Globular cluster x-ray sources

David Pooley

Eureka Scientific, Rosedale Avenue, Austin, TX 78756-2830

Edited by Harvey D. Tananbaum, Smithsonian Astrophysical Observatory, Cambridge, MA, and approved March 11, 2010 (received for review December 22, 2009)

Globular clusters and x-ray astronomy have a long and fruitful history. *Uhuru* and *OSO-7* revealed highly luminous (>10^{36} ergs^{-1}) x-ray sources in globular clusters, and *Einstein* and *ROSAT* revealed a larger population of low-luminosity (<10^{33} ergs^{-1}) x-ray sources. It was realized early on that the high-luminosity sources were low-mass x-ray binaries in outburst and that they were orders of magnitude more abundant per unit mass in globular clusters than in the rest of the galaxy. However, the low-luminosity sources proved difficult to classify. Many ideas were put forth—low-mass x-ray binaries in quiescence (qLMXBs), cataclysmic variables (CVs), active main-sequence binaries (ABs), and millisecond pulsars (MSPs)—but secure identifications were scarce. In *ROSAT* observations of 55 clusters, about 25 low-luminosity sources were found. *Chandra* has now observed over 80 Galactic globular clusters, and these observations have revealed over 1,500 x-ray sources. The superb angular resolution has allowed for many counterpart identifications, providing clues to the nature of this population. It is a heterogeneous mix of qLMXBs, CVs, ABs, and MSPs, and it has been shown that the qLMXBs and CVs are both, in part, overabundant like the luminous LMXBs. The number of x-ray sources in a cluster correlates very well with its encounter frequency. This points to dynamical formation scenarios for the x-ray sources and shows them to be excellent tracers of the complicated internal dynamics. The relation between the encounter frequency and the number of x-ray sources has been used to suggest that we have misunderstood the dynamical states of globular clusters.

galaxy: globular clusters | stars: binaries | x-rays: binaries

The importance of x-ray sources in globular clusters lies in the fact that they are all close binaries or the descendants of close binaries. These exotic, close binaries exert a great influence on the dynamical evolution of the globular cluster. Heggie's law tells us that close binaries tend to become even closer through encounters with single stars or other less close binaries (1). While doing so, they increase their (negative) gravitational binding energy by transferring significant (positive) energy to other stars in their environment. One consequence is that primordial binaries can postpone deep core collapse of a globular cluster (2–5).

The interplay between stellar dynamics and stellar evolution, as external and internal factors modifying the binary properties, is highly complex, and many facets of these processes are not understood in depth. This is an area of active observational research and extremely intensive numerical simulation study. Bridging the gap between theory and observation has been very difficult. We observe a cluster in its current state, after it has undergone 13 billion years of complex evolution involving this interplay between its internal dynamics and the evolution of its constituent members. Likewise, the large-scale numerical simulations are taken through 13 billion years of integration from a certain set of initial conditions and input physics for the dynamics and evolution. Comparing the simulation results to observations is not straightforward. Until recently, there was no observational diagnostic of a globular cluster's internal dynamics. Now, thanks to *Chandra*, there is.

Luminous X-Ray Sources

Since the *Uhuru* and *OSO-7* satellites first revealed highly luminous ($L_x \gtrsim 10^{36}$ ergs^{-1}) low-mass x-ray binaries (LMXBs) in globular clusters, it has been noted that the formation rate per unit mass of these objects is orders of magnitude higher in globular clusters than in the galactic disk (6, 7). This discovery stimulated a flurry of theoretical work into the formation of globular cluster LMXBs by the processes of two- and three-body encounters (1, 8–11). These dynamical formation scenarios (as opposed to the independent evolution of primordial binaries) are a natural explanation for the high occurrence of LMXBs in globular clusters because the stellar densities, and hence encounter rates, are much higher in the cores of globular clusters than other regions of the galaxy. Verbunt and Hut (12) showed that the 11 bright LMXBs known at that time* in globular clusters were consistent with being formed dynamically through close encounters.

