Three New Long Period X-ray Pulsars Discovered in the Small Magellanic Cloud

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ABSTRACT

The Small Magellanic Cloud is increasingly an invaluable laboratory for studying accreting and isolated X-ray pulsars. We add to the class of compact SMC objects by reporting the discovery of three new long period X-ray pulsars detected with the Chandra X-ray Observatory. The pulsars, with periods of 152, 304 and 565 seconds, all show hard X-ray spectra over the range from 0.6 - 7.5 keV. The source positions of the three pulsars are consistent with known H-alpha emission sources, indicating they are likely to be Be type X-ray binary star systems.

Subject headings: — galaxies: individual (SMC) — pulsars: general — stars: neutron — X-rays: stars

1. Introduction

Our program of routinely evaluating the pulsar content of archival observations of the Small Magellanic Cloud has previously revealed five new X-ray pulsars (Macomb et al. 1999, Finger et al. 2001, Lamb et al. 2002a, Lamb et al. 2002b). To date, there are at least 31 known X-ray pulsars in the Small Magellanic Cloud, 25 of which were discovered in the last six years (Yokogawa 2002, Lamb et al. 2002a, Laycock et al. 2002, Corbet et al. 2002, Lamb et al. 2002b). This explosion in the number of known pulsars is due mainly to four X-ray missions, ASCA, ROSAT, RXTE, and Chandra, each of which has devoted time to long, sensitive observations of the SMC.

The advantages to studying the compact object content of the Magellanic Clouds are well known: a relatively small angular size, at a reasonably close and known distance, located at a high galactic latitude with little obscuration by the interstellar medium of the Galaxy.
In addition, there is evidence for recent star formation in the SMC over the last few 10’s of millions of years which creates an environment in which X-ray pulsars are expected to be plentiful (Haberl & Sasaki 2000, Maragoudaki et al. 2001).

Our analysis of a recent Chandra X-ray Observatory observation of the SMC reveals evidence for four X-ray pulsars. One, CXOU J011043.1-721134, is possibly an anomalous X-ray pulsar (Lamb et al. 2002b). This paper describes the discovery of X-ray pulsations from the other three sources: CXOU J005750.3-720756 (152.10 s period), CXOU J010102.7-720658 (304.49 s period) and CXOU J005736.2-721934 (564.83 s period). After a description of the discoveries, we address the characteristics of each source, followed by a discussion of the general significance of these detections.
Table 1. Names and positional information for the three X-ray pulsars. Errors are in parenthesis for each column.

<table>
<thead>
<tr>
<th>Source</th>
<th>Right Ascension (J2000)(^a)</th>
<th>Declination (J2000)(^a)</th>
<th>Proposed counterpart(^b)</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXOU J005750.3-720756</td>
<td>14.45975(2)</td>
<td>-72.13239(1)</td>
<td>[MA93] 1038</td>
<td>0.67</td>
</tr>
<tr>
<td>CXOU J010102.7-720658</td>
<td>15.26147(19)</td>
<td>-72.11614(6)</td>
<td>[MA93] 1240</td>
<td>1.14</td>
</tr>
<tr>
<td>CXOU J005736.2-721934</td>
<td>14.40123(10)</td>
<td>-72.32637(3)</td>
<td>[MA93] 1020</td>
<td>1.64</td>
</tr>
</tbody>
</table>

\(^a\)statistical error quoted; total systematic error on the position could be as much as 1 arcsecond

\(^b\)Source number from the catalog of Meyssonnier & Azzopardi 1993
2. Discovery of Pulsations

The discovery data were obtained from CHANDRA obsid 1881, a 100ks ACIS-I observation which began 2001 May 15. The ACIS-I read-out time for this observation was set at a coarse 3.241 seconds, giving a Nyquist frequency of 0.154 Hz. Processing of the ACIS field reveals 140 point sources detected at the 3 sigma level using a standard sliding box detection algorithm. We extracted photons for each point source in the field using an ellipse of varying size, defined by the source detection software, which encompassed 90% of the source photons.

The photon arrival times were barycentered and a fast Fourier transform performed for each individual source. With the average fft power normalized to one, we set a power threshold of 20 to flag potential signals. For a 100 ksec observation binned at 3.241 seconds, there are about 31000 independent trials. This gives a probability of around 1% that any peak power beyond 20 arises by chance for all of the 140 sources analyzed.

