Compact X-ray Binaries in and out of Core Collapsed Globulars

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Abstract

We review new Chandra and HST observations of the core collapsed cluster NGC 6397 as a guide to understanding the compact binary (CB) populations in core collapse globulars. New cataclysmic variables (CVs) and main sequence chromospherically active binaries (ABs) have been identified, enabling a larger sample for comparison of the $L_x$, $F_x/F_V$ and X-ray vs. optical color distributions. Comparison of the numbers of CBs with $L_x \gtrsim 10^{31}$ erg s$^{-1}$ in 4 core collapse vs. 12 King model clusters reveals that the specific frequency $S_X$ (number of CBs per unit cluster mass) is enhanced in core collapse clusters, even when normalized for their stellar encounter rate. Although core collapse is halted by the dynamical heating due to stellar (and binary) interaction with CBs in the core, we conclude that production of the hardest CBs – especially CVs – is enhanced during core collapse. NGC 6397 has its most luminous CVs nearest the cluster center, with two newly discovered very low luminosity (old, quiescent) CVs far from the core. The active binaries as well as neutron star systems (MSP and qLMXB) surround the central core. The overall CB population appears to be asymmetric about the cluster center, as in several other core collapse clusters observed with Chandra, suggesting still poorly-understood scattering processes.

Key words: globular clusters, X-rays: general, binaries: close, cataclysmic variables, X-ray binaries, millisecond pulsars

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1 Introduction

The high resolution imaging made possible by Chandra has enabled new insights into the compact binary population of globular cluster cores. In dense cores of globulars, compact or “hard” binaries with component stellar velocities much larger than the cluster velocity dispersion are both produced and
exchanged. They also provide the internal energy source to reverse core collapse, the process whereby mass segregation would otherwise lead to stellar mergers and production of an intermediate mass black hole (IMBH) with a signature cusp in the central density and velocity dispersion of the cluster (Bahcall and Wolf, 1976). Chandra’s ~0.5″ angular resolution within its central ~4′ field of view is both sufficient to locate the compact binaries (CBs) and conduct the first X-ray studies of their spectra and time variability down to the ~10^{29–32} erg s^{-1} luminosities characteristic of the 4 major classes of CBs. These are: active binaries (ABs), or near-contact binaries of main sequence stars (e.g. BY Dra type systems) in which X-ray emission occurs by chromospheric-coronal activity of these rapidly rotating stars; accreting white dwarfs (WDs) with main sequence companions, detected as cataclysmic variables (CVs); quiescent low mass X-ray binaries (qLMXBs) in which a neutron star (NS) primary sporadically accretes from a main sequence companion (usually evolved); and millisecond pulsars (MSPs), in which the detached secondary of a (former) qLMXB has allowed the spun-up NS to emit X-rays by (predominantly) the thermal emission from its polar caps heated by positron return currents. All of these classes of CBs have been discovered and detected with Chandra in both relaxed King model clusters (e.g., 47 Tuc; see Grindlay et al. (2001a) and Heinke et al. (2005)) and post core collapse (PCC) clusters (e.g. NGC 6397; see Grindlay et al. (2001b) and Grindlay et al. (2006; hereafter GvBB06), in preparation), and a comparison of these two clusters has been given recently by Grindlay (2005).

Here we extend this comparison between PCC and King model clusters and present additional new Chandra results for the PCC cluster NGC 6397 to derive constraints on the CB population that may be attributable to the core collapse process itself. We provide evidence for both CB destruction and creation before and during the PCC phase. Although only 2-3 of the MSPs in 47Tuc are likely doubly-exchanged, in NGC 6397 the single confirmed (radio) MSP as well as a second possible MSP (very similar in its X-ray and optical properties, but not detected as a radio MSP) has non thermal emission likely from shocked gas from its newly acquired main sequence companion, which is nearly filling its Roche lobe and interacting with the pulsar wind (Grindlay et al. 2002; Bogdanov et al. 2005). We present new results from both the Chandra (GvBB06) and HST (Cohn et al. 2006, in preparation; hereafter CLC06) observations of NGC 6397, which have now allowed X-ray/optical identifications for most of the CBs in the cluster with $L_x \gtrsim 10^{29.5}$ erg s^{-1} and have increased the number of confirmed CVs to 12 and possibly 13.