Some of *Chandra*'s earliest observations of globular clusters were to obtain precise positions for the 12 known bright LMXBs, all of which were known to be neutron star systems because they displayed Type I x-ray bursts (14). This led to one of the first surprises, which was that M15 contained not one but two persistently bright LMXBs (15). Perhaps this is not so surprising now that we know that several clusters contain many LMXB systems, most of them in quiescence. There is no reason, of course, that two of them cannot be active at the same time. Recently, NGC 6440 was observed to have a second transient LMXB (16) in addition to the known transient that was part of the 12 known about before *Chandra*. This new transient displays many unusual properties, including an active phase of only 3 d, and a fairly regular recurrence of roughly 30 d.

A discussion of luminous x-ray sources in globular clusters was presented at this Symposium by T. Maccarone (http://cxc.harvard.edu/symposium_2009/PDFs/Maccarone_10.pdf). His discussion dealt with these systems in much larger numbers in *Chandra* observations of other galaxies.

Low-Luminosity X-Ray Sources

An additional population of *low*-luminosity ($L_x \lesssim 10^{35}$ ergs^{-1}) globular cluster x-ray sources was discovered with the *Einstein* satellite (17, 18) and further explored with *ROSAT* (19). Unlike the luminous x-ray sources whose nature could be determined solely on the basis of the x-ray properties, the nature of this population remained elusive for nearly two decades. Early suggestions were cataclysmic variables (CVs) (17) and quiescent LMXBs (18, 20). Later, it was realized that millisecond pulsars (MSPs) (21) and magnetically active binaries (22) could also account for part of the population. The *Einstein* and *ROSAT* positions were not precise enough to allow for counterpart identification in the crowded inner regions of a globular cluster, and the uncertainty over the nature of the low-lumosity x-ray sources persisted until *Chandra* was launched. Before reviewing the *Chandra* observations, I will briefly discuss some relevant issues in globular cluster evolution.

Author contributions: D.P. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

*A 12th bright LMXB was discovered before the launch of *Chandra* (13).

[1]Email: davepooley@me.com.

 www.pnas.org/cgi/doi/10.1073/pnas.0913903107

Globular Cluster Evolution. It is a general property of self-gravitating systems that they are unstable against collapse without some source of internal energy. Stars solve this problem by undergoing nuclear fusion in their cores; they burn lighter elements into heavier ones and, in so doing, tap into the rest-mass energy of their constituent atoms to provide the necessary power to support themselves. Globular clusters can, in a sense, "burn" stars (23); a cluster taps into the potential energy of binary systems to provide the means of stabilization against collapse. Globular clusters are fairly weakly bound systems, with escape velocities from their cores of only tens of kilometers per second. Even a modest population of binaries contains a potential reservoir of gravitational binding energy that easily exceeds the kinetic energy of all single stars in the cluster.

Encounters between cluster members—whether they be between two single stars, a single star and a binary, two binaries, or even more exotic scenarios—are the means through which this reservoir is tapped. As an example, in an encounter between a binary system and a single star, one possible outcome of this three-body interaction is the "hardening" of the original binary, in which the two members of the binary are brought into a closer orbit. The negative gravitational potential energy of the original binary becomes more negative, imparting positive energy to the cluster. In this sense, a sort of stabilization can be achieved. As the core of a globular cluster begins to contract, the stellar density becomes higher, increasing the rate of encounters.

The evolution of a globular has three phases:

1. The *core contraction phase*, in which the core shrinks from its initial size.
2. When stellar densities become high enough for interactions between binaries and other cluster members, the *binary-burning phase* begins, during which time the core size is roughly constant. This is similar to the main-sequence period of a star's life.
3. When the cluster runs out of binaries, it enters into a deep core collapse which results in extremely high stellar densities in the very center of the cluster. Densities get so high that new binaries are formed, and the core rebounds. This process repeats and is called the *gravothermal oscillation phase*.

These three phases are marked on the results of a sophisticated Monte Carlo simulation (3) in Fig. 1.

It has long been believed that most (80%) globular clusters in the galaxy (those not observationally classified as "core collapsed"[†]) are in the binary-burning phase, whereas the remaining 20% (those classified as core collapsed) are in deep core collapse. This was supported by early calculations which showed the ratio of the core radius (r_c) to the half-mass radius (r_h) during binary burning is roughly consistent with most clusters, as well as the fact that the binary-burning phase is long-lived and stable and that globular clusters are extremely old objects. Recent developments, discussed below, may suggest otherwise.

