field is uncertain. One of the best ways to study this is to compare the spatial distribution of GC-LMXBs, field LMXBs, GCs, and optical light in the galaxies. Theoretical models and results of fits to the observed distributions are presented. Our multiple observations of NGC 4365 and NGC 4697 over several years allow us to study the variability of LMXBs. We have detected very luminous X-ray flares from three sources in NGC 4697 with durations of ∼70 to ∼3000 seconds, which have no clear analogue in our Galaxy. One suggestion is that these are due to micro-blazars; X-ray binaries with accreting black holes with jets which are pointed in our direction.

Key words: early-type galaxies; globular clusters; X-ray binaries .

1. INTRODUCTION

Chandra observations have resolved most of the X-ray emission in X-ray-faint early-type galaxies into individual point-like sources (e.g., Sarazin, Irwin, & Bregman, 2000). Given their properties and the stellar populations in these galaxies, these X-ray sources are assumed to be Low Mass X-ray Binaries (LMXBs). A significant fraction (∼20-70%) of the LMXBs are associated with globular clusters in the host galaxies (Sarazin et al., 2001; Angelini et al., 2001). The fraction of LMXBs located in GCs is much higher than the fraction of optical light, which indicates that stars in GCs are much more likely (by a factor of ∼500) to be donor stars in X-ray binaries than field stars. As has been known for a number of years, a similar result applies to our own Galaxy and to the bulge of M31 (e.g., Hertz & Grindlay, 1983). This is generally believed to result from stellar dynamical interactions in globular clusters, which can produce compact binary systems.

X-ray observations with *ASCA* indicated that the total luminosity of LMXBs in early-type galaxies correlated better with the number of GCs than with the optical luminosity of the galaxy (White et al., 2002). This is somewhat surprising, as a nontrivial fraction (∼ 50%) of the LMXBs in most of the early-type galaxies observed so far with *Chandra* are not identified with GCs. This suggests that most (perhaps all?) of the LMXBs in early-type galaxies were made in GCs (Grindlay, 1984; Sarazin et al., 2001; White et al., 2002). The field LMXBs might have been ejected from globular clusters individually by stellar dynamical processes (or possibly by supernova kicks), or emerged when globular clusters were destroyed by tidal effects. Alternatively, the field LMXBs may have been made in situ from primordial binaries.

2. STATISTICS OF LMXBS AND GC POPULATIONS

The fraction of LMXBs in a galaxy which are associated with GCs increases along a Hubble sequence from spiral bulges (∼10%) to S0s (∼20%) to giant ellipticals (∼50%) to cD galaxies (∼70%) (Sarazin et al., 2003). There is a well-established trend for the specific fre-