We then turn to other PCC clusters observed with Chandra for comparison. We find that PCC clusters have a higher specific frequency of CBs (mixture of all types, particularly CVs) than King model clusters. Additional very deep observations of NGC 6397 could provide important new tests of dynamical processes and binary populations in PCC clusters.
Fig. 1. Merged ACIS-I (2000) and ACIS-S (2002) Chandra photon images (0.3 - 6.0 keV) of NGC 6397 for the 3.3′×2.0′ region containing all 12 CVs identified thus far. The cluster center and optical core radius are measured (Taylor et al 2006, submitted; hereafter TGE06) to be 1″ NW of source U19 (CV2) and 4.4″, respectively, as marked by the black circle. All sources optically identified as cluster members are circled and Chandra source U numbers (Grindlay et al. (2001b), GvBB06) are given: CVs (red), ABs (green), MSP (blue), candidate MSP (yellow), and the qLMXB (cyan). The qLMXB (U24) is not identified optically but is still circled as a certain cluster member. U28 (magenta triangle) is a background AGN. The 9 remaining unidentified sources in this region are marked by black squares and source numbers. Most are likely cluster sources, bringing the total number in this region to 32. Several single-pixel count excesses (e.g. to right of label for U76) are likely CR background events and not consistent with the psf of real sources. The cluster half-mass radius, \( r_h = 2.3′ \), is just beyond the lower left corner of the box. Three AB counterparts are outside the box but inside \( r_h \): U42 (north) and U74, U77 (south). An additional 7 unidentified sources (north) and 3 (south) are outside the box but inside \( r_h \) and are probably dominated by the \( \sim 5-10 \) background AGN expected inside \( r_h \).

2 New Results for NGC 6397

At 2.3 kpc, NGC 6397 is the closest PCC globular cluster and only \( \sim 0.1 \)kpc farther (Harris, 1996) than M4, the closest globular of all. Combined with its relatively low mass, its population of stars vs. compact binaries in its central core is (by far) the best-resolved of any PCC cluster. Despite its very high central density in its collapsed core, with core radius 4.4±3.2″ for its brightest stars (V = 16.5-18.0) near the main sequence turnoff (TGE06), both HST imaging (Cool & Bolton (2002), TGE06, CLC06), and the first (July 2000)
Fig. 2. Distributions in $L_x$ (left) and $F_x/F_V$ (right) for the 26 sources in NGC 6397 with optical identifications and including 3 sources which are outside the box shown in Figure 1: U14, U42 and U77, which we identify with variables V35, V26 and V36 (Kaluzny et al. 2006), respectively. $L_x$ and $F_x$ are in the Sc band, and unabsorbed for the cluster log($N_H$) = 21.0, as are the measured (V magnitudes) optical fluxes, $F_V$. The 12 CVs are compared with the full population to show their characteristically different distribution in $F_x/F_V$ but not $L_x$.

Chandra observations (Grindlay et al. 2001b) resolve the core completely. In Grindlay (2005) we presented initial results from the second (May 2002) Chandra observations made with ACIS-S (vs. ACIS-I for the first observation). Here we give additional results of these observations (see GvBB06 for a complete report) as well as our new HST/ACS observations (CLC06), which together provide a nearly completely identified population of CVs, ABs and compact binary X-ray sources in the cluster. Figure 1 shows the central $\sim 3.3' \times 2.0'$ of the cluster for the combined (merged) ACIS-I and ACIS-S data in the 0.3 - 6 keV band.

