Chandra on Millisecond Pulsars in Globular Clusters

J.E. Grindlay, C.O. Heinke and P.D. Edmonds
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

F. Camilo
Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA

Abstract. We summarize the x-ray properties of the complete samples of millisecond pulsars (MSPs) detected in our Chandra observations of the globular clusters 47 Tuc and NGC 6397. The 47 Tuc MSPs are predominantly soft sources suggestive of thermal emission from the neutron star polar cap and have x-ray luminosities in a surprisingly narrow range ($L_x \sim 1-4 \times 10^{30}$ erg s$^{-1}$). The single MSP in NGC 6397 is both hard and apparently extended, probably due to shocked hot gas evaporating from its main sequence companion. In contrast to MSPs in the field and the cluster M28, which show correlation between x-ray luminosity and spin-down luminosity $L_x \propto E^\beta$ with $\beta \sim 1 - 1.4$, the 47 Tuc (and NGC 6397) sample display a relatively tight correlation with $\beta = 0.5 \pm 0.15$. The correlations of $L_x$ vs. $P/2P$ and light cylinder magnetic field values are also different. It is possible the magnetic field configuration has been altered (by episodic accretion) for old MSPs in dense cluster cores.

1. Introduction

X-ray studies of millisecond pulsars (MSPs) can constrain fundamental properties of their emission regions and, when combined with radio timing studies, their underlying neutron stars (NSs). In globular clusters both MSPs and low mass x-ray binaries (LMXBs), their likely progenitors, are significantly enhanced (per unit mass) over their values in the galactic disk by stellar and binary interactions. The dense cluster (core) environment needed for their excess formation may also alter their evolution. Thus cluster vs. field MSPs, as studied in x-rays and radio, can constrain intrinsic vs. extrinsic (evolutionary) properties of these oldest NS systems.

We have conducted a deep Chandra survey for MSPs as well as quiescent LMXBs and cataclysmic variables (CVs) in the globular clusters 47 Tuc (Grindlay et al. 2001a; GHE01a) and NGC 6397 (Grindlay et al. 2001b; GHE01b). The full details of the MSP survey are given in Grindlay et al. (2001c; GCH01). Here we present the highlights of this study, focusing on just the x-ray properties of the 16 MSPs with radio timing positions in 47 Tuc (Freire et al. 2001a, Freire 2001) and the one in NGC 6397 (D’Amico et al. 2001; DPM) as well as...
their comparison with the field MSP population (cf. Becker & Trumper 1997, 1999; BT97, BT99). We defer to the full paper the discussion of the total MSP populations and spatial distributions, which probe cluster dynamics.

2. X-ray Colors and Emission Models

The 47 Tuc MSPs were found initially (GHE01a) to be soft sources. In GCH01 we give the detected counts in 3 bands: softcts (0.2–1 keV), mediumcts (1–2 keV) and hardcts (2–8 keV) for each of the 14 resolved MSPs, with counts for 47 Tuc-G and -I (unresolved) estimated. From these bands, we form the hardness ratios $HR_1 = \text{mediumcts/softcts}$ and $HR_2 = \text{hardcts/mediumcts}$ and plot the MSPs, with counting statistics errors, in the color-color diagram shown in Figure 1 (left). The MSP colors are clustered in a relatively narrow range of $HR_1$ and $HR_2$ with 47 Tuc-J clearly harder, as was evident in the Xcolor distributions in GHE01a.

Using the PIMMS tool, we construct values of $HR_1$ and $HR_2$ for 3 simple models: thermal bremsstrahlung (TB), blackbody (BB) and power law (PL), with index values (kT or photon index) given in the caption of Figure 1 (left). The observed range of $HR_1$-$HR_2$ is roughly consistent with TB spectra with kT $\sim 1$ keV, BB spectra with kT $\sim 0.2$–0.3 keV (except for 47 Tuc-J) or PL spectra with photon index $\sim 3$. The weighted mean colors for all but 47 Tuc-J are consistent with a BB spectrum with kT $\sim 0.22$ keV, giving x-ray luminosities $L_x (0.5-2.5\text{keV}) \sim 1-4 \times 10^{30}$ erg s$^{-1}$ and thus mean bolometric $L_x - \text{bol} = 2.6 \times 10^{30}$ erg s$^{-1}$.