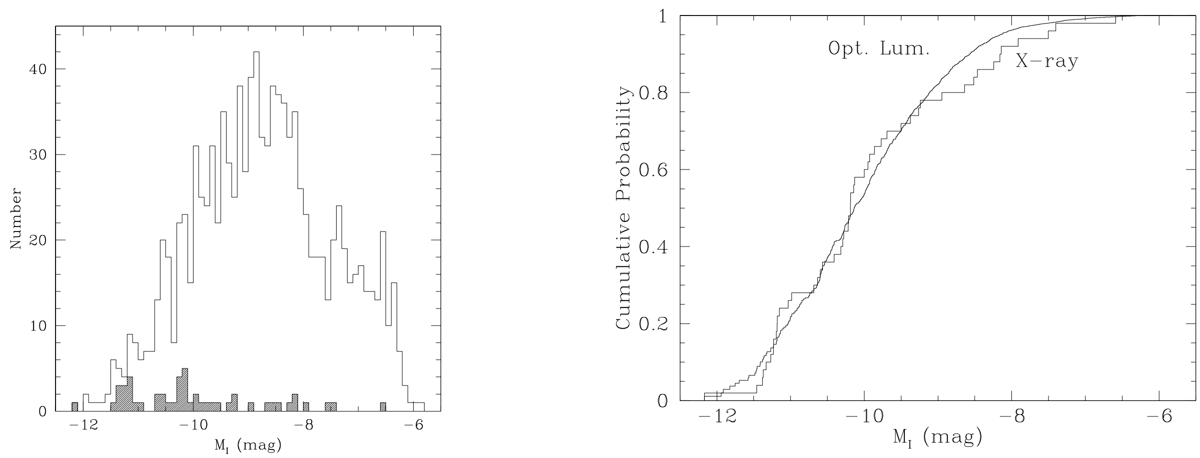

Figure 1. (a) Histograms of the number of globular clusters versus their absolute magnitude M_I in a sample of galaxies with Chandra data (Sarazin et al., 2003). The upper histogram is for all of the GCs in the galaxies. The lower shaded histogram shows the GCs which contain identified LMXBs. (b) Cumulative distribution functions for the probability that a GC contains an X-ray source ("X-ray") and for the optical luminosity of GCs ("Opt. Lum.").

quency of GCs in galaxies (S_N, the number of GCs per optical luminosity) to increase along the same Hubble sequence (e.g., Harris, 1991). The detailed correlation of the fraction of LMXBs in GCs with S_N is more consistent with most of the field LMXBs being made in situ in the field (Juett 2005; see also Maccarone et al. 2003; Sarazin et al. 2003). On the other hand, Irwin (2005) argued recently that a significant portion of the field LMXBs in S0 galaxies may have come from disrupted GCs.

The fraction of globular clusters which contain X-ray sources appears to be roughly constant from galaxy to galaxy. For samples of LMXBs with a high limiting X-ray luminosity, $L_X \gtrsim 10^{38}$ ergs/s, the fraction is $\sim$4% (Kundu et al., 2002; Sarazin et al., 2003). For NGC 4697, a nearby elliptical with deep X-ray and GC observations, the fraction reaches $\sim$10% for $L_X \gtrsim 10^{37}$ ergs/s (Sivakoff et al., 2006).

3. PROPERTIES OF GCS CONTAINING LMXBS

Figure 1(a) shows histograms of the absolute I magnitude, M_I, of the total GC sample (upper histogram) and of the GCs containing LMXBs (shaded histogram). The LMXBs seem to be associated preferentially with the more optically luminous GCs (Angelini et al., 2001; Kundu et al., 2002; Sarazin et al., 2003). For example, the median value of M_I for non-X-ray GCs is -8.7, while the corresponding value for the X-ray GCs is -10.2. Using the Wilcoxon or equivalent Mann-Whitney rank-sum tests, the distribution of X-ray and non-X-ray GC luminosities are found to disagree at more than the 6σ level.

Of course, a correlation between optical luminosity and the probability of having an X-ray source is not unexpected. LMXBs contain normal stars, and globular clusters which have higher luminosities have more stars as potential donors in LMXBs. Thus, it is interesting to test the hypothesis that the probability that a GC contains a LMXB is proportional to its optical luminosity. Figure 1(b) compares the cumulative probability distribution of LMXBs versus the cumulative distribution of the optical luminosity in GCs. The two cumulative distribution functions track one another fairly well. For example, half of the optical luminosity comes from GCs brighter than $M_I = -10.1$, while the medium absolute magnitude of GCs with LMXBs is -10.2. The KS two-sample test was used to compare the two distributions; they are not significantly different. Thus, the current data indicate that optically bright GCs are much more likely to contain LMXBs than faint GCs, but the distribution is consistent with a constant probability per unit optical luminosity (Kundu et al., 2002; Sarazin et al., 2003). Recently, Jordán et al. (2004) found a correlation between the density of stars in M87 GCs and the occurrence of LMXBs. This would be consistent with the formation of LMXBs by dynamical collision processes in GCs, although the detailed form of the correlation found by Jordán et al. (2004) was also nearly equivalent to a simple dependence on the number of stars.