The stacked ACIS-S (2 $\times$ 28ksec exposures, May 13 & 15, 2002) and ACIS-I (single 49ksec exposure, July 31, 2000) combined reach a detection threshold (3-5 cts) luminosity of $L_x \sim 2 \times 10^{29}$ erg s$^{-1}$in the Sc band (0.5 - 2.0 keV) for an assumed characteristic source temperature of $kT = 1$ keV. This is a factor of 2 below the $L_x$ limit for the ACIS-I data alone, as reported by Grindlay et al. (2001b). For an assumed source spectrum with $kT = 1$ keV, as appropriate for the optically identified ABs originally reported (Grindlay et al., 2001b) as well as the new AB counterparts identified by Kaluzny et al. (2006) and CLC06, we show in Figure 2 the distributions in $L_x$ and $F_x/F_V$ for the 23 sources in Figure 1 with optical identifications plus 3 source optically identified just outside the box (see caption for Figure 2). Using a spectral temperature $kT = 10$ keV, as is appropriate for the 6-8 brightest CVs (Grindlay et al. (2001b), GvBB06), would give $L_x$ and $F_x/F_V$ values larger by a factor of $\sim 2$.

It is striking how the 12 CVs (red histograms) are distinguished from the total population by having their log($F_x/F_V$) values significantly larger than the full
source population. This result is independent of the assumed X-ray spectrum: the $L_x$ and $F_x$ values in Figure 2 are derived for an assumed Bremsstrahlung spectrum with $kT = 1$ keV, which fits most of the ABs (Grindlay et al. 2001b, GvBB06), whereas for the Hc band (2.0 - 8.0 keV) and a harder source spectrum with $kT = 10$ keV (appropriate to the bright CVs), the overall distributions are very similar but shifted to larger values by $\sim 0.3$ in log($L_x$) or in log($F_x/F_V$) for the CVs. The $F_x/F_V$ distribution is consistent with that found for nearby field CVs observed with ROSAT (Verbunt et al., 1997). Comparison of the $F_x/F_V$ distribution (Figure 3) for the NGC 6397 CVs with those for dwarf nova (DN) or magnetic (AM Her or DQ Her) CVs in the galactic disk observed with ROSAT shows the CVs in NGC 6397 are likely a mixture of both types. Indeed, recent HST studies (Shara et al., 2005) show that at least two of the luminous CVs near the cluster center undergo dwarf nova (DN) like outbursts. While these may still be magnetic CVs (DQ Her type), as originally suggested on the basis of their HeII emission (Grindlay et al., 1995), they can still undergo DN-like outbursts though shorter outbursts are then expected if they are DQ Her systems. Longer time-based monitoring with HST to measure the outburst timescales can distinguish these possibilities.

The CVs also stand out from the cluster ABs in their X-ray colors. In Figure 4 we plot the X-ray color magnitude diagram (Grindlay et al. 2001a) (XCMD) using the hardness ratio Xcolor derived from the ratio of counts in the Sc/Hc bands for the 37 sources within the cluster half-mass radius. An additional 12 unidentified sources cannot be plotted since their total counts are too few to yield meaningful Xcolor values. The XCMD is plotted once again in the soft (Sc) band, but results are very similar in the Hc band. We also show the X-ray

Fig. 3. $F_x/F_V$ distributions of ROSAT CVs ($F_X$ in ROSAT band, or approximately Sc band) in the local field for both magnetic CVs and dwarf novae (from Verbunt et al. 1997), and the distribution for the 12 CVs in NGC 6397 (unabsorbed Sc band), which are likely a mixture.
color vs. $F_x/F_V$ ratio, which again demonstrates how the CVs are separated. We mark a possible CV candidate, U70, since it is in the CV domain in the XCMD. It may be identified with the He-WD candidate PC-5 reported by Taylor et al. (2001), for which the $V$ (F555W) magnitude 22.76 is used to compute $F_x/F_V$. The Hα absorption of the WD masks any Hα emission. It would thus resemble the lowest $L_x$ CVs U31 and U60 and if confirmed would increase the CV total in NGC 6397 to 13. Full details of the X-ray spectra, luminosities, temporal variability (including the X-ray detection of binary periods for several of the CVs) are given by GvBB06, and details of new HST identifications are given by CLC06.