The x-ray colors rule out TB models (surrounding column densities inconsistent with the MSP dispersion measures; DM) and PL fits (spectral indices implausible). Simple BB fits for $L_x - \text{bol}$ give emission radii of only $\sim 0.1$km whereas H (or He)-atmosphere models (Rajagopal & Romani 1996) typically give temperatures reduced (from BB) by a factor of $\sim 2$ and thus radii increased to $\sim 0.4$km. Either case suggests soft x-ray emission from a region smaller than the entire polar cap, as predicted in recent models of Harding & Muslimov (2001) for polar cap heating. Although the 3.2s temporal resolution of Chandra-ACIS prevents a pulsation analysis, the small thermal emission area suggests the emission would be pulsed, with a sinusoidal pulse shape appropriate to the fractional visibility of the isotropically radiating thermal polar cap. In contrast, the narrower pulse duty cycles of $\sim 10\%$ for some field MSPs (and one in the globular cluster M28; BT99) are probably due to non-thermal beamed emission.

3. X-ray vs. Pulsar Spin Properties

A key question for this rich Chandra dataset is the correlation of x-ray luminosity and pulsar spindown luminosity $\dot{E}$, which is found for field MSPs (with much more uncertain distances) to scale as $L_x (0.1-2.4\text{keV}) \sim 10^{-3} \dot{E}$ (BT97) and with a possibly steeper logarithmic slope (1.4) for $L_x$ in the 2-10keV band (Possenti et al. 2001; PCC). We derive intrinsic period derivatives, $\dot{P}_i$, corrected for the cluster acceleration by estimating the 3D positions of each MSP in the cluster from the observed DM value and the observed hot gas and thus electron
density in the cluster (Freire et al. 2001b) and then subtracting the cluster acceleration using a King model with cluster parameters derived by Meylan & Mayor (1986). Using a standard NS moment of inertia \( I = 10^{45} \text{ g cm}^2 \), we then derive \( \dot{E} = 4\pi^2 I P_i / P^3 \) for each MSP and plot them vs. \( L_x \) (0.5-2.5keV) in Figure 1 (right). Uncertainties in the \( \dot{E} \) values are typically 0.2–0.5 in the log but are not shown for clarity; uncertainties in \( \log(L_x) \) are typically 0.2, and extrapolating to the ROSAT band, 0.1-2.4keV, would increase \( \log(L_x) \) only by 0.1. For comparison with 47 Tuc, we plot the MSP in NGC 6397 (GHE01b), for which the \( \dot{E} \) uncertainty is small, and updated values (cf. GCH01) for the 10 field MSPs previously detected in x-rays as well as in the globular cluster M28.

Whereas the MSPs in the field and M28 show (Figure 1, right) a correlation \( \log L_x (0.1-2.4\text{keV}) = (1.13\pm0.15) \log \dot{E} - 7.5\pm5 \), the MSPs in 47 Tuc appear to have a weaker dependence: \( \log L_x (0.5-2.5\text{keV}) = (0.47\pm0.10) \log \dot{E} + 14.2\pm3.4 \) for the nominal cluster model with central velocity dispersion \( \sigma_0 = 11.6 \text{ km s}^{-1} \), where the errors \((\pm1\sigma)\) in both correlations are due to just the scatter in the points. Allowing for uncertainties in the cluster model and distance gives slope \( 0.48 \pm 0.21 \) and intercept \( 13.8 \pm 7.5 \). Including the errors for the \( \dot{E} \) values estimated for the 47 Tuc MSPs, but with the approximation that unequal errors (on \( \dot{E} \)) are simply averaged (which biases the slope to steeper values, since the unequal errors are much larger for smaller values of \( \dot{E} \)), increases the logarithmic slope to \( \beta = 0.62 \pm 0.29 \) and offset to \( 9.0 \pm 10.8 \). The best (median) estimate for the 47 Tuc MSPs alone is thus \( \beta \sim 0.55 \pm 0.2 \). Apart from the uncertain detection
$$\log(L_x) = -0.32 \log(Age) + 33.3 \quad (47\text{ Tuc})$$