Figure 2 shows histograms of the $V - I$ colors for the total GC sample (upper histogram) and for the GCs containing LMXBs (shaded histogram). Because the sample contains a number of different galaxies, the overall color distribution may be less obviously bimodal than that seen in some individual galaxies. The LMXBs appear to be associated preferentially with the redder GCs (larger values of $V - I$) (Angelini et al., 2001; Kundu et al., 2002; Sarazin et al., 2003). The median color of the non-X-ray GCs is $V - I = 1.07$, while the corresponding median for the X-ray GCs is 1.14. Using the Wilcoxon or Mann-Whitney rank-sum tests or the KS test, the probabilities that the two color distributions where drawn from the same distribution are <0.2%. Roughly, red GCs are three times as likely to harbor a LMXB as blue GCs.

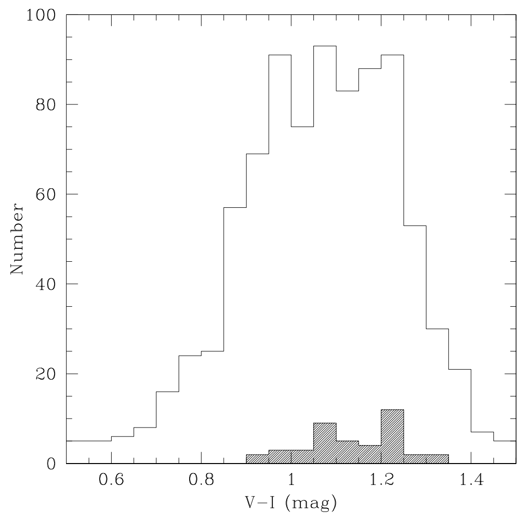

Figure 2. Histograms of the number of GCs versus their optical color, $V - I$ (Sarazin et al., 2003). The upper histogram is for all of the GCs, while the lower shaded histogram shows the GCs which contain LMXBs.

4. SPATIAL DISTRIBUTIONS OF STARS, GCS, AND LMXBS

The radial distribution of GCs in elliptical galaxies is more extended than that of the field stars; in particular, the optical light profiles of ellipticals typically show a central cusp, whereas the spatial distribution of GCs has a constant surface density core. This may indicate that GCs never formed in the central regions, or that the GCs which were initially formed there were disrupted by tidal effects. One way to test this would be to search the central regions of ellipticals for a stellar population which is characteristic of GCs. This is difficult for optical stars; however, as noted above, LMXBs are preferentially produced in GCs. At the same time, we would like to know what fraction of the field LMXBs were made in GCs. Some of the GC LMXBs might have escaped individually due to stellar dynamical interactions, or they may have been released when their host GC was disrupted by tidal effects. In either case, these field LMXBs would have a spatial distribution which reflected the initial spatial distribution of the GCs. Thus, by studying the spatial distributions of the optical light, GCs, and field and GC LMXBs in galaxies, we can constrain models for the formation and destruction of GCs and the origin of LMXBs.

Figure 3 shows models for the spatial distribution of field and GC LMXBs in an elliptical galaxy (Sarazin, 2006). The stellar and GC distribution were based on observations of NGC 4365, and the X-ray sources are from our earlier Chandra observation of this galaxy (Sivakoff et al., 2003). Here, I show only three extreme models. In Model 1, all field LMXBs were made in situ. This model probably provides an adequate fit to the existing data. Note the general result that the observed LMXB distribution is broader than that of the stars, reflecting the contribution of GC LMXBs. In Model 2, all LMXBs are made in GCs, and the field LMXBs were individually ejected from GCs. In this model, the predicted distribution of the LMXBs is broader than that observed. Finally, in Model 3, all LMXBs are also made in GCs, but the only mechanism for the release of the field LMXBs is the tidal disruption of GCs. In this model, the predicted distribution of field LMXBs is more strongly peaked than that observed due to the high rates of GC destruction at the center of the galaxy. Although better data are needed, the comparison of the models with the present data indicate that at least half of the field LMXBs were made in situ.