Concentrating on frequencies above 0.001 Hz (a 1000 second period), we find 21 of the 140 sources with powers beyond 20. Of these, all but four sources had powers at two set frequencies that appeared in multiple sources. The first frequency was near 0.001 Hz and the second at 0.001415 Hz, periods of 1000 and 706 seconds, both of which are attributable to known dithering effects (as described at http://cxc.harvard.edu/ciao/why/dither.html). Of the four remaining sources, one is CXOU J011043.1-721134 which is a 5.44 s pulsar (Lamb et al. 2002b), leaving us with three new candidate pulsars. Table 1 lists the Chandra centroid for each source along with the proposed counterpart.

The Fourier power distributions for the three remaining sources are shown in Figure 1. These pulsar timing distributions are based upon a slightly different photon set than for the general search. These refined photon selections encompassing the energy range from 0.6 - 7.5 keV are close to maximizing the Fourier power for all three sources. In addition, we chose position regions corresponding to an 80% encircled energy to further optimize pulsar timing parameters. These selections resulted in 5429 photons for the 152 s pulsar, 325 photons for the 304 second pulsar, and 3141 photons for the 565 second pulsar.

The first source, centered on a frequency of 0.0065747 Hz (152.10 seconds) has a peak power of 90 while the second is at a frequency of 0.0032842 Hz (304.49 seconds) with peak power 30.4. While this frequency is close to being twice the frequency of the 152 s pulsar, they are not precisely doubled. In addition, the fact these sources are in different ACIS chips and that neither of these frequencies show up in any other field source no matter the source strength indicates that they are in fact distinct signals. The third source is detected at a power of 57 at a frequency of 0.00177045 Hz (564.83).
In the case of the 152 and 565 second pulsars, a third harmonic of the fundamental frequency is clearly seen, and there is also a strong second harmonic for the 152 second pulsar. No other sources in the field of view have significant Fourier power at any of these frequencies. The implication is that these three sources are long-period X-ray pulsars. As their individual characteristics make clear, they are both likely to be examples of high-mass X-ray binary systems with Be star companions.

There is little evidence of variability from any of the three new sources over the 100 ksec Chandra observation. While a $\chi^2$ test of variability for the pulsars binned over single pulse periods for the 152 and 565 second pulsars and 5 pulse periods for the 304 second pulsar shows little gross variability, there is modest variability for the 565 second pulsar (3% chance of being consistent with a flat rate). There is no evidence for any of the pulsars dramatically changing their flux during the observation, i.e. an onset or end of an emission episode. Consequently, we have taken all spectral and timing information for these three pulsars from the full observation.
Table 2. Pulsar characteristics and power-law spectral fit information for the three X-ray pulsars. The luminosity values are for the energy interval 0.6 - 7.5 keV.

<table>
<thead>
<tr>
<th>Source</th>
<th>period(s)</th>
<th>pulse fraction</th>
<th>$n_H^a$</th>
<th>$\alpha$</th>
<th>norm$^b$</th>
<th>$\chi^2$ (dof)</th>
<th>L$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>005750.3-720756</td>
<td>152.098(16)</td>
<td>64 ± 3%</td>
<td>0.57 ± 0.05</td>
<td>1.01 ± 0.06</td>
<td>7.2 ± 1.1</td>
<td>0.98 (227)</td>
<td>26</td>
</tr>
<tr>
<td>010102.7-720658</td>
<td>304.49(13)</td>
<td>90 ± 8%</td>
<td>0.66$^d$</td>
<td>1.22 ± 0.26</td>
<td>0.4 ± 0.2</td>
<td>0.47 (13)</td>
<td>1.1</td>
</tr>
<tr>
<td>005736.2-721934</td>
<td>564.81(41)</td>
<td>48 ± 5%</td>
<td>0.76 ± 0.14</td>
<td>1.70 ± 0.23</td>
<td>4.1 ± 2.1</td>
<td>0.47 (134)</td>
<td>5.6</td>
</tr>
</tbody>
</table>

$^a$ units of $10^{22}$ cm$^2$

$^b$ normalization at 1 keV in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$

$^c$ Unabsorbed luminosity assuming a distance of 57 kpc in units of $10^{34}$ ergs/s

$^d$ $n_H$ value frozen at 0.66, the mean of $n_H$ for the other two pulsars, otherwise unconstrained
3. Individual Source Characteristics