***Chandra* Observations.** In the first few years of operation, deep *Chandra* observations of 47 Tuc (24), NGC 6397 (25), NGC 6752 (26), NGC 6440 (27), ω Cen (28), NGC 6626 (29), NGC 6093 (30), and NGC 6121 (31) not only discovered hundreds of x-ray sources, but in many cases they also allowed for much progress in classifying the members of the low-L_x population. Comparison with Hubble Space Telescope observations was essential in identifying large numbers of CVs and active binaries, and the radio timing positions showed that many of theses x-ray sources were MSPs. We now know that the low-luminosity

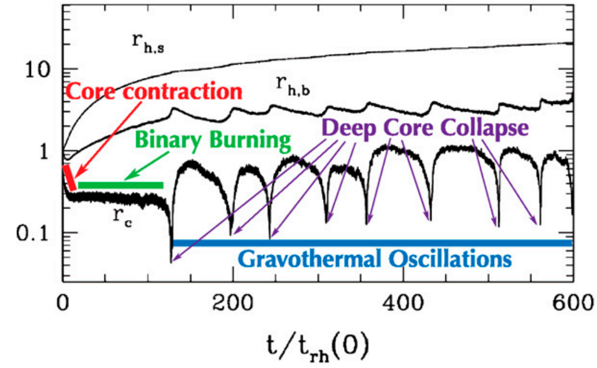

Fig. 1. Adapted from Fregeau et al. (3). This shows the results of a sophisticated, two-dimensional Monte Carlo code with the inclusion of primordial binary interactions for equal-mass stars (3). The evolutions of three radii are plotted in terms of the initial half-mass radius $r_h(0)$; from top to bottom, they are the half-mass radius of single stars ($r_{h,s}$), the half-mass radius of binaries ($r_{h,b}$), and the core radius (r_c). Time is shown in terms of the initial half-mass relaxation $t_{rh}(0)$. After a period of contraction (which can last tens of $t_{rh}(0)$), the core enters a much longer phase of stable binary burning, which can last a hundred times $t_{rh}(0)$. When the binary "fuel" has run out, the core goes into deep collapse and begins gravothermal oscillations. Fregeau (40) argues that the majority (80%) of galactic globular clusters are *not* in the binary-burning phase, as previously thought. Rather, they are still in the core contraction phase, which in physical units can be *comparable to or longer than a Hubble time!* The remaining 20% of globular clusters which have been classified as core collapsed are in fact in the binary-burning phase.

x-ray source population in globular clusters is a mixture of quiescent LMXBs, CVs, MSPs, and active binaries.

This dramatic improvement in our understanding of these sources is a direct result of the dramatic improvement in the spatial resolution of *Chandra* over previous satellites, illustrated in the series of images of 47 Tuc shown in Fig. 2. The images were made by searching for all high-resolution x-ray images in the High Energy Astrophysics Science Archive Research Center and merging them for each satellite.

On the basis of *Chandra* observations of a dozen globular clusters, Pooley et al. (32) found that the number of low-luminosity x-ray sources with $L_x \geq 4 \times 10^{30}$ ergs^{-1} in a cluster scales with the encounter frequency Γ significantly better than it scales with the mass M of the cluster. Similar findings for the quiescent LMXB population only were reported by Heinke et al. (33) and Gendre et al. (34). This was the first clear proof that the bulk of the population of x-ray sources in a globular cluster (and not just the LMXBs in outburst) is largely dynamically formed.

This finding was refined by Pooley and Hut (35), who were able to separate out the quiescent LMXBs from the rest of the low-luminosity x-ray sources. In addition, they worked in more appropriate specific units: $\gamma = \Gamma/M$ is the specific encounter frequency and $n_x = N_x/M$ is the specific number of sources of population x. With these units, there is a very simple test: If population x is primordial, then n_x should be roughly constant for all clusters. If it is not, then we can take the next step in complexity and assume some primordial contribution and some dynamical contribution: $n_x = C_x + A_x\gamma^{\alpha_x}$. This was applied to the LMXB population, which shows a remarkable agreement with being almost exclusively dynamically formed. They are thus an ideal tracer of the cluster's internal dynamics.

Another important finding of Pooley and Hut (35) was the resolution of a long-standing mystery in the field of globular cluster research, namely, whether or not CVs were overabundant in globular clusters. Over 25 years ago, Hut and Verbunt (36) argued that there should be at least as many white dwarf binaries as neutron star binaries in a globular cluster, and a later, more detailed study by Di Stefano and Rappaport (37) showed that there *should* be a large number of active CVs in globular clusters

[†]The classification is based on an unresolved core; the surface brightness profile rises to a cusp in the center, instead of flattening out as in other globular clusters.