5. VARIABILITY OF LMXBS: DISCOVERY OF LUMINOUS X-RAY FLARES

In order to detect fainter LMXBs and to study the variability of these sources, we have performed multi-epoch observations of two nearby, optically luminous, X-ray faint elliptical galaxies, NGC 4697 and NGC 4365. Each galaxy was observed a total of five times over about five years for a total exposure of about 200 ksec. (The fifth and final observation of NGC 4365 is scheduled for 2005 November; in this paper, we discuss only the observations from NGC 4697.) Hubble observations of the centers of these galaxies (Côté et al. , 2004; Jordán et al., 2004), reveal the globular clusters (GCs). Flanking fields of both galaxies will be observed in HST Cycle 14, providing essentially complete coverage of their GCs.

Variability studies of LMXBs in the Milky Way and in E/S0s are very complementary. Galactic LMXBs can be studied in great detail during both active ($L_X \gtrsim 10^{36}$ ergs s^{-1}) and quiescent ($L_X \lesssim 10^{34}$ ergs s^{-1}) states across all wavelengths. From this, binary properties (e.g., donor type, compact object mass, orbital period, jet presence) can be determined, allowing for a better understanding of LMXB formation and evolution. However, there are several limitations in studying Galactic LMXBs: source distances are known for only a small subset, it is difficult to observe the whole Galaxy at once, absorption columns vary from source to source, and the size of the observed sample is limited. The latter limitation means that we are less likely to encounter rare phenomena, particularly those associated with the more luminous sources. The large number of luminous LMXBs in each elliptical galaxy provides a significant chance to detect very unusual objects.

We developed a new technique for detecting and characterizing short flares from faint X-rays sources, which is based on searching the arrival times of individual photons for cases where a larger number of photons arrive within a short period.

In NGC 4697, we have discovered three sources which undergo very luminous X-ray flares (Sivakoff, Sarazin, & Jordán , 2005). Two sources (CXOU J124837.8−054652 and CXOU J124831.0−054828) show $\sim$ 1000 s flares with $L_{\rm bol} > 4 \times 10^{38}$ ergs s^{-1}. Both of these LMXBs appear to be located in GCs. Although the timescale of the