3.1. The 152 second pulsar: CXOU J005750.3-720756

A search of the ROSAT observation catalog shows many ROSAT HRI or PSPC observations overlapping the position of CXOU J005750.3-720756. In addition, the ROSAT results archive lists a source, RX J0057.8-7207, a source with an 11 arcsecond error radius that is within 6 arcsecond of the Chandra position centroid. No previous reports of X-ray pulsations from this source have been reported, however it was suggested as a Be binary pulsar candidate by Haberl & Sasaki (2000) based upon positional coincidence with an H-alpha region cataloged by Meyssonnier & Azzopardi (1993). Given the small positional difference between the CHANDRA position (absolute position good to approximately 0.6") and the centroid of the ROSAT/PSPC source (localization 5.1", Haberl & Sasaki 2000), it is likely that these two sources are the same. Unfortunately, a check of the three strongest ROSAT detections of this source does not reveal evidence for pulsed emission.

This is not surprising, however, when one considers the energy spectrum of this source. The spectrum of CXOU J005750.3-720756 has a hard photon index of $1.0 \pm 0.1$. The complete power law fit parameters are listed in Table 2, along with the estimated pulse period and period error. The error on the pulse period is calculated from the Rayleigh power, based upon the frequency points corresponding to a drop in power equal to the square root of the peak power. The source flux is the highest of these three sources. Given this very hard spectrum, it is likely that a soft X-ray telescope with reduced effective area such as the ROSAT/PSPC and ROSAT/HRI are less effective at detecting the periodicity.

Figure 2 shows the folded Chandra lightcurve for the 152.1 second pulsar. The pulse profile is complicated, showing a sharp dip with a duration of 10% of the pulse period. The pulsed fraction is $63 \pm 3\%$. A search of the full dataset over frequency derivative (binning at $1.0 \times 10^{-13}$ Hz/s) and frequency provides a small but statistically insignificant improvement in detected power. This is the case for all three pulsars, so all quoted pulse periods and frequencies are uncorrected for frequency derivative.

3.2. The 304 second pulsar: CXOU J010102.7-720658

The weakest of the three sources by an order of magnitude, CXOU J010102.7-720658 has a less well-defined pulse profile as shown by Figure 2. The source has a pulsed fraction of $90 \pm 8\%$, a fortuitously large value since if the pulsed fraction were more like the other two, we would not have detected the periodicity. This source, with only 470 total photons considered
for spectroscopy, has a spectral shape which is more difficult to quantify. Table 2 lists the power-law fit parameters. The spectrum is slightly softer than the 152 second pulsar, but the power-law spectral shape is not the best fit. A blackbody fit gives a temperature of 1.0 keV, consistent with it being a hard spectrum.

As with the 152 second pulsar, this previously known X-ray emitter was postulated to be an X-ray binary pulsar by Haberl & Sasaki and by Kahabka & Pietsch (1996) based upon correlations of the ROSAT X-ray source, RX J0101.0-7206, with an H-alpha emission source. The putative ROSAT counterpart is only 0.96 arcseconds from the CHANDRA detection, well within the combined source location errors for the two detectors indicating they are the same source. The most remarkable thing about this source is the extremely weak flux. Assuming a distance of 57 kpc for the SMC, the X-ray luminosity is only $1.1 \times 10^{34}$ ergs/s. This is a very small discovery flux, making it the weakest accreting SMC source for which X-ray pulsations have been discovered.

### 3.3. The 565 second pulsar: CXOU J005736.2-721934

The pulse profile of CXOU J005736.2-721934 is shown in Figure 2. The pulse profile is quite complicated, showing three distinct peaks, a characteristic indicated by the strong presence of the first three harmonics in the Fourier transform spectrum. This source is also formally the most variable of the three with a $\chi^2$ test for variability based upon binning the flux over a single pulse period shows that the flux is consistent with being constant at the 3% level unlike the other two sources, which are fully consistent with constant flux. This is not, however, conclusive evidence for pulse to pulse variability.