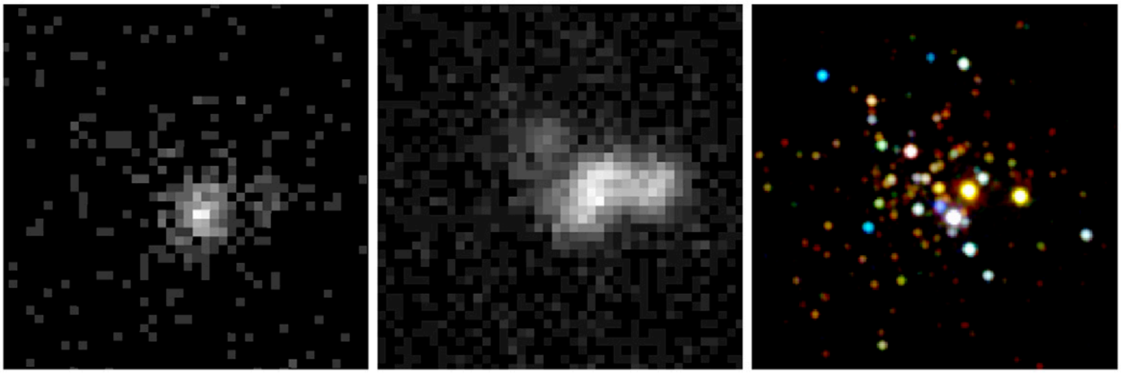

Fig. 2. Images of the core of 47 Tuc made from 8 ks of *Einstein* data (*Left*), 77 ks of *ROSAT* data (*Center*), and 240 ks of *Chandra* data (*Right*). The *Chandra* data have been color coded so that 0.5–1.2 keV photons are in red, 1.2–2.5 keV photons are in green, and 2.5–8 keV photons are in blue.

despite the lack of observational evidence. After the failure of the *Hubble Space Telescope* to find a sizable population of CVs (38), many observers concluded that the early predictions had been wrong. With the early *Chandra* observations, it was clear that the CVs were finally being found in large numbers, but it was not yet clear whether they were overabundant like the LMXBs. A recent theory paper by Townsley and Bildsten (39) argued that was no overabundance of CVs in 47 Tuc based on their predictions of how many CVs should exist in an old stellar population of a certain size.

Performing an analysis of the brighter, harder x-ray sources (which are dominated by CVs) similar to the analysis of the quiescent LMXBs, Pooley and Hut (35) showed that the specific number of CVs was not constant across globular clusters and scaled very well with encounter frequency, conclusively demonstrating that the CVs are, in fact, overabundant in globular clusters.

Globular Cluster Evolution Revisited. Fregeau (40) points out three results that provide a compelling argument for changing our understanding of the dynamical states of galactic globular clusters. First, recent *N*-body simulations (4) and Monte Carlo simulations (5) have independently come to the conclusion that the early calculations of the expected ratio r_c/r_h in the binary-burning phase overestimate the actual value by a factor of 10 or more. Because these recent simulations approach the problem in completely different ways (the former being a direct integration of the equations of motion with few assumptions and the latter being an approximate method with direct integration of binary encounters), their agreement lends support to the main conclusion. Further, they both agree with previous semianalytic methods (41) for the value of r_c/r_h in the binary-burning phase, with the end result being that now only those globular clusters classified as core-collapsed have values of r_c/r_h that are compatible with the binary-burning phase.

Second, Fregeau (40) derives an expression for the ratio of the number of dynamically formed x-ray sources in the binary-burning phase to the number of such x-ray sources in the core contraction phase. The treatment takes into account the finite lifetime of an x-ray binary (anywhere from 10^6 to 10^9 years) and relates the numbers to the commonly used Γ. The ratio ranges from ∼2–20. In other words, one would expect anywhere from 2 to 20× as many x-ray sources in a globular in the binary-burning phase compared to a similar cluster in the core contraction phase.

