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 s, all show hard X-ray spectra over the range 0.6–7.5 keV. The source positions of the three pulsars are consistent with known Hα emission sources, indicating they are likely to be Be-type X-ray binary star systems.

Subject headings: galaxies: individual (Small Magellanic Cloud) — 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, 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 6 years (Yokogawa 2002; Lamb et al. 2002a, 2002b; Laycock et al. 2002; Corbet et al. 2002). This explosion in the number of known pulsars is due mainly to four X-ray missions—ASCA, ROSAT, Rossi X-Ray Timing Explorer, 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 tens 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. 2002a). This Letter 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 discuss the characteristics of each source and then discuss the general significance of these detections.

2. DISCOVERY OF PULSATIONS

The discovery data were obtained from Chandra Observation ID 1881, a 100 ks ACIS-I observation that began 2001 May 15. The ACIS-I readout time for this observation was set at a coarse 3.241 s, giving a Nyquist frequency of 0.154 Hz. Processing of the ACIS field reveals 140 point sources detected at the 3σ 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 (FFT) was 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 ks observation binned at 3.241 s, there are about 31,000 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 s 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 s, both of which are attributable to known dithering effects. Of the four remaining sources, one is CXOU J011043.1—721134, which is a 5.44 s pulsar (Lamb et al. 2002a), 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 on a slightly different photon set than for the general search. These refined photon selections encompassing the energy range from 0.6 to 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 s pulsar, and 3141 photons for the 565 s pulsar.

The first source, centered on a frequency of 0.006574 Hz (152.10 s), has a peak power of 90, while the second is at a frequency of 0.003284 Hz (304.49 s) 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 that these sources are in different ACIS chips and that neither of these frequencies show up in any other field source.
Table 1: Names and Positional Information for the Three X-Ray Pulsars

| Source              | Right Ascension (J2000.0) | Declination (J2000.0) | Proposed Counterpart | Counterpart Offset |
|---------------------|---------------------------|-----------------------|----------------------|--------------------|
| CXOU J005750.3−720756       | 14.45975(2)               | −72.13239(1)          | [MA93] 1038          | 0.67               |
| CXOU J010102.7−720658       | 15.26147(19)              | −72.11614(6)          | [MA93] 1240          | 1.14               |
| CXOU J005736.2−721934       | 14.40123(10)              | −72.32637(3)          | [MA93] 1020          | 1.64               |

Note.—Errors are in parenthesis for each column.

* Statistical error quoted; total systematic error on the position could be as much as 1″.

* Source number from the catalog of Meyssonnier & Azzopardi (1993).

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 s).

In the case of the 152 and 565 s pulsars, a third harmonic of the fundamental frequency is clearly seen, and there is also a strong second harmonic for the 152 s 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 all 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 ks Chandra observation. While a $\chi^2$ test of variability for the pulsars binned over single pulse periods for the 152 and 565 s pulsars and five pulse periods for the 304 s pulsar shows little gross variability, there is modest variability for the 565 s 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.

3. Individual Source Characteristics

3.1. The 152 s Pulsar: CXOU J005750.3−720756

A search of the ROSAT observation catalog shows many ROSAT HRI or Position Sensitive Proportional Counter (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″ error radius that is within 6″ 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 on positional coincidence with an Hα 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 on 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 light curve for the 152.1 s pulsar. The pulse profile is complicated, showing a sharp dip with a duration of 10% of the pulse period. The pulsed fraction is 63% ± 3%. A search of the full data set over frequency derivative (binning at $1.0 \times 10^{-13}$ Hz s$^{-1}$) 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.
while the other two have more harmonic content. The weak, 304 s pulsar reveals only a single pulse, discovered. This source is also formally the most variable of the three, with distinct peaks, a characteristic indicated by the strong presence of the first three harmonics in the Fourier transform spectrum.

Figure 2. The pulse profile is quite complicated, showing three peaks, a characteristic indicated by the strong presence of the first three harmonics in the Fourier transform spectrum.

Table 2—Pulsar Characteristics and Power-Law Spectral Fit Information for the Three X-Ray Pulsars

| Source          | Period (s) | Pulse Fraction (%) | $n_{H}$ (× 10$^{-6}$ cm$^{-2}$) | $\alpha$ | Normalization* (× 10$^{-16}$ photons cm$^{-2}$ s$^{-1}$) | $\chi^2$ (dof) | $L^2$ (× 10$^{34}$ ergs s$^{-1}$) |
|-----------------|------------|--------------------|---------------------------------|---------|-------------------------------------------------|---------------|-------------------------------|
| 005750.3—720756 | 152.098(16) | 64 ± 3             | 0.57 ± 0.05                     | 1.01 ± 0.06 | 7.2 ± 1.1                                       | 0.98 (227)    | 26                            |
| 010102.7—720658 | 304.49(13)  | 90 ± 8             | 0.66                            | 1.22 ± 0.26 | 0.4 ± 0.2                                       | 0.47 (13)     | 1.1                           |
| 005736.2—721934 | 564.81(41)  | 48 ± 5             | 0.76 ± 0.14                     | 1.70 ± 0.23 | 4.1 ± 2.1                                       | 0.47 (134)    | 5.6                           |

Note.—The luminosity values are for the energy interval 0.6–7.5 keV.

* Normalization at 1 keV.

Unlike the previous two sources, there has been no previous suggestion that this is an accreting X-ray pulsar. This source is only 18" away, however, from source 19 of the ASCA SMC source catalog, well within the half-power radius of the ASCA X-ray telescopes (Yokogawa et al. 2000). Its pulsed fraction is 48% ± 5%, and it 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 of the Chandra position (star 1020 in Meyssonnier & Azzopardi 1993, with a J2000.0 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 that are themselves markers of regions containing massive stars (Kennicutt 1983).

We have assessed the possibility that the apparent association of these three 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 four were within 5″ of an H$\alpha$ source. The three closest coincidences were for these three pulsars—CXOU J005736.2—721934 (565 s) at a distance of 1′64, CXOU J005736.2—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 three distances to an H$\alpha$ source is 10$^{-4}$. 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″. In addition, the Chandra positions are expected to be good to within about 0′6. Thus, the distances for all three pulsars from the putative H$\alpha$ source are within a sum of the estimated Chandra and Meyssonnier & Azzopardi error radii (~1′6).

The second argument that 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 that 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 rather recent star formation activity, ~10$^7$ yr ago.

Further evidence for this episode of starburst 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° x 6°) field. The distribution of the SMC X-ray binaries follows very closely (with three exceptions) the distribution of the youngest stars, those having ages less than 8 x 10⁶ yr (Fig. 9 in Maragoudaki et al. 2001). This distribution differs considerably from the general distribution of 517 SMC X-ray sources cataloged by Haberl & Sasaki (2000). For example, 29% of the X-ray sources (149 of 517) fall in the southeastern region of the SMC (right ascension greater than 01h and declination less than −72°5). On the other hand, only 10% (three 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 then 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 ks 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.

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