X-ray Binaries in the Globular Cluster 47 Tucanae

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Abstract. Chandra observations of globular clusters provide insight into the formation, evolution, and X-ray emission mechanisms of X-ray binary populations. Our recent (2002) deep observations of 47 Tuc allow detailed study of its populations of quiescent LMXBs, CVs, MSPs, and active binaries (ABs). First results include the confirmation of a magnetic CV in a globular cluster, the identification of 31 additional chromospherically active binaries, and the identification of three additional likely quiescent LMXBs containing neutron stars. Comparison of the X-ray properties of the known MSPs in 47 Tuc with the properties of the sources of uncertain nature indicates that relatively few X-ray sources are MSPs, probably only $\sim 30$ and not more than 60. Considering the $\sim 30$ implied MSPs and 5 (candidate) quiescent LMXBs, and their canonical lifetimes of 10 and 1 Gyr respectively, the relative birthrates of MSPs and LMXBs in 47 Tuc are comparable.

INTRODUCTION

Globular clusters are efficient factories for the production of X-ray binaries from populations of primordial binaries (see papers by D’Antona et al. and Ivanova et al., this volume). Although the nature of bright ($L_X > 10^{36}$ erg s$^{-1}$) X-ray sources in globular clusters as low-mass X-ray binaries containing neutron stars has been long established [1,2], the nature of faint X-ray sources has been more difficult to determine. At least four types of low-luminosity ($L_X = 10^{30–34}$ ergs s$^{-1}$) X-ray systems are now known to exist in globular clusters: cataclysmic variables [CVs; 3], LMXBs in quiescence [qLMXBs; 3, 4], millisecond radio pulsars [MSPs; 5], and chromospherically active main-sequence binaries [ABs; 6]. A recent review of X-ray sources in globular clusters can be found in Verbunt and Lewin [7, see also Verbunt, these proceedings].

The advent of the Chandra X-ray Observatory has allowed detailed study of the populations of faint X-ray sources in globular clusters [8], especially in the dense and nearby cluster 47 Tuc [9]. The large MSP population in 47 Tuc [10] has been detected in X-rays with Chandra, allowing studies of the MSPs’ X-ray luminosities and spectra [11,12]. The precise positions have allowed identification of optical counterparts to 58% (45 of 77) of the X-ray sources detected within a deep HST imaging field [13, 14]. Within 47 Tuc, 22 CVs and 29 ABs have been unambiguously identified, in addition to two qLMXBs and 17 MSPs.
A major mystery associated with globular clusters is the formation mechanism of millisecond pulsars. The logical progenitors of MSPs, the LMXBs, appear at first glance to be far too small in numbers to produce the estimated numbers of MSPs \[15\]. The number of MSPs in 47 Tuc has been estimated at \(>200\) \[10\], suggesting \(~10000\) MSPs in the Galactic globular cluster system. However, only 13 bright LMXBs are known in our globular cluster system. For typically assumed lifetimes of 10 and 1 Gyr respectively, the MSP birthrate is two orders of magnitude higher than the LMXB birthrate. It is possible that many MSPs in globular clusters were born in the distant past from intermediate-mass X-ray binaries, and/or that X-ray heating greatly reduces the lifetimes of LMXBs \[16\]. However, the problem cannot be regarded as conclusively solved via these theoretical mechanisms at the present time. Here we discuss observations of 47 Tuc which may reduce this discrepancy in lifetimes by two orders of magnitude.

**CHANDRA OBSERVATIONS OF 47 TUC**

Following our successful 70 ksec *Chandra* observation of 47 Tuc in 2000 \[9\], we obtained a deeper 280 ksec observation in late 2002, spread over more than a week to constrain source variability. These observations used the backside-illuminated ACIS-S3 chip for maximal low-energy sensitivity. Within the 2.79′ half-mass radius of 47 Tuc, 300 sources were detected in the 2002 observations [Figure 1; Grindlay, these proceedings; \[17\]].