Third, core-collapsed globular clusters are observed to have just such an overabundance when observed with *Chandra*. In the initial study (32), NGC 6397 was found to have about 5× as many x-ray sources as would be expected based on the power-law relation that fits the other (non-core-collapsed) globular clusters extremely well. Recently, NGC 7099 was found to have about twice as many x-ray sources as the power-law relation would predict (42), and Terzan 1 was found to have about 20× as many (43).

Taken together, these results strongly suggested that we needed to reevaluate our thinking about the current dynamical states of globular clusters. Instead of 80% of globular clusters being in the binary-burning phase and 20% being in deep core collapse, it would appear that only 20% are in the binary-burning phase and 80% are still in the contraction phase. However, the observational linchpin was based on only three outlying clusters. More observations were needed.

Recent Observations. In order to further explore the Pooley and Hut (35) results, a large *Chandra* program to observe another two dozen clusters (including several core-collapsed ones) was undertaken. The observations took place from January 2008 to February 2009. To test the hypothesis of Fregeau (40), another six core-collapsed clusters were observed from February 2009 to July 2009.

An preliminary x-ray color magnitude diagram with nearly 1,500 sources from 77 globular clusters is shown in Fig. 3. Using the brighter end of the sources, the analysis of Pooley and Hut (35) was repeated, and a preliminary n vs. γ plot based on sources from 63 globular clusters is shown in Fig. 4. Binning was performed on each set of globular clusters (the core-collapsed and the "normal" sets) in which several globular clusters around the same γ were considered as an aggregate cluster. This was done to achieve a high enough number of sources in the bin for useful analysis. Tests of the robustness of this binning have not yet been

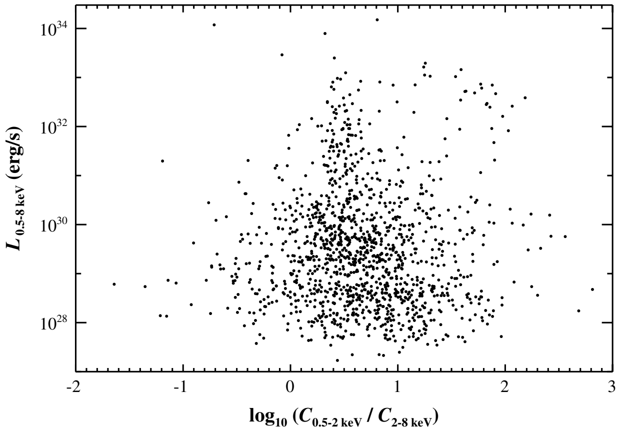

Fig. 3. X-ray color-magnitude diagram based on over 3 Msec of *Chandra* observations of 77 globular clusters. Over 1500 sources are represented in this figure, about 250 of which are background objects. The x-ray color is defined as the ratio of counts in the 0.5–2 keV band to those in the 2–8 keV band.

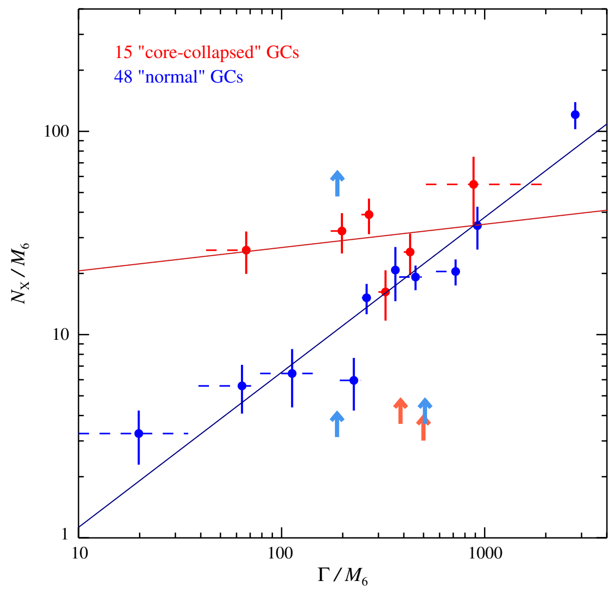

Fig. 4. Number of $L_x > 10^{31}$ ergs^{-1} sources per unit mass in a globular cluster versus the encounter frequency Γ per unit mass of the cluster. Core-collapsed globular clusters are shown in red, and normal ones are shown in blue.

performed, but the preliminary result is that the core-collapsed and normal clusters show a different relationship between the number of sources in a cluster and the cluster's encounter frequency, with the core-collapsed globular clusters having more sources for a given encounter frequency. This supports the assertion by Fregeau (40) that core-collapsed globular clusters are observed to have an overabundance of close binaries compared to normal clusters.

