A search for X-ray counterparts of the millisecond pulsars in the globular cluster M28 (NGC 6626)

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Abstract. A recent radio survey of globular clusters has increased the number of millisecond pulsars drastically. M28 is now the globular cluster with the third largest population of known pulsars, after Terzan 5 and 47 Tuc. This prompted us to revisit the archival Chandra data on M28 to evaluate whether the newly discovered millisecond pulsars find a counterpart among the various X-ray sources detected in M28 previously. The radio position of PSR J1824−2452H is found to be in agreement with the position of CXC 182431-245217 while some faint unresolved X-ray emission near to the center of M28 is found to be coincident with the millisecond pulsars PSR J1824-2452G, J1824-2452J, J1824-2452I and J1824-2452E.

Key words. globular clusters:general — globular clusters:individual (M28 – NGC 6626) — stars:neutron — x-ray:stars — binaries:general — pulsars:general — pulsars:individual (PSR J1824-2452)

1. Introduction

About 10% of the 1765 known radio pulsars are millisecond pulsars (MSPs). The majority of them, currently 134, are located within 24 globular clusters (GCs) which, because of their extreme stellar core density, lead to dynamical interactions that apparently play a significant role in the formation of MSPs. The first MSP discovered in a globular cluster was PSR J1824−2452A in M28 (Lyne et al. 1987). Its inferred pulsar parameters make it the youngest (P/2P = 3.0 × 10^-7 yrs) and most powerful (E = 2.24 × 10^{36} erg s^-1) pulsar among all known MSPs. A recently performed deep radio survey of M28 which was designed to search for more cluster pulsars led to the discovery of ten new MSPs (Bégin 2006). Together with the previously known PSR J1824−2452A, four of the M28 MSPs appear to be solitary. The others are in binaries. Two pulsars are found to be in highly eccentric binary systems with eccentricities of e = 0.847 and 0.776, respectively, and companion masses of at least 0.26 M⊙ and 0.38 M⊙ (Bégin 2006). M28 is now the globular cluster with the third largest population of known MSPs pulsars, after Terzan 5 and 47 Tucanae (Camilo et al. 2000, Ransom et al. 2005, Stairs et al. 2006).

In this letter we report on a re-analysis of Chandra ACIS-S data from the globular cluster M28. It was performed to search for X-ray counterparts of the newly discovered MSPs. The re-analysis builds partly on the analysis of the M28 Chandra data which was published by Becker et al. (2003).

2. Observations and Data Analysis

M28 was observed by the Chandra ACIS-S three times for approximately equal observing intervals of about 13 ksec between July and September 2002. These observations were scheduled so as to be sensitive to time variability on time scales up to weeks. The observations were made using 3 of the CXO Advanced CCD Imaging Spectrometer (ACIS) CCDs (S2,3,4) in the faint timed exposure mode with a frame time of 3.241 s. Standard Chandra data processing has applied aspect corrections and compensated for spacecraft dither. Level 2 event lists were used in our analyses. Events in pulse invariant channels corresponding to 0.2 to 8.0 keV were selected for the purpose of finding sources. Increased background corrupted a small portion of the third data set reducing its effective exposure time from 14.1 ksec to 11.4 ksec although no results were impacted by the increased background.

The optical center of the cluster at α2000 = 18h 24m 32.89s and δ2000 = −24° 52′ 11.4″ (Shaw and White 1986) was positioned 1′ off-axis to the nominal aim point on the back-illuminated CCD, ACIS-S3, in all 3 observations. A circular region with 3:1-radius, corresponding to twice the half-mass radius of M28, centered at the optical center was extracted from each data set for analysis. No correction for exposure was deemed necessary because the small region of interest lies far from the edges of the S3 chip.