Comparing the positions of the new X-ray sources with unusual objects in 47 Tuc, we find that an additional 31 active binaries, identified from *HST* variability studies \[18\], can be unequivocally identified with *Chandra* X-ray sources. None of the new CV candidates suggested by \[19\] are identified with X-ray sources. Eighty-seven X-ray sources show clear variability, on timescales ranging from hours and weeks (within the 2002 observations) to years (comparing the 2002 and 2000 observations) and decades (comparing the 2002 detections with the ROSAT results, \[20\]). Based on the radial distribution of the detected sources, roughly 70 of them are probably background sources.

Simple spectral fits to the individual sources find that the majority can be well-fit by absorbed thermal plasma models (VMEKAL in XSPEC) using the cluster metallicity. This is expected for CVs and ABs (though some of the brightest CVs require complicated multi-component spectra). However, the known qLMXBs and MSPs are generally not well-fit by thermal plasma models \[17, 12\]. There are three additional sources that are unusually soft and bright when compared to other CVs and ABs.

One, W37, shows eclipses with a 3.087 hour period and strong variations in \(N_H\), with an X-ray spectrum generally best described by a hydrogen-atmosphere model appropriate for neutron star surfaces \[21\]. The other two, X4 and W17, have X-ray spectra best described by a hydrogen-atmosphere model with a strong power-law component. X4 also shows short-term variability, which may be from either component. The hydrogen-atmosphere models give implied radii consistent with 10-13 km for all three sources, indicating that all three are probably quiescent LMXBs. However, the relative strength of the power-law components (60-65% of the 0.5-10 keV unabsorbed flux) and low luminosities (\(\sim 5 \times 10^{31} \) ergs s\(^{-1}\)) for two, and high absorption for the third, indicate
Cataclysmic variables in globular clusters seem to have higher X-ray fluxes, and lower optical fluxes, than CVs in the rest of the Galaxy [14]. This has led to speculation that the accretion flow onto CVs in globular clusters may be generally controlled by the magnetic field of the white dwarf, since such systems (DQ Her and AM Her systems) have little or no disk and relatively high X-ray/optical flux ratios [23]. However, only one DQ Her-type system has been suggested in a globular cluster [X9 in 47 Tuc, 9].

Our new Chandra observations identify a large-amplitude sinusoidal modulation with a 4.7-hour period from the CV X10, and a very soft blackbody component to its X-ray spectrum, identifying this CV as an AM Her, or polar. We also identify an \( N_H \) column above the cluster value for 12 of the 22 CVs, possibly indicating a DQ Her nature. Period searches are underway to confirm this possibility (Grindlay et al. 2005, in prep.).
MILLISECOND PULSARS IN 47 TUC

Of the 22 known MSPs in 47 Tuc, 17 have known positions, 16 through radio timing \[10, 24\], and one through matching an X-ray source to a variable optical source with an orbital period and phase that match those of 47 Tuc-W \[25\]. The MSPs G and I, separated by only 0.1″, are detected as a single source in the Chandra image. The MSPs F and S, separated by only 0.74″, are detected as a single, extended source. All other MSPs with known positions are clearly detected in this image.

Comparing the independently detected MSPs’ radio pseudoluminosities \[10\] with their X-ray luminosities, no correlation is seen. This implies that MSPs with lower radio pseudoluminosities will have X-ray luminosities similar to those of the known MSPs. The X-ray emission is probably mostly from the hot polar caps of the neutron stars \[11\], while the radio emission originates higher in the magnetosphere. Gravitational bending assures that we will see virtually all MSPs in the X-ray, regardless of radio beaming fractions \[12\]. Thus, nearly all MSPs in 47 Tuc should be detected among our X-ray sources, with X-ray luminosities between \(2 \times 10^{30}\) and \(2 \times 10^{31}\) (30-350 counts).

We can compare the X-ray properties (X-ray “colors”, variability, and spectral fits) of the unknown sources in this luminosity range to those of the known MSPs, CVs and ABs. We show in Figure 2 the distributions of MSPs, good candidate MSPs, ABs, and unknown sources in an X-ray color-color plot. (Likely background sources, located farther than 100″ from the center of 47 Tuc, are also indicated, and are somewhat harder on average.) The distributions of MSPs and ABs are seen to be significantly different, and the unknown source distribution is more similar to the ABs than the MSPs.

