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CHANDRA EXPOSES THE CORE-COLLAPSED GLOBULAR CLUSTER NGC 6397

J. E. Grindlay, C. O. Heinke, P. D. Edmonds, S. S. Murray,[1] and A. M. Cool[2]
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ABSTRACT

We report results of the *Chandra* deep-imaging observation of the closest post–core-collapse globular cluster, NGC 6397. Some 25 sources are detected within 2′ of the cluster center, of which ∼20 are likely cluster members, with $L_X \gtrsim 3 \times 10^{29}$ ergs s^{-1}. The X-ray spectra suggest identifications with one quiescent low-mass X-ray binary (qLMXB) detected by the thermal emission from its neutron star (NS) and nine cataclysmic variables (CVs), eight of which are identified in our deep *Hubble Space Telescope* (*HST*) imaging survey (reported separately). Three (of 16) BY Dra main-sequence binary candidates identified in our earlier *HST* imaging study (Taylor et al.) are detected, of which one is indeed the counterpart of the eclipsing millisecond pulsar (MSP) as recently identified by Ferraro et al. Two other BY Dra candidates are also detected, whereas none of the probable He white dwarf (WD) binaries identified by Taylor et al. are, indicating they do not contain MSP primaries. The ratio of CVs to MSPs appears to be ∼10 times greater than in 47 Tuc.

Subject headings: binaries: close — globular clusters: individual (NGC 6397) — novae, cataclysmic variables — pulsars: general — stars: neutron — X-rays: stars

1. INTRODUCTION

The remarkable high-resolution X-ray imaging of the *Chandra X-Ray Observatory* has opened a new era for the study of compact binaries in the dense cores of globular clusters. These systems have now been imaged in 47 Tuc (Grindlay et al. 2001b; hereafter GHE01) and found to include neutron stars (both quiescent low-mass X-ray binaries [qLMXBs] and millisecond pulsars [MSPs]), white dwarfs (cataclysmic variables [CVs]), and main-sequence binaries (BY Dra stars). X-ray spectral imaging and timing enables particularly direct discovery and study of these systems, which constrain stellar and binary evolution as well as the dynamical evolution of clusters.

We report initial results for our *Chandra* observation of the closest (2.5 kpc) core-collapse globular cluster, NGC 6397. Our *ROSAT* observations of NGC 6397 discovered a population of faint X-ray sources (Cool et al. 1993), several of which we identified with the *Hubble Space Telescope* (*HST*) as the first CV sample in a globular cluster (Cool et al. 1995; Grindlay et al. 1995). Deeper *ROSAT* observations of NGC 6397 were reported by Verbunt & Johnston (2000). The *Chandra* observations are a factor of 30 more sensitive and ∼10 times higher resolution. Together with deeper *HST* imaging studies (Taylor et al. 2001, hereafter TGE01; J. Grindlay et al. 2002, in preparation, hereafter GTE02), a nearly complete census of compact binaries is now possible for this dynamically interesting globular cluster.

2. *CHANDRA* OBSERVATIONS AND ANALYSIS

We obtained a 49 ks observation of NGC 6397 with ACIS-I starting at UT 15:31 2000 July 31, in timed exposure mode in a single continuous observation. The cluster center (Sosin 1997) was placed at 1′ in from the I3 chip boundaries so that the full core could be observed without chip gap complications. Standard *Chandra* processing tools (CIAO 2.1)[3] were used to reduce the data. WAVDETECT revealed 68 sources within the central 4′ radius field; for this paper we restrict analysis to the central 2′ radius, in which 25 sources are detected in the medium band (0.5–4.5 keV) above a threshold (95% confidence) of 3 counts. Source locations and a color composite *Chandra* image of the central sources are shown in Figure 1.

Event files were extracted using the WAVDETECT source regions, which include ∼94% of the counts associated with each source. The number of counts in each of three bands, 0.5–4.5 keV ("medcts"), 0.5–1.5 keV ("softcts"), and 1.5–6 keV ("hardcts") were extracted from these events files. The results are plotted as an instrumental X-ray color-magnitude diagram (cf. GHE01) in Figure 2, and source positions, fluxes, spectral fits, and probable identifications (see below) are given in Table 1.