Applying a wavelet source detection algorithm, the X-ray position of PSR J1824−2452A was measured separately using the three data sets and the merged data. The set-averaged position is the same as that derived using the merged data set and was found to be in agreement with the pulsar’s radio position. The result is summarized in Table 1. The root-mean-
square (rms) uncertainty in the pulsar position, based on the 3 pointings, is $0^\circ.042$ in right ascension and $0^\circ.029$ in declination. The radio position and proper motion of the pulsar, as measured by Rutledge et al. (2003), places the pulsar at the time of the observation only $\Delta_\alpha = 0^\circ.083$, $\Delta_\delta = -0^\circ.042$ away from the best-estimated X-ray position. In what follows the X-ray positions of all sources have been adjusted to remove this offset.

Table 1. PSR J1824–2452A Positions (J2000)

| Date       | Position       | Offset (arcsec) |
|------------|----------------|-----------------|
| 2002 July 4| 18 24 32.015   | -24 52 10.81    |
| 2002 Aug 8 | 18 24 32.016   | -24 52 10.76    |
| 2002 Sep 9 | 18 24 32.009   | -24 52 10.83    |
| average    | 18 24 32.013   | -24 52 10.80    |
| rms (arcsec) | 0.042         | 0.029           |
| merged data| 18 24 32.013   | -24 52 10.80    |
| radio (8/02)| 18 24 32.008   | -24 52 10.76    |

In addition to the 37.6 ksec of ACIS-S data we reanalyzed about 100 ksec of HRC data which were available from M28 in the Chandra archive. Part of this data were taken in 2002 October 11. and were used by Rutledge et al. (2003) to investigate the temporal X-ray emission properties of PSR J1824–2452A. The second half of the HRC-S data was taken more recently, in 2006 May 27. & 28., for the purpose of Chandra on-board clock calibration. However, both HRC data sets were taken in timing mode and hence suffer from very high background as in this mode all photons which are registered in the detector are transmitted to the ground to allow a correction for the detectors timing bug (cf. Tenant et al. 2001). As far as the detection of faint sources is concerned the available ACIS-S data supersede the HRC data in sensitivity, albeit more than 60% shorter in exposure time. We therefore did not further consider the HRC data for the search of X-ray counterparts of the newly discovered MSPs.

Amongst the many interesting results we obtained from the ACIS-S observation and which were reported already in detail in Becker et al. (2003), this data detected 46 X-ray sources in a field of 4 arcmin near to the pulsar PSR J1824–2452A. 12 of these sources are located within the 14.4 arcsec cluster core radius. The properties of these sources along a detailed spectral analysis for the brightest among them was published in Becker et al. (2003) so that we can omit to repeat all details of our previous analysis here again. To briefly summarize few basic findings in the following, though, might be convenient for the reader.

The brightest source in the ACIS-S data (#26 in Table 3 of Becker et al. 2003), which is also the one with the softest spectrum, was identified as a candidate LMXB in quiescence, whereas all the other sources in the field turned out to have rather hard X-ray spectra. Source #19 (cf. Table 3 of Becker et al. 2003 and Figure 1 below), which emits the hardest X-rays, is the millisecond pulsar PSR J1824–2452A. Several of the other X-ray sources seen in M28 were found to show variability on time scales of hours to weeks and are still unidentified.

The superior ~ 1 arcsec angular resolution of Chandra not only allowed us to resolve PSR J1824–2452A from nearby sources which in the ROSAT HRI were only seen as diffuse unresolved emission, it furthermore provided the first uncontaminated, phase-averaged, spectrum from the brightest among all millisecond pulsars. This spectrum was found to be best described by a power law with photon index $1.2^{+0.15}_{-0.13}$. PSR J1824–2452A thus has a very hard X-ray spectrum which made it to detect the pulsar up to ~ 20 keV with RXTE (Mineo et al. 2004). Exciting to note and most interesting, however, is the evidence of an emission line feature centered at ~ 3.3 keV in the pulsar spectrum (cf. Fig. 2 in Becker et al. 2003). This line feature can be interpreted as cyclotron emission from a corona above the pulsar’s polar cap if the magnetic field is different from a centered dipole configuration. The significance of the feature, however, is at the edge of detectability which prevents any final conclusion and clearly calls for confirmation in a further deeper observation.

