

# Black Hole X-ray Binaries in the Elliptical Galaxy NGC 1399

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**Abstract** We present results from analysis and comparison of 2000 and 2003 *Chandra* X-ray Observatory observations of the population of X-ray binaries in the giant elliptical galaxy NGC 1399. A number of variable low-mass X-ray binaries are identified, including some candidate transient sources. Evidence for the presence of black hole binaries in NGC 1399 is strong, and the case most compelling for the globular cluster sources. The most luminous source declined from  $5 \times 10^{39}$  erg s<sup>-1</sup> to  $2 \times 10^{39}$  erg s<sup>-1</sup> while maintaining a soft spectrum. Such behavior is seen in (high state) black hole binaries; however, none of these are found in Milky Way globular clusters.

**Key words:** galaxies: star clusters – X-rays: binaries – X-rays: galaxies

## 1 INTRODUCTION

*Chandra* observations of external galaxies reveal rich and diverse populations of X-ray binaries, opening a new window onto stellar formation and evolution. We are studying the characteristics and nature of Low Mass X-ray Binaries (LMXBs) in globular clusters (GCs), and the existence and nature of ultraluminous X-ray Sources (ULXs) in elliptical galaxies. Our means to address these is analysis and comparison of 2000 and 2003 observations of NGC 1399, the giant elliptical in the center of the Fornax Cluster.

In the Milky Way (MW), globular clusters are  $\sim 100\times$  more likely per unit mass than the field to contain LMXBs (Clark 1975), with metal-rich (red) GCs preferred as hosts (Bellazini et al. 1995). Even so, there are only 13 Galactic LMXBs with  $L_X > 10^{36}$  erg s<sup>-1</sup> – all, evidently, are neutron star systems (Verbunt & Lewin 2004). These facts beg the questions of the universality of the preference of LMXBs for red GCs, whether LMXBs primarily originate in GCs, and whether black hole binaries may form and be retained in GCs. Elliptical galaxies are ideal laboratories to address these since they may host up to  $\sim 10^2\times$  the number of GCs in the MW, and black hole binaries emitting near their Eddington luminosities are easily detectable for nearby ellipticals. NGC 1399 is a prime example due to its proximity ( $d = 20.5$  Mpc), high GC specific frequency, and exceptional integrated hard X-ray spectral component luminosity.

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## 2 X-RAY EMISSION AND X-RAY BINARIES IN ELLIPTICAL GALAXIES

X-ray luminosities of normal elliptical galaxies are  $L_X = 10^{39} - 10^{42}$  erg s<sup>-1</sup>, and integrated spectra display two components. The soft component from hot ( $kT = 0.3\text{-}1$  keV) plasma with solar or subsolar abundances and  $\sim$ solar abundance ratios dominates high- $L_X$  ellipticals, while the hard ( $kT > 5$  keV) component from X-ray binaries dominates low- $L_X$  ellipticals.

*Chandra* has resolved most of the hard spectral component into up to hundreds of  $> 2 \times 10^{37}$  erg s<sup>-1</sup> LMXBs, representing the first large sample of X-ray binaries in elliptical galaxies and, thus, extending the study of stellar populations into the X-ray regime. The population is dominated by sources with  $L_X > L_{\text{Edd}}(1.4M_\odot)$ , where  $L_{\text{Edd}} = 1.3 \times 10^{38}$  erg s<sup>-1</sup>( $M/M_\odot$ ) is the Eddington luminosity. A fundamental question is whether these “super-Eddington” sources are black hole binaries or multiple sources. There are no such sources in MW GCs; this is a brand new class of object.

## 3 LOW MASS X-RAY BINARIES IN NGC 1399 – THE GLOBULAR CLUSTER CONNECTION

The results of our analysis of the 2000 *Chandra* observation of NGC 1399 (Angelini et al. 2001) are summarized as follows. Approximately two-thirds of LMXBs in a region that overlaps with the field-of-view of a *Hubble Space Telescope* WFPC2 pointing are associated with GCs (Fig. 1). The likelihood for GCs to host luminous LMXBs is enhanced in brighter GCs (Fig. 2) and in redder (more metal-rich) GCs (Fig. 3). GC LMXBs tend to be brighter than field LMXBs. Those LMXBs associated with, and those not associated with, GCs are not spectrally distinguishable in terms of their composite spectra (Fig. 4) or hardness ratio (Fig. 5). In the latter figure, filled symbols mark the expected locations of absorbed power-law spectra; circles, small boxes, and large boxes denote  $N_H = 3 \times 10^{22}$  (power-law indices 2, 3, 4, 5),  $3 \times 10^{21}$  (indices 1, 2, 3, 4, 5), and  $3 \times 10^{20}$  cm<sup>-2</sup> (indices 1, 2, 3), respectively.