Summary

The greatest success of *Chandra* in this field is that it is, by far, the most efficient and effective means of finding large numbers of the important class of close binaries in a globular cluster. It has been shown independently by a number of groups that the x-ray sources (in particular the LMXBs) are dynamically formed in the dense environs of a globular cluster, and that they are a great tracer population for the large-scale numerical simulations currently being performed. A decades-old mystery concerning the lack of CVs in globular clusters has been put to rest because *Chandra* has found large numbers of them in almost every globular cluster observed to date, and they have been shown to be overabundant, as well. Finally, based in large part on the *Chandra* results, it looks like we may be on the verge of a revolution in our understanding of the current states of globular clusters.

ACKNOWLEDGMENTS. The author appreciates the help and advice from numerous colleagues, collaborators, and friends including Piet Hut, Walter Lewin, Frank Verbunt, Lee Homer, Scott Anderson, Cees Bassa, Jeroen Homan, Bruce Margon, Vicky Kaspi, Brian Gaensler, Josh Grindlay, Craig Heinke, Peter Edmunds, Albert Kong, Simon Portegies Zwart, and John Fregeau. He also gratefully acknowledges support from *Chandra* Grants GO8-9031X and G09-0032A. His research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center, provided by NASA's Goddard Space Flight Center.

1. Heggie DC (1975) Binary evolution in stellar dynamics. *Mon Not R Astron Soc* 173:729–787.
2. Goodman J, Hut P (1989) Primordial binaries and globular cluster evolution. *Nature* 339:40–42.
3. Fregeau JM, Gürkan MA, Joshi KJ, Rasio FA (2003) Monte Carlo simulations of globular cluster evolution. III. Primordial binary interactions. *Astrophys J* 593:772–787.
4. Heggie DC, Trenti M, Hut P (2006) Star clusters with primordial binaries—I. Dynamical evolution of isolated models. *Mon Not R Astron Soc* 368:677–689.
5. Fregeau JM, Rasio FA (2007) Monte Carlo simulations of globular cluster evolution. IV. direct integration of strong interactions. *Astrophys J* 658:1047–1061.
6. Clark GW (1975) X-ray binaries in globular clusters. *Astrophys J* 199:L143–L145.
7. Katz JI (1975) Two kinds of stellar collapse. *Nature* 253:698–699.
8. Fabian AC, Pringle JE, Rees MJ (1975) Tidal capture formation of binary systems and X-ray sources in globular clusters. *Mon Not R Astron Soc* 172:15–18.
9. Hills JG (1975) Encounters between binary and single stars and their effect on the dynamical evolution of stellar systems. *Astron J* 80:809–825.
10. Hills JG (1976) The formation of binaries containing black holes by the exchange of companions and the x-ray sources in globular clusters. *Mon Not R Astron Soc* 175:1P–4P.
11. Sutantyo W (1975) The formation of globular cluster x-ray sources through neutron star-giant collisions. *Astron Astrophys* 44:227–230.
12. Verbunt F, Hut P (1987) The globular cluster population of x-ray binaries. *The Origin and Evolution of Neutron Stars*, (D. Reidel Publishing, Dordrecht, The Netherlands), 125, pp 187–197.
13. Predehl P, Hasinger G, Verbunt F (1991) ROSAT discovery of bright x-ray sources in globular cluster TER 6 and NGC 6652. *Astron Astrophys* 246:L21–L23.
14. Kuulkers E, et al. (2003) Photospheric radius expansion x-ray bursts as standard candles. *Astron Astrophys* 399:663–680.
15. White NE, Angelini L (2001) The discovery of a second luminous low-mass x-ray binary in the globular cluster M15. *Astrophys J* 561:L101–L105.
16. Heinke CO, et al. (2009) Discovery of a second transient low-mass x-ray binary in the globular cluster NGC 6440. ArXiv:0911.0444.
17. Hertz P, Grindlay JE (1983) X-ray evidence for white dwarf binaries in globular clusters. *Astrophys J* 267:L83–L87.