Figure 1 shows the central region of M28 as seen by Chandra ACIS-S3 between July and September 2002. The image was created with a spatial binning of 0.5 arcsec. Positions of PSR J1824–2452A and nine newly discovered millisecond pulsars are indicated (cf. Table 2). Inspecting the data for possible emission from the newly discovered MSPs shows that there is some faint unresolved X-ray emission near to the center of M28 (cf. Figure 1) which is coincident with the locations of four of the new MSPs: PSR J1824–2452G, J1824–2452J, J1824–2452I and J1824–2452E. The position of the eclipsing binary millisecond pulsar PSR J1824–2452H reported by Bégin (2006) is found to be ~ 0.2 arcmin north from the position of CXC 182431–245217 which is source #18 reported in Becker et al. (2003). More accurate radio timing solutions, however, had found that the position of PSR J1824–2452H is indeed in agreement with CXC 182431–245217 (Ransom 2007, priv. com.). The identification of this X-ray source as a pulsar is further supported by the similarity of its hardness ratio with that of PSR J1824–2452A and the lack of long-term variability (cf. Table 3 in Becker et al. 2003). By measuring the counts within a circle of 2 arcsec (encircled energy ~ 95%) at the MSP source positions, we have determined the counting rates and upper limits for the 10 out of 11 pulsars in M28. The results are listed in Table 2 together with the a summary of the millisecond pulsar parameters from Bégin (2006).

Because of the low ACIS-S instrument background, the counts obtained from the location of the MSPs J1824–2452G, J1824–2452I and J1824–2452J suggest that there is significant emission from these sources, albeit unresolved and at the edge of sensitivity in the available data. This suggests, however, that in a deeper Chandra ACIS-S observation it will be possible to resolve and detect the emission from all these new pulsars and to obtain spectral information from them. The pulsar PSR J1824–2452H (respectively CXC 182431–245217) is detected with a signal-to-noise ratio of 2.88. Determining its counting rate yields $(2.9 \pm 0.9) \times 10^{-5}$ cts/s, corresponding to an $0.2–8.0$ keV

2 The position of J1824–2452K is not available in Bégin (2006)
X-ray luminosity of $1.2 \times 10^{30}$ erg/s for an assumed power-law spectrum with a photon-index of 2, a source distance of 5.5 kpc and a column absorption of $0.18 \times 10^{22}$ cm$^{-2}$. Albeit this is only a rough luminosity estimate, the X-ray conversion concluded from it is only $3.6 \times 10^{-5}$.

3. Discussion

Since the *Einstein* era it has been clear that globular cluster contain various populations of X-ray sources of very different luminosities (Hertz & Grindlay 1983). The stronger sources ($L_x \approx 10^{36} - 10^{38}$ erg s$^{-1}$) were seen to exhibit X-ray bursts which led to their identification as low-mass X-ray binaries (LMXBs). The nature of the weaker sources, with $L_x \leq 3 \times 10^{34}$ erg s$^{-1}$, however, was more open to discussion (e.g., Cool et al. 1993; Johnston & Verbunt 1996). Although many weak X-ray sources were detected in globulars by ROSAT (Johnston & Verbunt 1996; Verbunt 2001), their identification has been difficult due to low photon statistics and strong source confusion in the crowded globular cluster fields. It was therefore clear that Chandra with its sub-arcsecond angular resolution would contribute tremendously to the investigation of globular clusters. The results which have been published on this subject so far has shown that these expectations were justified. Among
the results we obtained on M28 (Becker et al. 2003) important work has been done on Terzan 5 (Heinke et al. 2006) and of 47 Tuc = NGC 104. From the latter, Grindlay et al. (2001) reported the detection of 108 sources within a region corresponding to about 5 times the 47 Tuc core radius. Nineteen of the soft/faint sources were found to be coincident with radio-detected millisecond pulsars (Bogdanov et al. 2006) and Grindlay et al. (2001a, 2002) concluded that more than 50 percent of all the unidentified sources in 47 Tuc are MSPs. This conclusion is in concert with theoretical estimates on the formation scenarios of short-period (binary) pulsars in globular clusters (e.g. Rasio, Pfahl & Rappaport 2000).

