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Globular cluster X-ray sources

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Abstract. We know from observations that globular clusters are very efficient catalysts in forming unusual binary systems, such as low-mass X-ray binaries (LMXBs), cataclysmic variables (CVs), and millisecond pulsars (MSPs), with formation rates per unit mass exceeding those in the Galactic disk by orders of magnitude. The high stellar densities in globular clusters trigger various dynamical interactions: exchange encounters, direct collisions, destruction of binaries, and tidal capture. This binary population is, in turn, critical to the stabilization of globular clusters against gravitational collapse; the long-term stability of a cluster is thought to depend on tapping into the gravitational binding energy of such close binaries. I will present an overview of the current state of globular cluster X-ray observations, as well as our work on deep Chandra observations of M4, where we reach some of the lowest X-ray luminosities in any globular cluster (comparable to the deep observations of 47 Tuc and NGC 6397). One of M4 X-ray sources previously classified as a white dwarf binary is likely a neutron star binary, and another X-ray source is a sub-subgiant, the nature of which is still unclear.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Luminous X-ray source—those with $L_{\rm x} \gtrsim 10^{36}$ erg s^{-1}—have long been associated with globular cluster dynamics (e.g., Clark 1975; Heggie 1975; Hills 1976; Katz 1975), and it is well established that those seen thus far are neutron-star low-mass X-ray binaries in outburst. In the pre-*Chandra* era (before 2000), there were twelve globular clusters known to host a luminous X-ray source. Seven of these globular clusters hosted a persistent source, and five hosted a transient source. It was assumed that they each hosted one such source.

After some of the early *Chandra* observations showed that several clusters had a rich population of quiescent neutron-star low-mass X-ray binaries, we began to question the assumption of only one transient source per cluster and have sought *Chandra* observations of all new transient outbursts in the direction of a globular cluster in order to precisely localize the luminous X-ray source and determine whether the outburst is from a known transient or a new one. Through these proposals, we have determined that there (at least) two transient sources in NGC 6440 (Homan et al. 2015), three in Terzan 5 (Pooley et al. 2010, 2011a; Homan & Pooley 2012), and a new one in each of M 28 (Homan & Pooley 2013), NGC 6388 (Pooley et al. 2011b), and NGC 2808 (Homan et al. 2016). Figure 1

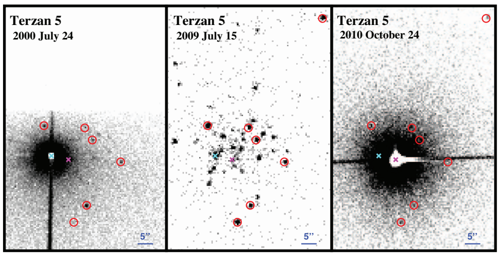

Fig. 1. Three views of Terzan 5 with *Chandra*. The cyan and magenta x's mark the locations of two transient sources, and the red circles mark low-luminosity sources common to at least two of the observations. The first and third panels each show a transient source in outburst.

shows *Chandra* observations taken during outbursts from two different transients and when no low-mass X-ray binaries are in outburst.

These, and the second persistent source in M 15 (White & Angelini 2001), bring the current tally to 15 globular clusters which host a total of 19 luminous X-ray sources: eight persistent sources in seven clusters, and 11 transient sources in eight clusters.

2. Link to dynamics: N vs. Γ

An additional population of *low*-luminosity ($L_x \lesssim 10^{35}$ erg s^{-1}) globular cluster X-ray sources was discovered with the *Einstein* satellite Hertz & Grindlay (1983a,b) and further explored with *ROSAT* Verbunt (2001). This is a heterogenous population comprising low-mass X-ray binaries in quiescence, cataclysmic variables, active main-sequence binaries, and millisecond pulsars. There is an established link between the total number of low-luminosity X-ray sources in a globular cluster and the encounter frequency, Γ, of the cluster (Pooley et al. 2003). Similar findings for the quiescent LMXB population only were reported by Heinke et al. (2003) and Gendre et al. (2003).

3. Refinements in Γ, subtleties in N

The calculation of Γ has been done in different ways by different authors. At its heart, it involves a a volume integral of ρ^2/v where ρ is the stellar density and v is the relative velocity. Some authors have used the fact that ρ and v are roughly constant inside the core radius to truncate the integral at the core radius and approximate it as $(\rho^2/v) \times r_c^3$, which simplifies to $\rho^{1.5}\, r_c^2$ for a virialized cluster. Other authors have used King model fits to the surface brightness profiles to integrate ρ^2/v from the center to the half-mass radius (generally the region in which *Chandra* studies are done).

Bahramian et al. (2013) improved the calculations of Γ in two significant ways. The density profiles were calculated via nonparametric deprojection of the surface brightness profiles, rather than from King model fits, and the authors ascertained confidence intervals for each cluster's Γ via Monte Carlo inclusion of the uncertainties in each quantity in the integral.

While the N part of the N vs. Γ relation may seem trivial in comparison, it is not as straightforward as one might assume. Most X-ray sources are highly variable on several timescales, and the numbers of globular cluster X-ray sources reported in the literature are usually based on snapshot observations. I took the three clusters with the most *Chandra* exposure time and broke them up into several independent data sets of identical exposure times for each cluster. I then ran the standard *Chandra* software wavdetect tool to detect sources and counted the number of detected sources within the half-mass radius in each independent data set. The results are summarized in Table 1. The number of detected sources from observation to observation can vary as much as ~20% (in 47 Tuc) to a factor of 2 (in M 4). Further, when I counted up all of the unique sources detected across these independent data sets, the numbers were far higher than what is seen in *any* individual observation. It is not immediately clear how to take this into account in determining the relationship between Γ and the number of X-ray sources in a cluster.