For sources with medcts $\gtrsim 50$, spectra were extracted in bins 117 eV wide, which were grouped for $\gtrsim$9 counts per bin. Background spectra, derived from a 43 pixel radius including no sources, were subtracted, and sources were fitted to blackbody (BB), power law (PL), thermal bremsstrahlung (TB), and two-component BB and PL models with XSPEC.[4] TB models were acceptable fits (defined as $\chi^2_\nu < 1.5$, null hypothesis probability >5%) for all sources, and are recorded in Table 1 for all sources except U24 (*ROSAT* source B; see below). BB models alone are excluded for five (U17, U18, U19, U22, U23) of the seven brightest sources ($\chi^2_\nu > 1.5$, probability <5%). PL models are also acceptable fits to each of the sources (except U24), with best-fitting photon indices in the range 1.5–1.7, except for U12 ($1.4^{+0.5}_{-0.4}$), and U18 ($1.0^{+0.3}_{-0.1}$). BB + PL models could be rejected as having physically unrealistically small BB radii (∼10 m). All spectral fits include the absorption column N_H, which is significantly enhanced above the cluster value ($N_H = 1 \times 10^{21}$ cm^{-2}) for source U10 (the blue source in Fig. 1, *bottom*) as well as most of the CVs, but not for the MSP or BY Dra stars (see below).

Source U24 is similar in X-ray color (Fig. 2) and spectral shape to the quiescent low-mass X-ray binaries (or soft X-ray transients in quiescence) in ω Cen (Rutledge et al. 2001) and 47 Tuc (GHE01; Heinke et al. 2001, hereafter HGL01). A BB spectral fit is acceptable ($kT = 0.19 \pm 0.02$ keV, $N_H = 5 \pm 5 \times 10^{20}$ cm^{-2}), as are power-law fits (with an unrealistic

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; josh@cfa.harvard.edu.
[2] Department of Physics and Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132; cool@sfsu.edu.
[3] CIAO 2.1 is available at http://asc.harvard.edu/ciao/.
[4] XSPEC is available at http://xspec/gsfc.nasa.gov/docs/xanadu/xspec.

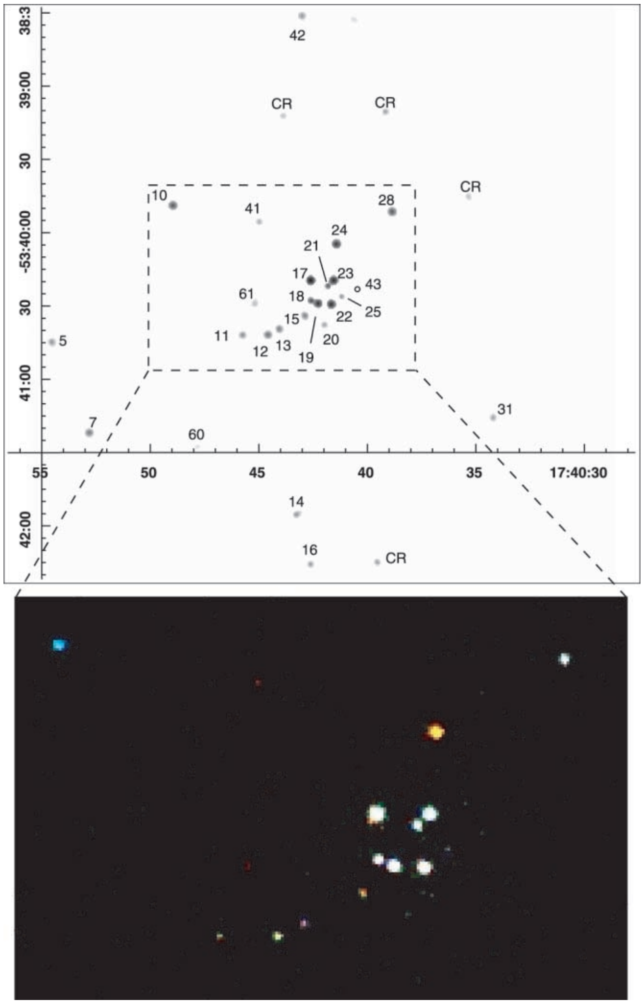

FIG. 1.—*Top*: Finding chart for sources detected with WAVDETECT in medium band (0.5–4.5 keV), with four probable cosmic-ray events (all counts recorded within $\lesssim$30 s) marked. *Bottom*: X-ray color image constructed from soft (0.5–1.2 keV; *red*), medium (1.2–2 keV; *green*), and hard (2–6 keV; *blue*) bands for sources detected with *Chandra* in the central ∼1′ in NGC 6397. The cluster center is within ∼1″ of U19 (CV2).