Unlike the previous two sources, there has been no previous suggestion that this is an accreting X-ray pulsar. This source is only 18 arcseconds away, however, from source 19 of the ASCA SMC source catalog, well within the half-power radius of the ASCA XRT (Yokogawa et al. 2000). Its pulsed fraction is $48 \pm 5\%$, and it is is has the softest spectrum of the three sources. There are no reported ROSAT detections of this source. A search of stellar databases does show that there is an H-alpha emission line source located within 0.8 arcsecond of the CHANDRA position (Meyssonier & Azzopardi - Star 1020 with a J2000 location of 00 57 36.0 -72 19 34. This lends support to the interpretation of this source as yet another SMC Be-binary.
4. DISCUSSION

There are two independent arguments that these pulsars have high mass companions. The first is their apparent association with H-alpha sources which are themselves markers of regions containing massive stars (Kennicutt 1983).

We have assessed the possibility that the apparent association of these 3 pulsars with known H-alpha sources is due to an accidental overlap in position. A cross-check of the Chandra positions with the H-alpha catalogs of Meyssonnier & Azzopardi (1996) and Murphy & Bessell (2000) shows that of the 140 Chandra sources in our field, only 4 were within 5 arcseconds of an H-alpha source. The three closest coincidences were for these 3 pulsars - CXOU J005736.2-721934 (565 s) at a distance of 1.64", CXOU J010102.7-720658 (304 s) at a distance of 1.14", and CXOU J005750.3-720756 (152 s) at a distance of 0.67". The binomial probability of these three particular sources having the smallest 3 distances to an H-alpha source is $10^{-6}$. Meyssonnier & Azzopardi do not quote precise error radii for their sources, but indicate that overall “seeing” for the observations was on the order of 1 arcsec. In addition, the CHANDRA positions are expected to be good to within about 0.6 arcsec. Thus, the distances for all three pulsars from the putative Halpha source are within a sum of the estimated Chandra and Meyssonnier & Azzopardi error radii (~1.6").

The second argument which supports the identification of these pulsars as high mass systems is given by the empirical correlation noted by Corbet (1986) which, for X-ray pulsars with spin periods in excess of 100 s, implies a companion which is either a Supergiant or a Be star.

Thus, like virtually all other SMC pulsars (31 total), these three are associated with high mass binaries. In contrast, from the Milky Way with approximately 100 times the mass of the SMC only about 40 such objects have been detected. This overabundance has been discussed in some detail by Schmidtke et al. 1999 and Yokogawa et al. 2000. This overabundance points to a rather recent star formation activity $\sim 10^7$ yr ago.

Further evidence for this episode of star burst activity comes from examination of the spatial distribution of the SMC X-ray binaries. Maragoudaki et al. (2001) have recently analyzed the star content of the SMC using UV photometry over a large (6° by 6°) field. The distribution of the SMC X-ray binaries follows very closely (with 3 exceptions) their distribution of the youngest stars, those having ages less than $8\times10^6$ yr (figure 9, Maragoudaki et al.) This distribution differs considerably from the general distribution of 517 SMC X-ray sources catalogued by Haberl et al. (2000). For example, 29% of the X-ray sources (149 of 517) fall in the south-eastern region of the SMC (RA greater than 01h and Dec. less than -72.5°). On the other hand only 10% (3 of 31) of the X-ray pulsars are located...
in this region. This is another reflection of the fact that the population of the SMC pulsars are prominently (if not, exclusively) high mass and therefore generally younger than other types of X-ray sources. Further detailed comparisons between the star maps of Maragoudaki et al. and the distribution of the SMC X-ray binaries may provide useful constraints on evolutionary scenarios of high mass X-ray binaries.

Despite the relatively poor timing resolution (3.241 s) of this particular observation, the single 100 ksec exposure reveals four new X-ray pulsars, increasing the number of known SMC pulsars by over 10%. A longer exposure with the Chandra instruments at much higher time resolution would probably provide even more discoveries and allow important assessments of the underlying distributions of SMC pulsars.

This work made use of software and data provided by the High-Energy Astrophysics Archival Research Center (HEASARC) located at Goddard Space Flight Center. Additional use was made of the SIMBAD catalogue at CDS, Strasbourg France, and NASA’s Astrophysics Data System (ADS).

REFERENCES


Fig. 1.— FFTs of the CHANDRA sources CXOU J005750.0-720755 (152.10 s period), CXOU J010102.4-720657 (304.49 s), and CXOU J005735.8-721933 (564.83 s). The arrow marks the fundamental frequency for each source.
Fig. 2.— Pulse profiles for the three new X-ray pulsars with an energy restriction of 0.6 to 7.5 keV. The weak, 304 second pulsar only reveals a single pulse, while the other two have more harmonic content. The dashed line in each case shows the off-source background level.