Subsequent analyses of other elliptical galaxies confirms and extends the NGC 1399 results. The high incidence of LMXBs in GCs in NGC 1399 is evidently due to its high GC specific frequency; the fraction of GCs with luminous LMXBs is typical ( $\sim 4\%$ ). Galaxies with more prominent GC populations also tend to have more field LMXBs, as well, supporting scenarios where a significant fraction of all LMXBs are created in GCs.

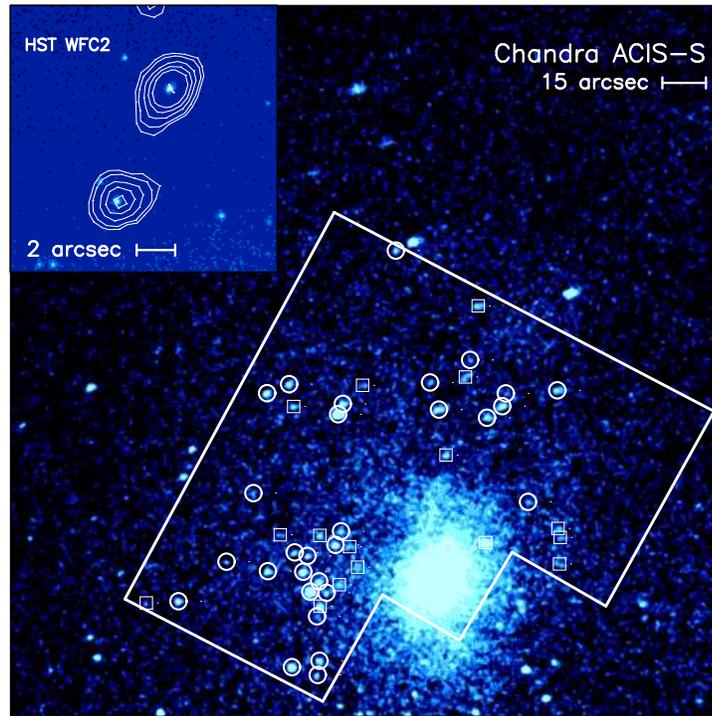
The enhanced probability of LMXBs in GCs that are redder and/or brighter, is interpreted as due to the effects of metallicity and central density (Jordan et al. 2004). Integrated spectra and luminosity functions (Kim & Fabbiano 2004) prove to be fairly universal in their respective shapes, with the former ( $\sim 5$  keV bremsstrahlung) similar in form to the average MW LMXB spectrum.

These data have raised many questions. Do all (or most) LMXBs originate in GCs? If so, how are they formed and retained? What is the role of GC age, metallicity, and density? What is this telling us about GC stellar dynamics and/or primordial star formation? What are the proportions of neutron star and black hole systems, and are their natures and origins distinct? Are the LMXBs persistent or transient? What are the differences between LMXBs in and out of GCs?

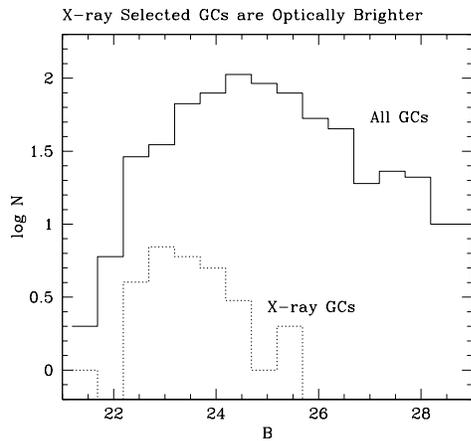
## 4 A SECOND EPOCH OBSERVATION OF NGC 1399

Comparing the 2000 and 2003 Observations of NGC 1399 (Fig. 6) may shed light on some of the puzzles enumerated above (Angelini et al., in preparation).