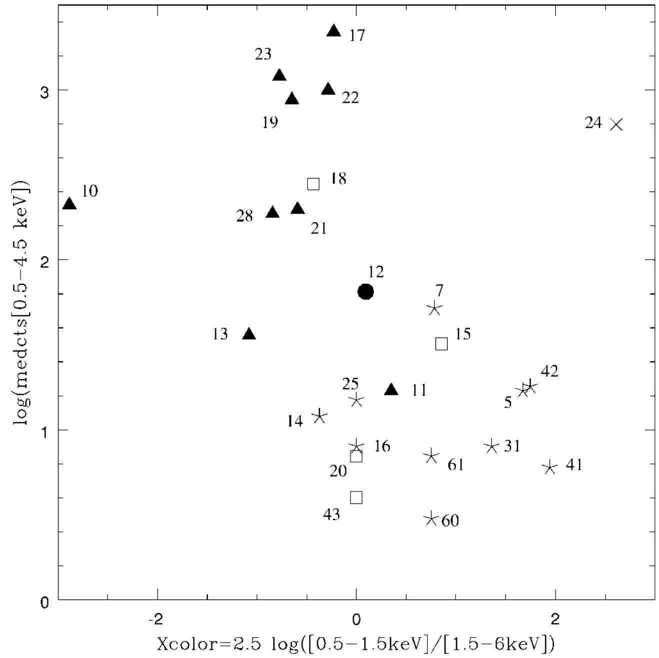

FIG. 2.—X-ray color-magnitude diagram, with probable source types labeled (as in GHE01): *cross*: qLMXB; *filled circle*: MSP; *filled triangles*: CV; *open squares*: BY Dra; *five-point stars*: unidentified. Source numbers correspond to those in Table 1.

photon index of 6 ± 1 and high N_H, $5^{+2}_{-1} \times 10^{21}$ cm^{-2}) and thermal bremsstrahlung fits (with $kT = 0.33 \pm 0.05$ keV, $N_H = 2.2 \pm 1 \times 10^{21}$ cm^{-2}). None of these are physically realistic models, and we turn to hydrogen or helium atmosphere neutron star (NS) models (Zavlin, Pavlov, & Shibanov 1996; Rajagopal & Romani 1996) physically motivated by radiation of heat accumulated in the core of an accreting neutron star during transient episodes and reradiated during quiescence (Brown, Bildsten, & Rutledge 1998).

We fit the unmagnetized NS atmosphere models of D. Lloyd & L. Hernquist (2002, in preparation), which assume opacity as a result of coherent electron scattering and free-free absorption. A NS surface gravity of $\log g_s = 14.38$ (redshift 0.306) was assumed. Either a hydrogen or helium atmosphere gives a good fit (see Table 1 for $kT_{\rm eff}$), with implied radii of the NS (R_∞, as seen at infinity) of 4.9^{+14}_{-1} km for a hydrogen atmosphere, and 12.0^{+3}_{-7} km for a helium atmosphere. These are consistent with theoretical predictions for $R_\infty \sim 10$–18 km (Lattimer & Prakash 2001), and the similarity of the fits to better constrained fits on X5 and X7 in 47 Tuc (HGL01) suggests that we are indeed seeing thermal emission from the whole surface of the NS. No PL component is seen, with only 1% of the total emission above 2.5 keV and only one photon above 3.3 keV. The lack of variability and a hard component suggest that no accretion onto the NS surface is currently taking place (see HGL01).

3. PROBABLE IDENTIFICATIONS

The X-ray spectral results suggest nine CVs, all with moderately hard TB spectra and internal self-absorption. The intrinsic N_H, particularly for U10 (CV6), suggests that these systems may be dominated by magnetic CVs, which show internal absorption from their "accretion curtains" (cf. GHE01 and references therein). Three of these CVs (CVs 1–3) were originally identified as such in our initial *HST* Hα survey (Cool et al. 1995). Two others (CVs 4 and 5) were found via variability or as counterparts to *ROSAT* HRI sources (Cool et al. 1998; Grindlay 1999). CVs 6–8 were discovered in our deeper follow-up *HST* Hα survey (GTE02). The ninth (*ROSAT* source A) we identify as a CV on the basis of its *Chandra* spectrum, which closely resembles that of U21 (CV4); it lies outside the *HST* field of view. Several of the CVs are clearly variable in the *Chandra* data, as reported in detail, and compared with the optical (*HST*) data, in GTE02: U23 (CV1) shows a total eclipse (∼0.5 hr) midway through the 49 ks observation, consistent with the 11.3 hr period discovered with *HST* for this eclipsing CV; U17 (CV3) shows a factor of ∼1.5 increase over ∼3 hr, followed by a ∼10 hr decline; and U21 (CV4) shows a possible 6 hr modulation.