We compare the numbers of MSPs, ABs, CVs, and background sources with each property (variability, spectral agreement with a VMEKAL model, colors within one of three classes) to the total number of unknown sources with that property. We assume that the ratio of unknown members of a class (e.g. ABs) to the known members of that class is the same (within binomial statistics) for each property. That is, if the number of ABs not yet identified is 60% of the number of identified ABs, and 20 known ABs are variable, then \(\sim 12\) unknown variable sources are probably ABs. We fit the numbers of unknown sources with each property using the numbers of known sources, to determine the ratios of unknown to known sources in each class. We can thus estimate the number of unidentified MSPs as \(7^{+10}_{-7}\). These unidentified MSPs must include the five known MSPs without known positions, suggesting that few MSPs remain undetected. The 95% single-sided upper limit on the total number of MSPs is 42; varying our choice of information to include gives a range of upper limits up to 56. Because our CV sample is X-ray selected, we cannot provide a similar constraint upon the number of CVs.

Can this estimate be missing a significant number of radio MSPs? Radio-faint MSPs could be X-ray faint also. However, there is no evidence of such a correlation among the known MSPs. Submillisecond pulsars or pulsars in very tight orbits could escape radio detection, but since these would be relatively energetic they would tend to be X-ray brighter, not fainter, than the known MSPs. The most likely way for MSPs to remain hidden is to be completely enshrouded in ionized gas from a nondegenerate companion (see Grindlay, these proceedings), similar to (but more extreme than) 47 Tuc W \[10, 12\]. This would obscure the radio signal, and the shock from the pulsar would also emit X-rays, altering the X-ray emission spectrum. However, 47 Tuc W is rather
FIGURE 2. X-ray color-color plots showing sources with 30-350 counts in 47 Tuc. Left: Locations of MSPs (large filled dots), candidate MSPs (open octagons), and ABs (open squares). Right: Locations of sources of unknown nature (stars), and the subset of unknown sources located beyond 100″ from the center of the cluster (stars enclosed by squares); the latter are likely dominated by background sources. Model spectral tracks are plotted in both, with small dots representing (lower left to upper right): H-atmosphere for 75, 100, 125, 150, 175 eV; VMEKAL thermal plasma for 0.4, 0.5, 0.7, 1, 2, 3, 5, 10 and 30 keV; and a power-law with photon index 3, 2.5, 2, 1.5, 1. Error bars are plotted for all MSPs, and a few other representative faint sources. Increasing $N_H$ moves sources up and to the right.

luminous for an MSP (and since the X-rays from the shock would need to obscure the thermal component, any “hidden” MSPs would be similarly luminous). There are very few X-ray sources of unknown nature in 47 Tuc of similar luminosity as 47 Tuc W. We conclude that unless there exists a class of MSPs that are very different from the MSPs we know, there are probably not more than 60 MSPs in 47 Tuc. This estimate agrees with independent constraints from HST identifications of X-ray sources [14] and integrated radio continuum flux measurements [26].

We extrapolate from this constraint in two directions. Two lines of evidence suggest that of order 10% of the neutron stars in a dense cluster are recycled into MSPs. Six of the eighty known MSPs in globular clusters have companions of masses $\sim 0.1 - 0.2 M_\odot$, yet are eclipsing. All of these systems with optical identifications are probably MSP–main sequence binaries, suggesting binary exchange of a white dwarf for a main sequence star and putting the pulsar on a path to further recycling. Since 7% of these pulsars were doubly recycled, the recycling rate for neutron stars in dense clusters is likely to be of the same order. Recent cluster simulations [27] also suggest a neutron star recycling rate of 5-15%, higher for denser clusters. Thus we can extrapolate a total number of $\sim 300$ neutron stars in 47 Tuc (a rough, but empirical estimate). This is significantly less than has been previously predicted, and helps to resolve the neutron star retention problem in
globular clusters [28]. The other direction is toward relative LMXB/MSP birthrates. These studies of 47 Tuc have increased the inferred number of qLMXBs and decreased the inferred number of MSPs, producing a ratio of $\sim 30/5=6$ (compare to a ratio of $\sim 1000$ from [15]). If qLMXBs can be counted among the progenitors of MSPs as a stage in the outburst cycle of LMXBs, and LMXB/qLMXBs live for $\sim 1$ Gyr, then there is no longer an MSP birthrate problem in 47 Tuc, and in globular clusters generally.

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