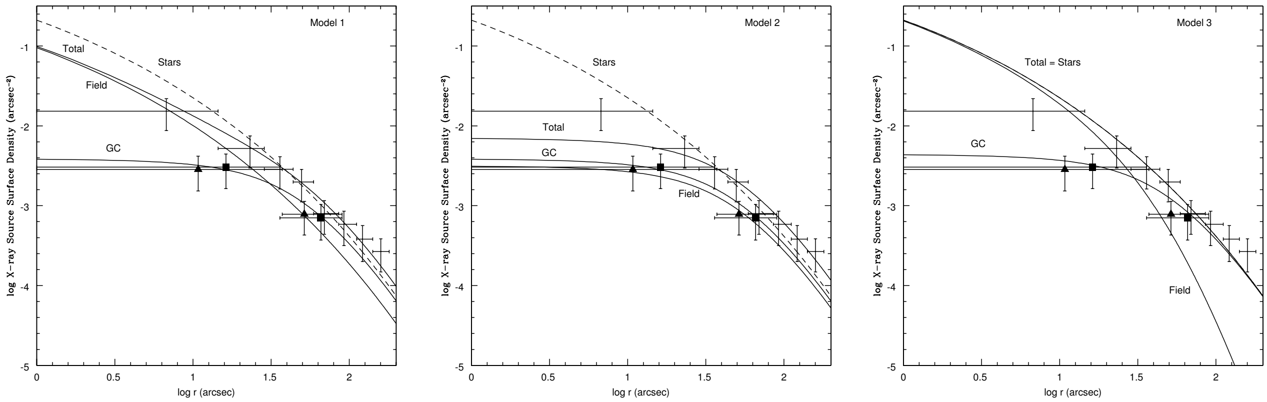

Figure 3. Predicted surface densities distributions of X-ray sources in elliptical galaxies (Sarazin, 2006). The solid curves labeled GC, Field, and Total show the surface densities of LMXBs in GCs, in the field, and in total, respectively. The dashed curve shows the total X-ray distribution if the X-ray sources followed the distribution of field stars. The data points are from NGC 4365. The error bars with triangles are the field LMXBs, those with squares are the GC sources, and the plain error bars are the total source distribution. Model 1 assumes that no GC LMXBs are lost from GCs either due to individual ejection or GC destruction. In Model 2, all LMXBs are made in GCs, no GCs are destroyed, but all of the field LMXBs were individually ejected from GCs. In Model 3, all LMXBs are made in GCs, and all field LMXBs result from the tidal disruption of GCs.

flares is similar to superbursts, the luminosity is higher than expected for a neutron star (NS). Furthermore, the recurrence timescale of flares is probably on the order of ∼10 hours, much shorter than the approximately year-long timescale of Galactic superbursts. Recently, Maccarone (2003) proposed that these sources are slightly eccentric binaries in GCs which flare at periastron.

An even more perplexing source (CXOU J124839.0−054750) with recurrent $\sim 70\,\mathrm{s}$ flares was also found, with a flaring luminosity of $L_X \gtrsim 5 \times 10^{39}$ erg s^{-1} (Fig. 4). This source is not coincident with a GC. The flare behavior of CXOU J124839.0−054750 does not have a clear analog in our own Galaxy. Its peak luminosity is clearly super-Eddington for an NS; the flare is at least 8 times the Eddington luminosity of a helium burning NS. This shows it is not a Type-I X-ray burst. Since NGC 4697 is an elliptical galaxy, it is unlikely that this source is an HMXB like LMC X−4 or V4641 Sgr. The flare timescale is similar to rapid transients seen in the BH-XRBs, GRS1915+105 and V4641 Sgr.

One possibility is that CXOU J124839.0−054750 (and possibly the other two flaring sources as well) are related to Galactic microquasar sources. Microquasars are XRBs with accreting BHs which produce relativistic jets (e.g., Mirabel & Rodríguez, 1999). In most of the known Galactic examples, we are observing the sources at a large angle from the jet axis (see, however, Orosz et al., 2001). The very high luminosity of CXOU J124839.0−054750 might be explained if we are seeing this source along the jet axis. In analogy to their AGN counterparts, microquasars observed along the jet axis are referred to as microblazars (Mirabel & Rodríguez, 1999). Blazars are known to undergo relatively short timescale outbursts; the same phenomena, scaled to microblazars, might account for the X-ray flares in CXOU J124839.0−054750.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration through Chandra Award Numbers GO3-4099X, AR4-5008X, GO4-5093X, GO5-6081X, and GO5-6086X, and Hubble Space Telescope Award Number HST-GO-10003.01-A.

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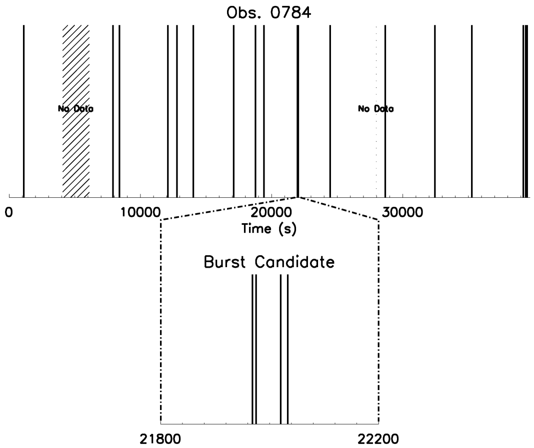

Figure 4. Impulse diagram indicating the time of arrival of photons from the flaring source CXOU J124839.0-054750 in NGC 4697. This source has a ∼70 sec flare.

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