Using the identifications with CVs 1–8, the required shifts in R.A. and decl. between *Chandra* and *HST* are 1″.24 and 0″.03, due (primarily) to the difference in absolute astrometry of their respective guide-star systems (all positions in Table 1 are on the *Chandra* reference frame, currently accurate to ∼0″.6 [1 σ]; Aldcroft et al. 2000). This solution allows precise ($\lesssim$0″.1) positional searches for the BY Dra stars identified (two from TGE01, and two from subsequent analysis). The *HST*-detected

CVs and BY Dra stars are marked in the color-magnitude diagrams of Figure 3. No star is seen at the position of the likely qLMXB, and we set a limit for the optical companion of $M_V > 11$.

Given the *Chandra-HST* astrometry, we identify ($\lesssim 0\farcs1$) U12 with the BY Dra star (WF 4-1) discovered as a 33.9 hr binary by TGE01 and now identified by Ferraro et al. (2001) as the probable optical counterpart of the eclipsing binary MSP PSR J1740−5340 in NGC 6397 (D'Amico et al. 2001a) on the basis of its timing position (D'Amico et al. 2001b) and very similar binary period. The offset in position, (radio–X-ray) δ(R.A., decl.) $= +0\farcs16, +0\farcs94$, is consistent with the *Chandra* astrometric uncertainties, and the *Chandra-HST* offset (given above) now links the *HST* frame with any further MSP identifications. The BY Dra signatures (possible binary sequence member, weak Hα emission) are likely due to MSP heating (or shock excitation) of the main-sequence companion in this long-period (1.35 day) binary MSP system, which is evident in the X-ray variation of U12: the X-ray flux increases from 0.001 counts s^{-1} measured during binary phase (D'Amico et al. 2001a) interval $\delta\phi = 0.15$–0.35 to 0.002 counts s^{-1} during $\delta\phi = 0.4$–0.55. This agrees to withhin $\delta\phi \sim 0.1$ of the phase of egress from radio eclipse, and confirms the identification of the MSP as the "BY Dra" system. Further details, including the light curve and comparison with the MSPs detected by *Chandra* in 47 Tuc (GHE01), are given in Grindlay et al. (2001a; hereafter GCH01).

Surprisingly, none of the "non-flickerers" (Cool et al. 1998; TGE01), which we have identified as containing He white dwarfs (Edmonds et al. 1999), are detected with *Chandra*. The suspected *ROSAT* detection (Verbunt & Johnston 2000) of NF3 (TGE01) is in fact U18, identified here with a BY Dra candidate (or possible MSP; see below) offset by $1\farcs1$. This suggests that the He white dwarfss in NGC 6397, with radial distribution indicating they contain "dark" binary companions (TGE01), do not have MSPs as their companions. As suspected on evolutionary grounds, the primaries are probably CO white dwarfs (Hansen et al. 2001).

4. DISCUSSION AND CONCLUSIONS

Comparison of Figure 1 (*top*) and Table 1 reveals that the unidentified sources are all at $\gtrsim 1'$ from the cluster center, except for U25 and U61, both of which have possible faint blue counterparts (GTE02). *Chandra* deep surveys (Giacconi et al. 2001) predict ∼5 active galactic nucleus background sources in this exposure out to $2'$. Indeed, our study of the radial source distributions measured with *Chandra* and *HST* (GTE02) shows that the *Chandra* sources are fitted by a King model with core radius $r_c \sim 6''$ and a power-law index slope of -2.5 at larger radii, with 20 cluster sources within $2'$ (∼20 core radii) and $L_X \gtrsim 3 \times 10^{29}$ ergs s^{-1} (or 15 sources at $L_X \gtrsim 10^{30}$ ergs s^{-1}). In contrast, 47 Tuc contains 187 sources within $4'$ (∼16 X-ray core radii) and $L_X \gtrsim 10^{30}$ ergs s^{-1} (GCH01). Although the ∼1 : 12 ratio of X-ray source numbers in NGC 6397 versus 47 Tuc scales nearly with cluster mass (∼1 : 6; cf. Pryor & Meylan 1993), the source population of NGC 6397 is relatively devoid of the faint, soft sources in the lower right of the X-ray color-magnitude diagram (Fig. 2), which contain most of the MSPs in 47 Tuc. The distribution of L_X for the NGC 6397 sources (Table 1) is much flatter than the corresponding distribution in 47 Tuc (Fig. 2 of GHE01).

