X-ray and Optical Studies of Millisecond Pulsars in 47 Tucanae

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Abstract. Our Chandra X-ray observation of the globular cluster 47 Tuc clearly detected most of the 16 MSPs with precise radio positions, and indicates probable X-ray emission from the remainder. The MSPs are soft (BB $kT \sim 0.2-0.3$ keV) and faint ($L_X \sim$ few $10^{30}$ ergs s$^{-1}$), and generally consistent with thermal emission from small polar caps. An additional 40 soft X-ray sources are consistent with the known MSPs in X-ray colors, luminosity, and radial distribution within the cluster (and thus mass). We note that these MSPs display a flatter $L_X$ to $\dot{E}$ relation than pulsars and MSPs in the field, consistent with polar cap heating models for younger MSPs and may suggest the surface magnetic field has been modified by repeated accretion episodes to include multipole components. Correlating HST images, radio timing positions, and the Chandra dataset has allowed optical searches for MSP binary companions. The MSP 47 Tuc-U is coincident with a blue star exhibiting sinusoidal variations that agree in period and phase with the heated face of the WD companion. Another blue variable star (and X-ray source) agrees in period and phase with the companion to 47 Tuc-W (which lacks an accurate timing position); this companion is probably a main sequence star.

X-ray and optical studies of the millisecond pulsars (MSPs) in 47 Tuc (Freire et al. 2001a; Lorimer, these proceedings) allow us to probe the physics of the polar caps, the evolutionary state of the binary systems in which many reside, and the complete population of millisecond pulsars, many of which have not yet been discovered in the radio. Chandra is the only X-ray telescope capable of resolving the faint MSPs from the quiescent LMXBs, cataclysmic variables (CVs), and active (flaring) main-sequence binaries in the crowded central regions of globular clusters, and Hubble Space Telescope (HST) archival data allows deep searches for the intrinsically faint white dwarf (WD) binary companions expected for the MSPs.
1. **Chandra X-ray Studies**

Using the source-detection tool WAVDETECT, we have identified 103 sources in the central 2'×2.5' region containing the 16 MSPs with known timing positions (Grindlay et al. 2001, GHE01). Ten identified X-ray sources were identified with timing positions of 12 MSPs (including the unresolved pairs F & S, G & I); aligning the radio and X-ray frames revealed probable emission from the locations of the remaining four (not formally detected due to crowding with brighter sources, or for 47 Tuc-C, low exposure on a chip gap). The MSPs show a remarkable similarity in luminosities; all are clearly identified with 0.5-2.5 keV luminosities in the range $10^{30.0–30.6}$ ergs s$^{-1}$ except for two unresolved pairs and 47 Tuc-C, also consistent with this range. No correlation is seen between the X-ray and radio luminosities.

The MSPs are clearly “softer” than the majority of the other X-ray sources. Grindlay et al. 2002 (GCH02) plotted two hardness ratios for the identified MSPs (Fig. 1a), along with predicted ratios for simple spectral shapes (using the column density to 47 Tuc). Most of the MSPs, with the notable exception of 47 Tuc-J, are consistent with 0.2 to 0.3 keV blackbody emission and inconsistent with a simple powerlaw of photon index 1 to 2. This implies that most of the MSPs exhibit predominantly thermal emission from part of their polar caps; the temperature and emitting radius (~ 0.2 km for a BB, 0.8 km for H-atmosphere model) are consistent with the higher-temperature thermal component identified by Zavlin et al. (2002) in the nearby MSP J0437-4715.

GCH02 compare the relation of the 0.5-2.5 keV X-ray luminosities of the 47 Tuc MSPs to their rotational energy loss $\dot{E}$ (calculated for these globular cluster
MSPs using a three-dimensional model of the cluster gas and potential, Freire et al. 2001b) to that for field MSPs, following Becker & Trümper (1999). In contrast to the field MSPs, for which $L_X \propto \dot{E}^{1.13 \pm 0.15}$ (consistent with emission from pulsars generally), we find that the 47 Tuc MSPs show $L_X \propto \dot{E}^{0.5 \pm 0.2}$ (see Fig. 1b). This flatter dependence of $L_X$ on $\dot{E}$ is predicted by the models of Harding & Muslimov (2002) for polar cap heating. However, the MSPs retain this dependence to larger characteristic ages than predicted by the model, leading GCH02 to propose that the MSPs have had their surface magnetic fields altered toward multipole configurations through repeated accretion episodes.