$$\log(L_x) = -1.46 \log(Age) + 44.9 \quad (\text{Field} \& \text{ M28})$$

$28.00 \quad 29.00 \quad 30.00 \quad 31.00 \quad 32.00 \quad 33.00 \quad 34.00 \quad 35.00$

$7.00 \quad 7.50 \quad 8.00 \quad 8.50 \quad 9.00 \quad 9.50 \quad 10.00 \quad 10.50 \quad 11.00$

$\log(Age, \text{ years})$

$\log(L_x)$

$1821-24/\text{M28}$

$6397-A$

$J$

$$\log(L_x) = 0.66 \log(B_{lc}) + 27.2 \quad (47\text{ Tuc})$$

$$\log(L_x) = 1.70 \log(B_{lc}) + 23.0 \quad (\text{Field} \& \text{ M28})$$

$28.50 \quad 29.00 \quad 29.50 \quad 30.00 \quad 30.50 \quad 31.00 \quad 31.50 \quad 32.00 \quad 32.50 \quad 33.00 \quad 33.50$

$3.50 \quad 4.00 \quad 4.50 \quad 5.00 \quad 5.50 \quad 6.00 \quad 6.50$

$\log(B_{lc}, \text{ gauss})$

$\log(L_x)$

$6397-A$

$\text{NGC 6397}$

$\text{J in 47 Tuc}$

**Figure 2.** Left: $L_x$ vs. characteristic age ($P/2\dot{P}_i$) for MSPs in 47 Tuc (diamonds) and field (triangles). MSP in NGC 6397 (box) is labeled as is J in 47 Tuc. Right: $L_x$ vs. $B_{lc}$, inferred magnetic field strength at the light cylinder ($r_{lc} = cP/2\pi$) for MSPs in 47 Tuc (diamonds) and field (triangles). MSP in NGC 6397 (box) is labeled as is J in 47 Tuc. Values for MSPs in field and M28 from data given in GCH01, with $B_{lc}$ derived assuming standard $1/r^3$ dependence of dipole field (see text).

of 47 Tuc-C (GCH01), the MSPs in 47 Tuc have $L_x$ (0.5–2.5 keV) values within a factor of $\sim 4$ despite a range of $\sim 25$ in $\dot{E}$. Figure 1 (right) shows that 6397-A, the MSP in NGC 6397, is consistent with the $L_x - \dot{E}$ correlation shown by the 47 Tuc MSPs. Including 6397-A in the fit yields $\beta = 0.50 \pm 0.08$ (scatter only) or $0.55 \pm 0.15$ (with averaged $\pm 1\sigma$ errors for the 47 Tuc $\dot{E}$ values).

The smaller $\beta$ values for 47 Tuc and NGC 6397 may be due to the different formation histories and possibly different physical parameters of their MSPs vs. the field objects. In Figure 2 (left) we plot $L_x$ vs. spindown ages, $P/2\dot{P}_i$, for MSPs in the field (and M28) vs. the 47 Tuc and NGC 6397 sample. Error bars on the age parameter are not shown, for clarity, but are typically $\sim 0.3$ in the log and primarily due to the 47 Tuc acceleration model. Despite the uncertainties, the correlation is striking: the field MSPs show a declining $L_x$ with “age,” and the 47 Tuc MSPs appear to fall on this trend but with a flatter $L_x$ vs. age slope. However, spindown ages correspond only approximately to actual ages, and while these estimates are consistent with the formation of most 47 Tuc MSPs early in the cluster history, this would not by itself provide an explanation for the different $L_x$ vs. $\dot{E}$ correlations found for MSPs in 47 Tuc and NGC 6397 vs. the field.