The one MSP in NGC 6397 now detected in X-rays (U12) has X-color similar to the "bluest" MSP (47 Tuc-J) in 47 Tuc.

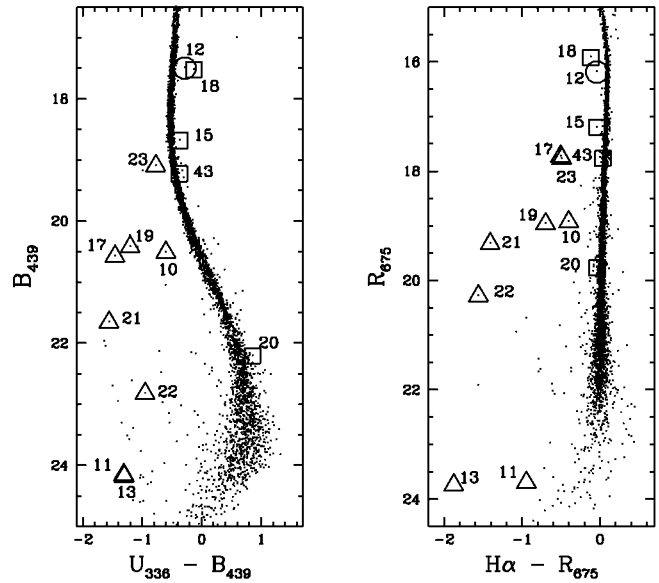

FIG. 3.—*HST* color-magnitude diagrams (cf. GTE02) for $U-B$ vs. B (*left*), and H$\alpha-R$ vs. R (*right*). *Chandra* sources identified with CVs (*open triangles*), BY Dra stars (*open squares*), and the MSP from Ferraro et al. (2001; *open circles*) are numbered with the source numbers given in Table 1. Stars for which membership has been confirmed by proper motion (Cool & Bolton 2001) are shown as dots.

It is possible that the hard source U18, a BY Dra candidate with optical colors similar to U12 (Fig. 3), is also a luminous MSP with a reexchanged secondary, since X-ray emission from chromospherically active stars is usually soft except in extreme flares—yet U18 appears constant over the full 13.5 hr observation. Possible "red" MSP candidates in the central regions of NGC 6397 are U61 and U41, as well as a soft source just visible in the wings of the bright CV U17 (cf. Fig. 1, *bottom*) at R.A. $17^h40^m42\fs72$ (3), decl. $-53°40'21\farcs1$ (5). Crowding prevented its detection by WAVDETECT, but we estimate medcts ~ 10 ($L_X \sim 1 \times 10^{30}$) and X-color $\gtrsim 1.3$ from examination of the image. U5, U7, U31, and U42 are also all possible MSPs, although at such large offsets from the core they would have to have been ejected. We note that the rough co-alignment of sources between U7 and U28 with the line of five bright blue stragglers in the cluster core (Auriere, Ortolani, & Lauzeral 1990) may suggest preferential cluster rotation and binary ejection; U12 is along this line, as expected if it was ejected in an exchange encounter. We estimate a total of perhaps 4–5 MSPs in NGC 6397 if the X-color distribution from 47 Tuc (GHE01) is a guide.

The numbers of detected (radio) versus suspected (X-ray) MSPs in NGC 6397 (1 vs. ∼5) compared to 47 Tuc (22 vs. $\lesssim 90$) are similar in ratio (∼1 : 5, which may indicate radio vs. X-ray beaming factors), but scale a factor of ∼3 below that for cluster mass. In contrast, for $L_X \gtrsim 10^{30}$ ergs s^{-1}, NGC 6397 appears to have ∼10 CVs, whereas 47 Tuc has ∼20–30. Thus, the CV to MSP ratio is ∼10 times larger in NGC 6397, and the two clusters suggest a dichotomy of compact objects and binary production: NGC 6397 has overproduced CVs (for its mass), perhaps because of two-body captures during core collapse. Its relatively lower MSP production might be due to a lower NS retention or fraction due to differences in the cluster initial mass functions, in turn due to their very different metallicities. The populations of BY Dra systems detected in X-rays in NGC 6397 versus 47 Tuc (4 vs. 6 *Chandra* sources,