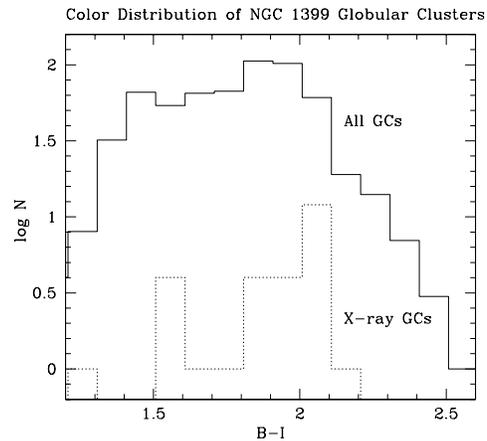
5 of the 39 sources detected in 2000 within the WFPC2 FOV were undetected in 2003, with limits  $3 - 10\times$  below the original luminosities; four of these are in globular clusters. This



**Fig. 1** In NGC 1399, LMXBs are found twice as frequently in GCs (circles) as in the field (squares).

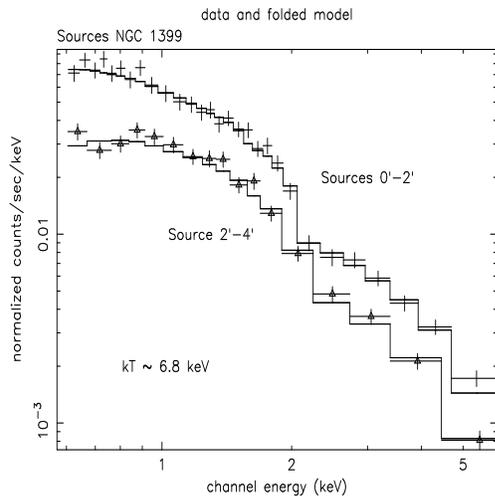


**Fig. 2** Optical color distribution. X-ray selected GCs are redder, on average.

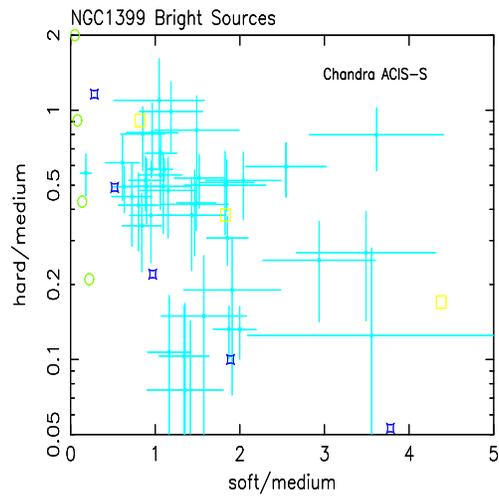


**Fig. 3** Optical luminosity distribution. X-ray selected GCs are brighter, on average.

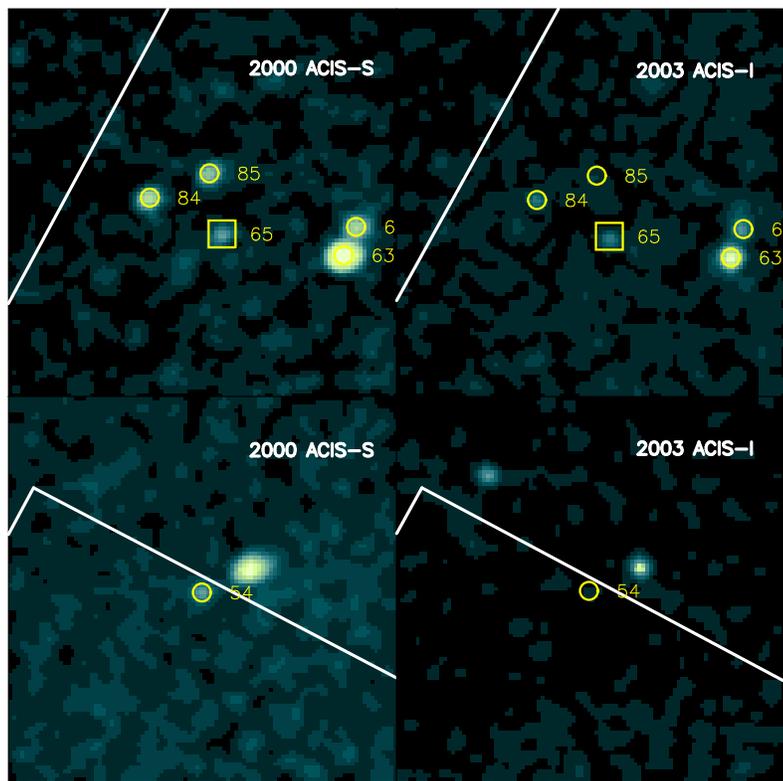
behavior is consistent with the properties of (bright) neutron star LMXBs in the MW. Thus, the GC X-ray sources may be transient or multiple sources. An additional 6 sources show variability at  $> 5\sigma$ ; five of these are in globular clusters.