Some of the unresolved excess of X-ray emission from within the central part of M28 that we reported in Becker et al. (2003) is likely due to point sources that were just below the 38-ksec sensitivity limit. The recent discovery of the new MSPs, which are partly in positional agreement with this excess emission, strongly support the conjecture. We also know from Chandra observations of 47 Tuc that the soft emission from millisecond pulsars, like those found in that cluster, tend to be below the sensitivity limit of the previous Chandra M28 observation because of the higher absorption towards M28. Hence it is quite likely that a deeper exposure will reveal more, faint, X-ray sources which might turn out to be millisecond pulsars as well. Apart from resolving the diffuse emission, a second deeper observation will add significant information to those faint sources for which a detailed spectral modeling was precluded by limited photon statistics in the existing 38-ksec ACIS-S data.

As all these MSPs in M28 are virtually located at the same distance from us detecting them will allow one to investigate their relative X-ray efficiency, $L_x/E$, unbiased by distance uncertainties. Grindlay et al. (2002) found that the dependence of $L_x$ on $E$ for 47 Tuc MSPs may be $L_x \propto E^{0.5}$, i.e. significant flatter than the $L_x/E = 10^{-3}$ observed for pulsars located in the galactic plane (cf. Becker & Trümper 1997). The 47 Tuc MSPs were found to be consistent with the X-radiation being emitted from heated polar caps. Whether this will be the dominating X-ray emission process of the newly discovered MSPs in M28 and whether their X-ray efficiency will be consistent with $L_x \propto E^{0.5}$ or with $L_x/E = 10^{-3}$ will be a question one can address with data of higher photon statistics.

Several of the other sources we detected previously in M28 exhibit variability on time scales of weeks. Our M28 X-ray survey also found a large number of objects that were bright in only a single observation. Some of these latter objects were bright because they flared during the observation (i.e., not only were they bright in one observation, they were bright for only part of the observation). We suspect that these sources are flare stars (RS CVn or BY Dra). There were a few additional sources seen in the HRC observation of M28 by Rutledge et al. (2004), performed only a few weeks after the ACIS-S observations. These sources either turned on at, or in between, the two observations. As long as each star is only seen to flare in one observation then all that we know is that the total population is larger than the number that we have seen in the previous 38-ksec observation. However, if one sees the same flare stars more than once it will allow one to better estimate the total source population.

Table 2. Basic properties of millisecond pulsars located in the globular cluster M28 and their counting rates in Chandra ACIS-S data.

The position of J1824-2452H is the Chandra X-ray position while for the other pulsars it is the radio timing position from Bégı̈n (2006).