4. Current work on M 4

M 4 is one of only a few globular clusters, along with 47 Tuc and NGC 6397, observed to very deep limits (~10^{29} erg s^{-1}) with *Chandra*. This is important to get an accurate assess-

Table 1. Number of sources detected (by standard wavdetect tool) in independent data sets of identical exposure times

Cluster	Obs.	$N_{\rm det}$	$\langle N \rangle \pm \sigma_N$	$N_{\rm uniq}$
47 Tuc	14	70 – 88	78.9 ± 6.4	180
M 4	5	7 – 14	10.2 ± 2.1	22
6397	11	10 – 16	13.3 ± 2.1	25

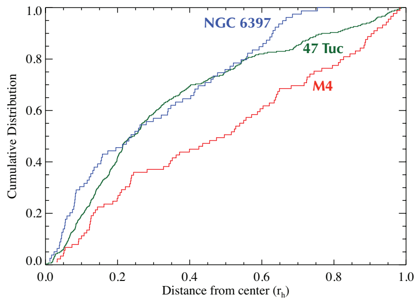

Fig. 2. Cumulative distributions of X-ray sources in M 4, 47 Tuc, and NGC 6397 as functions of projected distance (in terms of half-mass radius) from cluster center. The population of M 4 is significantly less concentrated toward the center than the populations of 47 Tuc and NGC 6397.

ment of the population of active main sequence binaries. Most clusters have X-ray limits of a few $\times 10^{30}$ erg s^{-1}. According to the X-ray luminosity of active binaries (Dempsey et al. 1997), ~60% of RS CVn and only ~10% of BY Dra systems have luminosities above a few $\times 10^{30}$ erg s^{-1}. Going down to a few 10^{29} erg s^{-1}, one expects to detect ~90% of RS CVn and ~75% of BY Dra systems, a dramatic increase. In particular, in the BY Dra systems which would be more common in globular clusters, it is only in M 4, 47 Tuc, and NGC 6397 that we have deep enough exposures to detect the bulk of the population.

One of our preliminary results on the X-ray sources in M 4 as a whole is that they appear less centrally concentrated than those in 47 Tuc and NGC 6397. Figure 2 shows the distributions of sources as a function of distance (in terms of the half-mass radius) from the centers of these three globular clusters.

Work on identifying the natures of all of the X-ray sources in M 4 is progressing, and there are already some noteworthy results on individual systems. Preliminary analysis suggest that a source which was tentatively classified earlier as a cataclysmic variable (CX1 from Bassa et al. 2004) is most likely a neutron star system (see also Kaluzny et al. 2012). In addition, one of the X-ray sources in M 4 appears to be a sub-subgiant (Nascimbeni et al. 2014), the nature of which is still unclear.

To make further progress in classifying the sources, accurate X-ray positions are necessary to facilitate optical cross-identifications. Near the aimpoint of *Chandra*, this is a straightforward process, but the PSF shape becomes distorted and asymmetric beyond distances of ~1.5′ from the aimpoint, making the determination of the position and its associated uncertainties more difficult. There is no standard software for this situation, but it is important to accomplish correctly given the large number of sources in M 4 at distances of arcminutes from the center (e.g., see Figure 2). An example of an off-axis source in M 4 is shown in Figure 3, along with its simulated PSF.

The current strategy is to compute, for each source, the Cash statistic for every possible location of the center of the PSF in the vicinity the source. The minimum of this Cash statistic surface represents the best determination of the location of the X-ray source, and Monte Carlo simulations using the PSF model are used to generate each source's Cash statistic distribution, which is used to determine the confidence intervals around the position estimate.

5. X-ray emissivity

As has been pointed out at previous conferences by Craig Heinke and Frank Verbunt, globular clusters appear deficient in X-ray sources compared to other old stellar populations, providing confirmation of the scenario described by Davies (1997) in which the stellar encounters in globular clusters will destroy

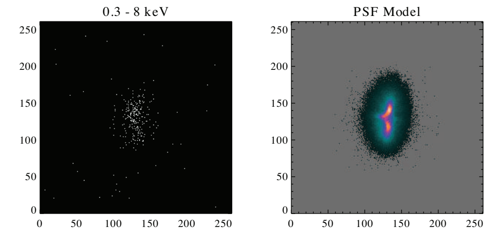

Fig. 3. *Chandra* image of an off-axis source in M 4 (left), and the simulated PSF for the source (right).

the progenitors of what would have evolved in cataclysmic variable systems in the field.

A recent paper by Ge et al. (2015) shows that the 0.5–2 keV emissivities (total X-ray luminosity per unit mass) of globular clusters is below that of other old stellar populations (like open clusters). The deficiency may be even more striking than Ge et al. point out because the soft X-ray emissivity of a globular cluster could be dominated by small number of quiescent neutron star low-mass X-ray binaries.

6. A look to the future

We currently have medium-depth *Chandra* observations of the half-mass region of many dozens of globular clusters and deep observations of three, and we should think about the optimum use of additional *Chandra* exposure in the coming years. Will we benefit more from repeated medium-depth observations of a large number of clusters to assess variability and total number of X-ray sources? Or would it be better to observe additional clusters to very deep limits of10^{29} erg s^{-1}? I welcome input from the non-X-ray members of the globular cluster community to weigh in on this and the following, very important matter.

The science case for the X-ray Surveyor is starting to be crafted now. This satellite will have spatial resolution comparable to or better than *Chandra* over a larger field of view with an effective area ~50 times larger. What open questions can this sensitivity help answer? How can these capabilities help advance our field? Please let me know your input on this!

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