Another possible physical difference between the 47 Tuc and field MSPs might be magnetic field strength at the light cylinder (at which the corotation speed equals $c$), since this likely affects the relative importance of non-thermal (magnetospheric) emission. For an assumed dipole field, this is given by $B_{lc} = 9.35 \times 10^5 \dot{P}_i^{1/2} P_{\text{msec}}^{-5/2}$ G, with $\dot{P}_i$ in units of $10^{-20}$. In Figure 2 (right) we plot $L_x$ vs. $B_{lc}$. Again, considered as a homogeneous group, the MSPs in the field (and M28) lie on a steeper slope than the 47 Tuc MSPs. In support
of the hypothesis that $B_{lc}$, rather than the field $B_{surf} = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G at the NS surface, is more closely related to $L_x$ is the fact that the correlation of $L_x$ with $B_{surf}$ is less defined and with larger scatter, and with logarithmic slopes differing even more: 0.05±0.27 for the 47 Tuc MSPs vs. 2.80±0.99 for the field MSPs. We note that 3 out of the 4 MSPs with $B_{lc} \gtrsim 10^{5.5}$ G display x-ray emission that is seemingly magnetospheric, with the nature of emission from the 4th (the eclipsing MSP B1957+20) indeterminate (BT99; Takahashi et al. 2001). Conversely, field pulsars with $B_{lc} < 10^5$ G have x-ray emission that is typically either thermal or of indeterminate character (BT99). Considering the small numbers of such pulsars studied, and that most of them have highly uncertain distances, it seems possible that field pulsars with $B_{lc} \lesssim 10^5$ G may show an $L_x-B_{lc}$ trend that is fairly flat and roughly consistent with the better determined relation for the 47 Tuc MSPs. However for this interpretation to hold, a few field MSPs with relatively well determined distances (e.g. 0437−4715 and 1744−1134; cf. GCH01) must be accounted for and the even larger deviations of 0751+1807 and 1024−0719 from the 47 Tuc correlation line would require factor $\gtrsim 3$ adjustments in these MSP distances.

4. Conclusions

The MSPs in 47 Tuc are primarily very soft x-ray sources, consistent with thermal emission from the pulsar polar caps. The MSPs in both 47 Tuc and NGC 6397 seem to have a less efficient conversion of rotational spindown energy ($\dot{E}$) into soft x-rays ($L_x$) than most field MSPs, even those with correspondingly low values of their magnetic field at the light cylinder. For $L_x \propto \dot{E} \beta$, the 47 Tuc-NGC 6397 samples are fit by $\beta = 0.5 \pm 0.15$ whereas the updated (GCH01) field (and M28) sample are consistent with the value $\beta \sim 1 - 1.4$ found previously (BT97; PCC and references therein).

The soft colors for the 47 Tuc MSPs and the extended emission from 6397-A (GCH01) indicate a lack of beamed magnetospheric emission, which may suggest they have different $B_{lc}$ values or configurations. We speculate their B fields may have a multipole field geometry (and thus lower dipole component) and be less efficient particle accelerators. Unlike MSPs in the field, those in dense cluster cores have a possibility of being driven back into contact and an accretion phase, as a re-cycled LMXB (from a MSP)! Renewed accretion (and 6397-A is presently close to filling its Roche lobe; cf. DPM) would likely continue the B-field burial process thought to be responsible (e.g. Romani 1990) for field decay from the $\gtrsim 10^{11}$ G fields at NS birth to the $\lesssim 10^9$ G values typical of MSPs. The 47 Tuc MSPs have spent their $\tau \gtrsim 1$ Gyr lifetime in a dense ($n \sim 10^5$ pc$^{-3}$) cluster core, where they undergo scattering interactions with both single stars and other binaries. Such scattering causes the binding energy $x$ of a hard binary to secularly increase. Thus, while angular momentum transfer to the secondary acts to detach the binary, scattering events tend to drive it back toward contact.