18. Hertz P, Grindlay JE (1983) An x-ray survey of globular clusters and their x-ray luminosity function. *Astrophys J* 275:105–119.
19. Verbunt F (2001) A census with ROSAT of low-luminosity x-ray sources in globular clusters. *Astron Astrophys* 368:137–159.
20. Verbunt F, Elson R, van Paradijs J (1984) X-ray sources in globular clusters. *Mon Not R Astron Soc* 210:899–914.
21. Saito Y, et al. (1997) Detection of magnetospheric x-ray pulsation from millisecond pulsar PSR B1821-24. *Astrophys J* 477:L37–L40.
22. Bailyn CD, Grindlay JE, Garcia MR (1990) Does tidal capture produce cataclysmic variables?. *Astrophys J* 357:L35–L37.
23. Hut P (1983) Binaries as a heat source in stellar dynamics—Release of binding energy. *Astrophys J* 272:L29–L33.
24. Grindlay JE, Heinke C, Edmonds PD, Murray SS (2001) High-resolution x-ray imaging of a globular cluster core: Compact binaries in 47Tuc. *Science* 292:2290–2295.
25. Grindlay JE, Heinke CO, Edmonds PD, Murray SS, Cool AM (2001) Chandra exposes the core-collapsed globular cluster NGC 6397. *Astrophys J* 563:L53–L56.
26. Pooley D, et al. (2002) Optical identification of multiple faint x-ray sources in the globular cluster NGC 6752: Evidence for numerous cataclysmic variables. *Astrophys J* 569:405–417.
27. Pooley D, et al. (2002) Chandra observation of the globular cluster NGC 6440 and the nature of cluster x-ray luminosity functions. *Astrophys J* 573:184–190.
28. Rutledge RE, Bildsten L, Brown EF, Pavlov GG, Zavlin VE (2002) A possible transient neutron star in quiescence in the globular cluster NGC 5139. *Astrophys J* 578:405–412.
29. Becker W, et al. (2003) Chandra x-ray observatory observations of the globular cluster M28 and its millisecond pulsar PSR B1821-24. *Astrophys J* 594:798–811.
30. Heinke CO, et al. (2003) A Chandra x-ray study of the globular cluster M80. *Astrophys J* 598:516–526.
31. Bassa C, et al. (2004) X-ray sources and their optical counterparts in the globular cluster M4. *Astrophys J* 609:755–765.
32. Pooley D, et al. (2003) Dynamical formation of close binary systems in globular clusters. *Astrophys J* 591:L131–L134.
33. Heinke CO, et al. (2003) Analysis of the quiescent low-mass x-ray binary population in galactic globular clusters. *Astrophys J* 598:501–515.
34. Gendre B, Barret D, Webb N (2003) Discovery of a quiescent neutron star binary in the globular cluster M 13. *Astron Astrophys* 403:L11–L14.
35. Pooley D, Hut P (2006) Dynamical formation of close binaries in globular clusters: Cataclysmic variables. *Astrophys J* 646:L143–L146.
36. Hut P, Verbunt F (1983) White dwarfs and neutron stars in globular cluster x-ray sources. *Nature* 301:587–589.
37. Di Stefano R, Rappaport S (1994) Predictions of a population of cataclysmic variables in globular clusters. *Astrophys J* 423:274–293.
38. Shara MM, Bergeron LE, Gilliland RL, Saha A, Petro L (1996) Cataclysmic and close binaries in star clusters. IV. The unexpectedly low number of erupting dwarf novae detected by the Hubble Space Telescope in the core of 47 Tucanae. *Astrophys J* 471:804–815.
39. Townsley DM, Bildsten L (2005) Classical novae as a probe of the cataclysmic variable population. *Astrophys J* 628:395–400.
40. Fregeau JM (2008) X-ray binaries and the current dynamical states of galactic globular clusters. *Astrophys J* 673:L25–L28.
41. Vesperini E, Chernoff DF (1994) The range of core size of postcollapse clusters supported by primordial binaries. *Astrophys J* 431:231–236.
42. Lugger PM, Cohn HN, Heinke CO, Grindlay JE, Edmonds PD (2007) Chandra x-ray sources in the collapsed-core globular cluster M30 (NGC 7099). *Astrophys J* 657:286–301.
43. Cackett EM, et al. (2006) A Chandra x-ray observation of the globular cluster Terzan 1. *Mon Not R Astron Soc* 369:407–415.