Since the $F_x/F_V$ distribution appears to readily identify CVs, we can more confidently compare the CV vs. AB, MSP and qLMXB populations in globular clusters than by comparing XCMDs or $L_x$ distributions alone. Additional details are given in GvBB06, but a comparison with 47Tuc with the expanded sample of CBs in NGC 6397 extends the earlier conclusion of Grindlay (2005): the CVs are over-produced relative to ABs in NGC 6397. The optical IDs yield a relative fraction of identified CVs to ABs, $f_{CV/AB} = N_{CV}/N_{AB} = 12/12 = 1.0\pm0.41$ in the central portion (Fig. 1) of NGC 6397 vs. the ranges for $N_{CV}$ vs. $N_{AB}$ derived for 47Tuc by Heinke et al. (2005) which give $f_{CV/AB} = (24-113)/(89-178) = 0.51\pm0.38$.

It is also instructive to compare the spatial distributions of the CBs (CVs vs. ABs, MSPs and qLMXB) in NGC 6397. The distribution of the CVs in Figure 1 has most of the highest luminous CVs nearest the cluster center, surrounded by the ABs. The MSP (U12) and qLMXB (U24) are also at larger offsets, though the MSP candidate (U18) is in the central concentration of luminous CVs. In Figure 5 we plot the X-ray luminosity vs. radius (in core radius...
Fig. 5. X-ray luminosity (in Sc band) vs. radial offset (in units of cluster core radius) for sources in NGC 6397. The most luminous CVs are centrally concentrated, whereas the two lowest luminosity CVs are at (nearly) the largest offsets. CVs may be preferentially created during core collapse, while ABs are preferentially “burned” in the central core.

units, adopting \( r_c = 4.4'' \) from TGE06 for the CVs, NS systems (qLMXB and MSP(s)) and ABs together with the regression lines for each. The scatter is appreciable but is consistent with a radial dependence of CV luminosity (only). The two lowest luminosity CVs, U60 (CV9) and U31 (CV11), are at the largest offsets. Their optical counterparts (CLC06), discovered with new HST/ACS photometry, show them to be “quiescent CVs”, with relatively weak H\( \alpha \) emission – presumably due to the emission being offset in part by the broad H\( \alpha \) absorption from the white dwarf. This suggests the oldest CVs are farthest from the core; and that the luminous systems near the cluster center may then have formed in the (most recent) core collapse episode. As CVs (or any CBs) “age” they are more likely to be scattered out of the core by binary-binary or binary-stellar encounters (which may be disruptive). Recently formed \( (<10^8 y) \) CBs, however, would be most likely to be filling their Roche lobes and the most luminous accretors. Depending on the binary parameters, more luminous systems (e.g. U7 and U10; see Figure 1) can still be maintaining higher mass transfer long after having been scattered out of the core region in which they were most likely created.

The fact that the ABs appear (Figure 1) to “surround” the CVs in the core (though three [U15, U20, and U70] are at comparably small offsets from the cluster center) is consistent with binary “burning” in the central most core during the core collapse episode.
3 Other PCC Clusters

The web-based version of the [Harris (1996)](Harris1996) catalog of globular clusters lists 30 globulars (of 148 in the Galaxy with full data) as being possible PCC clusters. We drop those that are only possibly PCC (listed as ?), leaving 21 as almost certainly PCC. Of these, only 4 have been observed with Chandra to probe their low luminosity compact binary population down to luminosities $L_x > 10^{31}$ erg s$^{-1}$ (Liller 1, the Rapid Burster, was also observed but only in a shallow HRC observation). Several PCC globulars contain persistently luminous LMXBs (e.g. NGC 6624 and M15), which preclude even Chandra studies of the low luminosity source populations in the cluster cores given the bright wings of the psf from the luminous LMXB(s) in the core. So, in addition to NGC 6397, only 3 other globulars (Terzan 1, NGC 6752 and NGC 7099/M30) are available. Of the 111 globulars that are well described by a King model (i.e. isothermal and non-core collapsed) radial profiles, and excluding again the luminous LMXB clusters or those observed with the Chandra gratings (e.g. Terzan 2), 11 (47Tuc, NGC 5139, 5272, 6093, 6121, 6205, 6266, 6440, 6626, 6652, and Terzan 5) have been observed with Chandra and have published data available. We use the compilation of early Chandra results provided by [Heinke et al. (2003)](Heinke2003) as well as from [Cackett et al. (2006)](Cackett2006) for Terzan 1 and from [Lugger et al. (2006)](Lugger2006) for NGC 7099.