A complication in this picture is that since MSPs are extremely hard binaries, the secular increase in $x$ is largely the result of infrequent strong scattering events, which are likely to eject the binary from the cluster core or even the cluster. Nevertheless, it appears plausible that a typical old ($\tau \gtrsim 1$ Gyr) MSP in a dense cluster core might undergo one or more MSP-LMXB transformation
cycles. Thus a few percent of the MSPs at any one time may be in (or near) this recurrent LMXB phase. This might explain the puzzling luminous qLMXBs X5 and X7 (GHE01a and Heinke et al. 2002) in 47 Tuc; they might be recently (∼10^5−6 yr) detached LMXBs, in which their underlying MSP nature is hidden by their evaporating (from MSP-driven winds?) fossil disks, thus explaining their lack of any detectable low-level accretion signatures.

The younger system in NGC 6397 has the advantages of having been recently scattered out of a still higher density (∼10^6 pc^-3) core collapsed cluster core and possibly having exchanged its companion (Ferraro et al. 2001, GHE01b). Either or both would likely have restored an accretion phase. Thus 6397-A need not be just “born,” as suggested by Ferraro et al. (2001); it may instead have just been reborn. In contrast, the MSP in M28 is both ∼10× younger, single and in a lower density core and so is unlikely to have gone through a renewed accretion phase.

Acknowledgments. We thank H. Cohn and P. Lugger for discussions of MSP recycling, described in GCH01. This work was supported in part by NASA grants GO0-1098A and HST-AR-09199.01-A (JG) and NAG5-9095 (FC).

References

Becker, W., & Trumper, J. 1997, A&A, 326, 682 (BT97)
Becker, W., & Trumper, J. 1999, A&A, 341, 803 (BT99)
D’Amico, N., Possenti, A., Manchester, R. N., Sarkissian, J., Lyne, A. G., & Camilo, F. 2001, ApJ, 561, L89 (DPM)
Ferraro, F. R., Possenti, A., D’Amico, N., & Sabbi, E. 2001, ApJ, 561, L93
Freire, P. C. 2001, Ph.D. thesis, Univ. Manchester
Freire, P. C., Camilo, F., Lorimer, D. R., Lyne, A. G., Manchester, R. N., & D’Amico, N. 2001a, MNRAS, 326, 901
Freire, P. C., Kramer, M., Lyne, A. G., Camilo, F., Manchester, R. N., & D’Amico, N. 2001b, ApJ, 557, L105
Grindlay, J. E., Heinke, C. O., Edmonds, P. D., & Murray, S. S. 2001a, Science, 292, 2292 (GHE01a)
Grindlay, J. E., Heinke, C. O., Edmonds, P. D., Murray, S. S., & Cool, A. M. 2001b, ApJ, 563, L53 (GHE01b)
Grindlay, J. E., Camilo, F., Heinke, C. O., Edmonds, P. D., Cohn, H. & Lugger, P. 2001c, ApJ, submitted (GCH01)
Harding, A. K. & Muslimov, A. G. 2001, ApJ, submitted
Heinke, C. O., Grindlay, J. E., Lloyd, D. A., & Edmonds, P. D. 2002, ApJ, submitted (see also Heinke et al., these proceedings)
Meylan, G., & Mayor, M. 1986, A&A, 166, 122
Possenti, A., Cerutti, R., Colpi, M. and Mereghetti, S. 2001, A&A, submitted (http://xxx.lanl.gov/archive/astro-ph/0109452) (PCC)
Rajagopal, M. & Romani, R. 1996, ApJ, 461, 327
Romani, R. 1990, Nature, 347, 741
Takahashi, M. et al. 2001, ApJ, 554, 316