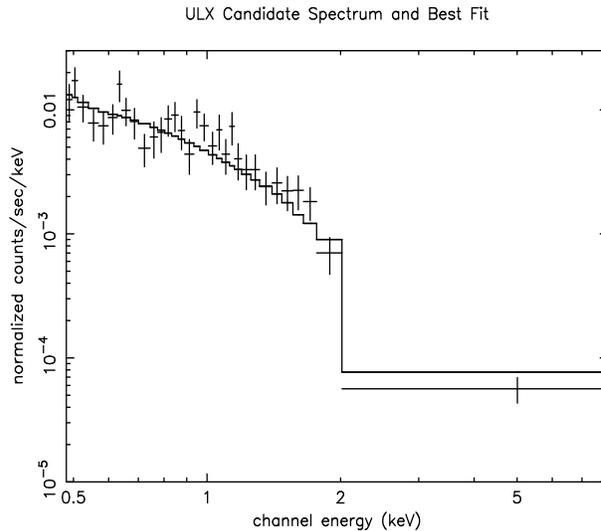
**Fig. 4** Composite spectra for NGC 1399 LMXBs in two annuli.



**Fig. 5** X-ray color-color diagram for sources detected at greater than  $5\sigma$  (see text for symbols).



**Fig. 6** Close-ups of regions in NGC 1399 with sources that varied between the 2000 (left) and 2003 (right) observations. The white line marks the HST FOV as in Fig. 1. Note that 2000 source 85 is undetected in 2003 while sources 63 and 84 significantly faded.



**Fig. 7** Epoch 2000 *Chandra* ACIS-S spectrum of the brightest GC source and best-fit power-law model.

Among these variable sources are the three brightest (GC) sources, the most luminous of which declined from  $5 \times 10^{39} \text{ erg s}^{-1}$  to  $2 \times 10^{39} \text{ erg s}^{-1}$  while maintaining a soft spectrum. Such behavior is seen in (high state) MW black hole binaries, although none are found in MW GCs. The epoch 2000 spectrum and best-fit model (an unabsorbed power-law with slope 2.6) are shown in Figure 7.

## 5 EVIDENCE FOR BLACK HOLE X-RAY BINARIES IN NGC 1399

There are dozens of sources in NGC 1399 emitting at luminosities above the neutron star Eddington luminosity. While some might be composite sources, many are likely to be black hole binaries. The evidence is even more compelling for the subset of GC LMXBs where variability is common and where, because the presence of  $> 2$  massive binaries is unlikely from a stellar dynamics point of view, sources with  $L_X > \text{a few} \times 10^{38} \text{ erg s}^{-1}$  are strong black hole candidates. The ultraluminous, variable, soft source described above represents perhaps the most convincing single case of a black hole in a GC, and is the best example of an ULX in an elliptical galaxy.

While the population of MW GC LMXBs displays many similar characteristics to those in elliptical galaxies such as NGC 1399 (e.g., similar average spectra, similar overabundance – per unit mass – compared to the field), such black hole LMXB candidates are not observed in the Galaxy. Whether this is a result of sparse sampling in the MW due to its low GC specific frequency, or an intrinsic distinction in the nature of its GCs is not known.

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