In Figure 6 we plot the specific frequency of CBs per globular, or number of sources per unit cluster mass (left) and further normalized for the collision rate $\Gamma \propto \rho^{1.5} r_c^2$ in the core (with stellar density $\rho$ and core radius $r_c$) of each cluster (right). We derive $S_x$ as the number of CBs with $L_x > 10^{31}$ erg s$^{-1}$ in order to discriminate against chromospherically active binaries (ABs). Thus $S_x$ is an approximate measure of the CV, qLMXB and (most luminous) MSP content of a globular cluster. We intentionally do not restrict the source count to be within just the central core, but rather the cluster half-mass radius, in order to include those systems that have been scattered out of the core. The larger area included thus increases the probability of background source contributions to $S_x$, but this is still small for most clusters. In both $S_x$ and particularly for $S_x$ normalized to the stellar encounter rate, $\Gamma$, in the cluster core, there is evidence that PCC clusters are indeed more abundant in their efficiency of production of accretion-powered CBs.

4 Discussion

The spatial distribution, and relative numbers, of CVs vs. ABs in NGC 6397 provide direct clues to processes occurring during cluster core collapse. The overabundance of CVs vs. ABs in or near the cluster center provides the
the first direct evidence that CBs (including CVs, and perhaps qLMXBs) are produced, rather than destroyed, in the core collapse process itself. In contrast, Figure 1 suggests that ABs, the (usually) less tightly bound ms-ms binaries (e.g. BY Dra systems) that are generally surviving primordial cluster binaries, are in fact destroyed in the PCC process: no ABs (green circles marking source positions) are in the central \(\sim 10''\) of the cluster core. All are in fact exterior to the CVs (red circles). As noted above where ranges are given, the numbers of CVs vs. ABs in NGC 6397 appear to be different from what is seen in 47Tuc. Using the firm IDs for ABs vs. CVs in 47 Tuc (Heinke et al., 2005) the ratio of ABs:CVs is 60:22 vs. 12:12 (or possibly 12:13 if U70 is also a CV) in NGC 6397. The clear inference is that ABs have indeed been “burned” (dynamically disrupted) in the core collapse process while at the same time, CVs have not been destroyed but rather (when scaled per unit cluster mass and collision number) in fact created.

Another fact presents itself: the distribution of sources (ABs, CVs, qLMXBs and MSPs) in NGC 6397 is decidedly anisotropic. We have commented on this for NGC 6397 before (Grindlay et al., 2001b; Grindlay, 2005), noting that the sources are predominantly to the South East (SE) of the cluster center and appear in a roughly linear configuration aligned with the 5 brightest blue stragglers (Grindlay et al., 2001b) and possibly consistent with the plane of the apparent cluster rotation equatorial plane (Grindlay, 2005). With the addition now of the PCC cluster Terzan 1 (Cackett et al., 2006) to the Chandra inventory, it joins NGC 6397 and NGC 6752 (Pooley et al., 2002) in having decidedly non-spherical distribution of sources around the cluster center. In NGC 6397, at radii \(\gtrsim 20''\) from the cluster center, no cluster sources are found to the NE (U28 is a background AGN) whereas they extend beyond 1.9’’ (U5) to the SE; and in NGC 6752, 13 of the 14 brightest sources are S of the cluster center. In Terzan 1, the 13 brightest sources are aligned in a symmetric (about

Fig. 6. Specific frequency of CBs in GCs for all 16 clusters observed with Chandra showing their contributions from King model clusters (blue) vs. PCC clusters (red). Distributions are plotted for Sx = number of sources per unit cluster mass (left) and for Sx per unit collision rate (right).
the cluster center) linear configuration (NW-SE). These may all be relatively small N statistics chance configurations, and simulations are planned, but the similarity is striking and begs explanation. Whereas “linear” or bar-like configurations may reflect scattering effects driven by angular momentum in core collapse, the asymmetries in NGC 6397 and NGC 6752 suggest proper motion effects (both are roughly aligned; but in the opposite sense, when put in the frame of the galactic halo (GvBB06)).