| Name            | Ra       | Dec      | P  | $E$  | $B_1$ | ACIS-S net counts | ACIS-S rate |
|-----------------|----------|----------|----|------|-------|-------------------|-------------|
| J1824-2452A     | 18 24 32 007 | -24 52 10 49 | 3.1054 | 22.243 | 1100 | 2.63e-2          |
| J1824-2452B     | 18 24 32.545 | -24 52 04 29 | 6.5466 | < 0.4 | 3 | 7.89e-5          |
| J1824-2452C     | 18 24 33 089 | -24 52 13 57 | 5.4191 | < 0.8 | 5 | 1.32e-4          |
| J1824-2452E     | 18 24 31 812 | -24 49 25 03 | 2.4511 | < 0.5 | 1 | 2.63e-5          |
| J1824-2452F     | 18 24 31.025 | -24 52 17 32 | 5.90095 | 3.4228 | 16 | 4.47e-4          |
| J1824-2452H     | 18 24 31.591 | -24 52 17 49 | 6.62941 | 3.2586 | 11 | 2.89e-4          |
| J1824-2452I     | 18 24 32.32 | -24 52 12 00 | 3.93180 | 12 | 3.16e-4          |
| J1824-2452J     | 18 24 32.733 | -24 52 10 18 | 4.03968 | < 0.6 | 22 | 5.78e-4          |
| J1824-2452C     | 18 24 32 192 | -24 52 14 66 | 4.15828 | 9.3416 | < 1.2 | 3 | 7.89e-5          |
| J1824-2452D     | 18 24 32 422 | -24 52 25 90 | 79.8354 | 7.6183 | ~ 91.0 | 2 | 5.26e-5          |

References

Camilo, F., Lorimer, D.R., Freire, P., et al., 2000, ApJ, 535, 975
Cool, A.M., Grindlay, J.E., Krockenberger, M., & Bailyn, C.D., 1993, ApJ, 410, L103
Backer, D.C., & Sallmen, S. 1997, ApJS, 114, 1539
Becker, W., Swartz, D., Pavlov, G., Elsner, R., Grindlay, J., et al., 2003, ApJ, 594, 798
Bégı̈n, S., Thesis submitted to the Faculty of Physics, University of British Columbia, 2006
Bogdanov, S., Grindlay, J.E., Heinke, C.O., Camilo, F., Freire, P.C.C.,
Becker, W., 2006, ApJ, 646, 1104
Grindlay, J.E., Camilo, F., Heinke, C.O., Edmonds, P.D., Cohn, H.,
Lugger, P., 2002, ApJ, 581, 470
Grindlay, J.E., Heinke, C.O., Edmonds, P.D., Murray, S.S., Cool, A.
M.2001, ApJ, 563, 53
Grindlay, J.E., Heinke, C., Edmonds, P.D., & Murray, S.S., 2001a,
Science, 290, 2292
Gotthelf, E. V. & Kulkarni, S. R. 1997, ApJL, 490, L161
Haberl, F., in Astrophysics and Space Science, eds D.Page, R.Turolla
& S. Zane, astro-ph/0609066
Heinke, C.O., Wijnands, R., Cohn, H.N., et al., 2006, ApJ, 651,1098
Johnston, H.M., & Verbunt, F., 1996, A&A, 312, 80
Kawai N., Saito Y., 1999, Proc. 3rd INTEGRAL Workshop, Taormina,
Astroph. Lett. & Comm. 38, 1
Manchester, R. N., Hobbs, G. B., Teoh, A. Hobbs, M., Astron. J., 129,
1993-2006 (2005) (astro-ph/0412641)
Mineo, T., Cusumano, G., Massaro, E., Becker, W., Nicastro, L., 2004,
A&A, 423, 1045
Mori, K., Chonko, J.C.; Hailey, C.J., 2005, ApJ, 631, 1082
Ransom, S.M., Hessels, J.W.T., Stairs I.H., et al., 2006, AAS, 207,
3205
Ransom, S.M., Hessels, J.W.T., Stairs I.H., et al., 2006, Science, 307,
892
Rasio, F.A., Pfahl, E.D. & Rappaport, S., 2000, ApJ, 532, 47
Rutledge, R.E., Fox, D.W., Kulkarni, S.R., et al., 2004, ApJ, 613, 522
Sanwal, D.; Pavlov, G. G.; Zavlin, V. E.; Teter, M. A., 2002, ApJ,
574L, 61
Stairs, I.H., Begin, S., Ransom, S., et al., AAS Meeting 209, 2006
Verbunt, F. 2001, A&A, 368, 137
Zhang, C. M., Kojima, Y., 2006, MNRAS, 366, 137