GCH02 also investigated the larger populations of Chandra sources out to a radius of 4’. The MSP radial distribution is consistent with that of the soft sources, according to a Kolmogorov-Smirnov test, requiring no abrupt truncation of their spatial distribution (Fig. 2a). The soft sources are also consistent with a “generalized King model” (Lugger, Cohn & Grindlay 1995) profile, with a probable mass range of 0.9-1.4 $M_{\odot}$, and include CVs and active binaries as well as unidentified MSPs. GCH02 estimate that, if the radio and X-ray luminosities are uncorrelated, the number of MSPs in 47 Tuc lies in the range 35-90.

2. HST Optical Studies

Using the detection of six CVs and active binaries in the Chandra and HST data, we have fixed the HST and radio coordinate systems, allowing the detection of the first MSP companion in a globular cluster, 47 Tuc U (Edmonds et al. 2001).
A blue star was identified at the radio position (see fig. 2b), and low-amplitude sinusoidal variations were seen in the V-band data, with a period matching the radio orbital period. In addition, the phase of maximum brightness corresponds to the phase of maximum visibility of the side of the WD expected to be heated by the MSP wind. The position of 47 Tuc-U in the CMD indicates that the companion is indeed a helium WD of mass $\sim 0.17 \, M_\odot$.

Another MSP optical counterpart has been identified without a radio timing position for the MSP (Edmonds et al. 2002, EGC02). The Chandra X-ray source W29 (GHE01) was identified with a blue star showing large-amplitude (60-70%) sinusoidal variability. Phase-connecting HST data from several programs, including recent ACS calibration data, produced an accurate period, 0.132944(1) days, matching the radio orbital period of 47 Tuc-W within 0.5 s. The phase of optical maximum also matches the phase of maximum visibility of the heated side of the companion within 1.2 minutes (0.006 in phase). Camilo et al. (2000) noted that 47 Tuc-W has a short period (3.2 hours), but a much higher mass than other short-period systems ($\sim 0.15 \, M_\odot$), and eclipses in the radio. Its CMD location suggests that the companion is a main-sequence star, significantly heated by the MSP wind but not Roche-lobe filling. This implies that the companion is probably the result of an exchange encounter (common in dense cluster cores), and not the original companion.

Additional Chandra and simultaneous HST data will be collected by October 2002 (PI J. Grindlay), allowing deeper studies of the known MSPs and identification of other MSPs not yet detected in the radio.

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References

Becker, W. & Trümper, J. 1999, A&A 341, 803
Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G., & Manchester, R. N. 2000, ApJ 535, 975
Edmonds, P. D., Gilliland, R. L., Heinke, C. O., Grindlay, J. E., & Camilo, F. 2001, ApJ 557, L57
Edmonds, P. D., Gilliland, R. L., Camilo, F., Heinke, C. O., & Grindlay, J. E. 2002, ApJ (in press, astro-ph/0207426; EGC02)
Freire, P. C. et al. 2001a, MNRAS 326, 901
Freire, P. C. et al. 2001b, ApJ 557, L105
Grindlay, J. E., Heinke, C. O., Edmonds, P. D., & Murray, S. S. 2001a, Science 292, 2290 (GHE01)
Grindlay, J. E., Camilo, F., Heinke, C. O., Edmonds, P. D., Cohn, H., & Lugger, P. 2002, ApJ (in press, astro-ph/0208280; GCH02)
Harding, A. K. & Muslimov, A. G. 2002, ApJ 568, 862
Lugger, P. M., Cohn, H. N., & Grindlay, J. E. 1995 ApJ 439, 191
Serenelli, A. M., Althaus, L. G., Rohrmann, R. D., & Benvenuto, O. G. 2001, MNRAS 325, 607
Zavlin, V. E. et al. 2002, ApJ 569, 894