5 Conclusions

Compact binaries (CBs) of all stellar types are the engine that drive globular clusters away from completing their core collapse to form IMBHs. High resolution X-ray images are the most complete, and direct, way to capture the CB snapshot since examples of all known CB types are already detected or expected. AM CVn’s (CVs with WD secondaries) should be detected in deeper exposures, or may already have been found in NGC 6397 as the lowest $L_x$ CVs such as U60 (CV9), U31 (CV11) and possibly U70. Deep X-ray images thus can enable, and test, reconstructions of the dynamical interactions in cluster cores. The paradigm that CBs are destroyed to halt core collapse (“binary burning”) appears borne out in the population of primordial main sequence binaries, detected as ABs in X-rays. Perhaps not surprisingly, the CVs are the winners: exchanges of isolated cluster WDs into the initially much more abundant ABs destroy ABs but produce CVs in the cluster core of a PCC cluster. The high CV/AB ratios in NGC 6397 and NGC 6752 and probably also M30 support this claim. As usual, much deeper observations are needed. NGC 6397, as the closest PCC cluster, is the most promising prospect to probe the full CB population: both ABs and quiescent CVs can (and will) lurk at X-ray luminosities $L_x < 5 \times 10^{29}$ erg s$^{-1}$, as made clear by the discovery of the three new CVs, U25, U60 and U31 with log($L_{[Sc]}$) = 29.69, 29.38 and 29.00, respectively.

Likewise, and not otherwise discussed here, the CBs containing NS primaries (rather than WDs), namely the qLMXBs and their eternally-living (and thus dominant population) descendents, the MSPs, are another important probe. The Chandra source U18 appears in its X-ray spectral properties very similar (GvBB06) to the one confirmed MSP (U12) and has an optical counterpart that is also similar as a red straggler (TGE06; we note that the counterpart suggested by Kaluzny et al. (2006) is adjacent, but not astrometrically consistent with U18). Both U12 and U18 (if confirmed by radio detection) are re-exchanged binaries, again indicative of the high interaction rate locally in a PCC core. We also note the possibility of a significant number of “quiescent MSPs”, such as the two lowest X-ray luminosity MSPs in the field, J1024-0719 and J1744-1134, detected with ROSAT (Becker and Trumper 1999).
Both have X-ray luminosities ($L_x \sim 1$ and $\sim 4 \times 10^{29}$ erg s$^{-1}$, respectively) fixed by their parallax distances ($\lesssim 200$pc and 350pc, respectively) and could be detected in NGC 6397 in a deep exposure. Whereas both of these field systems are isolated, in PCC clusters they should also be found in CBs by exchange collisions. Subsequent exchanges (again, particularly in PCC clusters) then suggest a population of double NS binaries as the graveyard of CBs containing NSs (just as the AM CVn’s are the corresponding repository of quiescent CVs) in globular clusters. Both types may be abundant in PCC globular clusters, since these have preferentially exchanged WDs (primarily) and NSs into their primordial AB populations and then CB populations during what are likely to be repeated core collapse oscillations. The final result is then that PCC globulars are preferred sites for both WD-WD mergers (and thus possible SNIa events) and for NS-NS mergers (and thus a significant fraction of the short Gamma-ray Bursts – as we realized only recently (Grindlay, Portegies Zwart and McMillan 2006)).

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References

Bahcall, J. N. and Wolf, R. A. Oct. 1976. Star distribution around a massive black hole in a globular cluster. Astrophysical Journal, 209, 214-232.

Becker, W. and Trumper, J. Jan. 1999. The X-ray emission properties of millisecond pulsars. Astronomy and Astrophysics, 341, 803-817

Bogdanov, S., Grindlay, J. E., & van den Berg, M. Sept. 2005. An X-Ray Variable Millisecond Pulsar in the Globular Cluster 47 Tucanae: Closing the Link to Low-Mass X-Ray Binaries. Astrophysical Journal, 630, 1029-1036.

Cackett, E. M., Wijnands, R., Heinke, C. O. et. al. 2005. A Chandra X-ray observation of the globular cluster Terzan 1. Monthly Notices of the Royal Astronomical Society, in press [astro-ph/0512168].