TABLE 1
NGC 6397 *CHANDRA* SOURCES

Source (1)	R.A. (2)	Decl. (3)	Counts (0.5–4.5 keV) (4)	kT (keV) (5)	N_H (10^{21} cm^{-2}) (6)	log L_X (ergs s^{-1}) (7)	ID (8)
U5	17 40 54.51 (1)	−53 40 44.9 (1)	18	...	...	30.2	
U7	17 40 52.807 (8)	−53 41 21.89 (6)	54	...	...	30.7	
U10	17 40 48.948 (4)	−53 39 48.86 (3)	215	7–200	12–22	31.7	CV 6
U11	17 40 45.743 (9)	−53 40 41.99 (9)	17	...	...	30.2	CV 7
U12	17 40 44.571 (6)	−53 40 41.84 (4)	66	1–7	0.9–6	30.9	MSP
U13	17 40 44.054 (7)	−53 40 39.55 (6)	34	...	...	30.5	CV 8
U14	17 40 43.26 (1)	−53 41 55.46 (6)	12	...	...	30.0	
U15	17 40 42.873 (7)	−53 40 34.12 (9)	28	...	...	30.4	BY (PC-2)
U16	17 40 42.61 (1)	−53 42 15.8 (1)	8	...	...	29.9	
U17	17 40 42.607 (1)	−53 40 19.62 (1)	2243	6–10	1.6–2.3	32.3	CV 3
U18	17 40 42.567 (3)	−53 40 27.93 (2)	277	33–200	0–1.6	31.3	BY
U19	17 40 42.258 (2)	−53 40 29.03 (1)	881	11–91	2.5–4	31.9	CV 2
U20	17 40 41.98 (1)	−53 40 37.8 (1)	6	...	...	29.7	BY
U21	17 40 41.794 (4)	−53 40 21.66 (4)	188	5–120	2.1–4	31.3	CV 4
U22	17 40 41.659 (2)	−53 40 29.37 (1)	1019	9–30	1.1–2.0	31.9	CV 5
U23	17 40 41.551 (1)	−53 40 19.59 (1)	1217	6–11	4.5–6	32.2	CV 1
U24	17 40 41.421 (2)	−53 40 04.73 (2)	640	0.057–0.092	1–2.6	31.9	qLMXB
U25	17 40 41.20 (1)	−53 40 26.3 (1)	13	...	...	30.1	
U28	17 40 38.860 (3)	−53 39 51.45 (3)	189	6–200	2.7–7	31.3	CV
U31	17 40 34.21 (1)	−53 41 15.8 (1)	7	...	...	29.8	
U41	17 40 44.97 (1)	−53 39 55.6 (1)	6	...	...	29.7	
U42	17 40 43.01 (1)	−53 38 31.3 (1)	18	...	...	30.2	
U43	17 40 40.48 (1)	−53 40 23.0 (1)	3	...	...	29.4	BY (PC- 4)
U60	17 40 47.82 (3)	−53 41 27.7 (1)	3	...	...	29.4	
U61	17 40 45.19 (2)	−53 40 29.1 (2)	7	...	...	29.8	

NOTE.—Col. (1): WAVDETECT source number. Cols. (2)–(3): Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (4): Counts detected by WAVDETECT. Col. (5) Best-fit bremsstrahlung temperature, 90% confidence interval, allowing kT, N_H, normalization free. For U24, kT_{eff} is for H_{atm} model. Col. (6): Best N_H column fit (90% confidence) for bremsstrahlung (or H_{atm}) fit. Col. (7): Unabsorbed L_X values for 0.5-2.5 keV band, using best-fit spectrum (col. [5]), or assuming 1 keV bremsstrahlung spectrum, $N_H = 1 \times 10^{21}$ cm^{-2}, 2.5 kpc distance, and thus $L_X = 9.3 \times 10^{28}$ ergs s^{-1} $count^{-1}$. Col. (8): Probable source ID: BY (BY Dra main-sequence binaries; IDs from TGE01), CV (see text for numbering), MSP, and qLMXB.

respectively, but probably $\gtrsim$100 in 47 Tuc when crowding and the factor of ~2 higher L_X limits are considered) is consistent with the depletion of main-sequence binaries in the core of NGC 6397 (Cool & Bolton 2001). However, the identification of U12 as in fact a MSP raises the possibility that a number of optical variables and likely X-ray sources in 47 Tuc (e.g., BY Dra candidates) are in fact wide binary MSP systems, possibly resulting from double-exchange collisions, but which (unlike U12) have sunk back into the more massive cluster core. Optical periods and positions of plausible MSP companions can constrain the total MSP population, as well as radio timing solutions for MSPs detected but not yet located.

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