Cool, A. M., & Bolton, A. S. 2002. Blue Stars and Binary Stars in NGC 6397: Case Study of a Collapsed-Core Globular Cluster. ASP Conf. Series, 263, 163-177.

Grindlay, J. E., Cool, A. M., Callanan, P. J., Bailyn, C. D., Cohn, H. N., & Lugger, P. M. Dec. 1995. Spectroscopic Identification of Probable Cataclysmic Variables in the Globular Cluster NGC 6397. Astrophysical Journal Letters, 455, L47-L51.

Grindlay, J. E., Heinke, C., Edmonds, P. D., Murray, S. S., Jun. 2001. High-Resolution X-ray Imaging of a Globular Cluster Core: Compact Binaries in 47 Tuc. Science, 292, 2290-2295.
Grindlay, J. E., Heinke, C. O., Edmonds, P. D., Murray, S. S., & Cool, A. M. Dec. 2001, Astrophysical Journal, 563, L53-L56.
Grindlay, J. E., Camilo, F., Heinke, C. O., Edmonds, P. D., Cohn, H., & Lugger, Dec. 2002. Chandra Study of a Complete Sample of Millisecond Pulsars in 47 Tucanae and NGC 6397. Astrophysical Journal, 581, 470-484.
Grindlay, J. E. 2005. Interacting X-ray Binaries in Globular Clusters: 47Tuc vs. NGC 6397. AIP Conf. Proc. 797: Interacting Binaries: Accretion, Evolution, and Outcomes, 797, 13-22.
Grindlay, J., Portegies Zwart, S. and McMillan, S. Feb. 2006, Short gamma-ray bursts from binary neutron star mergers in globular clusters. Nature Physics, 2, 116-119.
Harris, W. E., Oct. 1996. A Catalog of Parameters for Globular Clusters in the Milky Way. Astronomical Journal 67, 1487-1488.
Heinke, C. O., Grindlay, J. E., Lugger, P. M., Cohn, H. N., Edmonds, P. D., Lloyd, D. A., Cool, A. M., Nov. 2003. Analysis of the Quiescent Low-Mass X-Ray Binary Population in Galactic Globular Clusters. Astrophysical Journal 598, 501-515.
Heinke, C. O., Grindlay, J. E., Edmonds, P. D., Cohn, H. N., Lugger, P. M., Camilo, F., Bogdanov, S., & Freire, P. C. Jun. 2005. A Deep Chandra Survey of the Globular Cluster 47 Tucanae: Catalog of Point Sources. Astrophysical Journal, 625, 796-824.
Kaluzny, J., Thompson, I. B., Krzeminski, W., Schwarzenberg-Czerny, A. Jan. 2006. Photometric study of the variable star population in the globular cluster NGC 6397. Monthly Notices of the Royal Astronomical Society, 365, 548-554.
Lugger, P. M., Cohn, H. C., Heinke, C. O., Grindlay, J. E., and Edmonds, P. D. 2006, Chandra X-ray Sources in the Collapsed-Core Globular Cluster M30 (NGC 7099). Astrophysical Journal, in press.
Pooley, D., Lewin, W., Homer, L., et al. Apr. 2002, Optical Identification of Multiple Faint X-Ray Sources in the Globular Cluster NGC 6752: Evidence for Numerous Cataclysmic Variables. Astrophysical Journal, 569, 405-417.
Shara, M. M., Hinkley, S., Zurek, D. R., Knigge, C., & Dieball, A. Oct. 2005. Erupting Cataclysmic Variable Stars in the Nearest Globular Cluster, NGC 6397: Intermediate Polars? Astronomical Journal, 130, 1829-1833.
Taylor, J. M., Grindlay, J. E., Edmonds, P. M., Cool, A. M. Jun. 2001. Helium White Dwarfs and BY Draconis Binaries in the Globular Cluster NGC 6397. Astrophysical Journal, 553, L169.
Verbunt, F., Bunk, W. H., Ritter, H., Pfeffermann, E. Nov. 1997. Cataclysmic variables in the ROSAT PSPC All Sky Survey. Astronomy and Astrophysics 327, 602-613.
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: CUP)