A LONG LOOK AT THE Be/X-RAY BINARIES OF THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We have monitored 41 Be/X-ray binary systems in the Small Magellanic Cloud over ~9 yr using PCA RXTE data from a weekly survey program. The resulting light curves were analyzed in search of orbital modulations with the result that 10 known orbital ephemerides were confirmed and refined, while 10 new ones were determined. A large number of X-ray orbital profiles are presented for the first time, showing similar characteristics over a wide range of orbital periods. Lastly, three pulsars, SXP 46.4, SXP 89.0, and SXP 165, were found to be misidentifications of SXP 46.6, SXP 91.1, and SXP 169, respectively.

Subject headings: galaxies: individual (Small Magellanic Cloud) — pulsars: general — X-rays: binaries

Online material: color figures

1. INTRODUCTION

The Small Magellanic Cloud (SMC) has become a fertile orchard of high-mass X-ray binaries (HMXBs), with 49 confirmed systems (Coe et al. 2005; McGowan et al. 2007). Given that, from extrapolation of the Milky Way’s population (and even correcting for the higher Be/B ratio in the SMC [Maeder et al. 1999]), one would expect to find only three or four systems, it is clear that the SMC is a special place where recent star formation has provided an abundance of HMXBs; indeed, the star formation rate/mass (SFR/M) of the SMC is 150 times that of the Milky Way (Grimm et al. 2003). Of particular significance is the fact that only one of these binary systems is not a Be/X-ray binary (SMC X-1 is the sole supergiant system discovered so far). This large number of Be/X-ray binary systems, conveniently located within the 3° x 3° area of the SMC, provides an unrivaled opportunity to study this population as a whole, as well as individually. With a 2° FWZI field of view, high timing resolution (1 μs), and sensitive enough to detect the 10^{35}-10^{38} ergs s^{-1} luminosities typical of these systems when in outburst, the Proportional Counter Array (PCA) instrument (Jahoda et al. 1996, 2006) on board the Rossi X-Ray Timing Explorer (RXTE) is well suited for a long-term monitoring survey of the SMC.

The different types of X-ray activity displayed by Be/X-ray transient systems were classified by Stella et al. (1986) into the following categories:

1. Persistent low-luminosity X-ray emission ($L_X \lesssim 10^{36}$ ergs s^{-1}) or none detectable (in which case the system is said to be in quiescence).
2. Type I outbursts: Outbursts of moderate intensity ($L_X \approx 10^{36}-10^{37}$ ergs s^{-1}) and short duration (a few days), generally recurring with the orbital period of the system and taking place at or close to the time of periastron passage.
3. Type II outbursts: Giant X-ray outbursts ($L_X \approx 10^{37}$ ergs s^{-1}) lasting for weeks or months that generally show no correlation with orbital phase.

The data presented in this paper span 1997 November–2006 November and build on the work of Laycock et al. (2005), who analyzed the first 4 years of data. Following is a brief description of the survey so far, which is still ongoing as of 2007 June.

1.1. The Survey

The initial observations of the SMC with RXTE began in 1997. The first observation took place in November of that year when an outburst detected by the all-sky monitor (ASM) was misidentified as SMC X-3. It was the second year of operation of RXTE, and only SMC X-1, 2, and 3 and SXP 2.76 and SXP 8.88 were known. From these initial observations it soon became apparent that there were more than five X-ray pulsars in the SMC. The observations carried out within the next year brought about the discovery of five new systems: SXP 46.6, 59.0, 74.7, 91.1 and 169. Other pulsars were also discovered or detected with the Einstein Observatory, ASCA, BeppoSAX, and Röntgensatellit (ROSAT).

The year 1999 marked the beginning of a coordinated survey of the SMC using the PCA. The PCA 2° field of view provides...
coverage of a wide area of the SMC, which allows many pulsars to be monitored with just one pointing. A number of different pointing positions have been used throughout the years and are given in Table 1 (see also Fig. 1); some of the less observed ones never received a name and are omitted from the table. The most frequently observed is position 1 (later renamed to A), which has been the main pointing position since AO4, except during AO6 and AO7, when position 5 was the main target. In total, the collected data spans ~9 yr.

The survey has gone through various phases characterized by different observing positions and/or observing modalities. Phases 1–4 have already been described in Laycock et al. (2005), but they are outlined here again, together with the two latest phases not included in previous studies.

Phase 1 (AO2–AO3).—These observations used positions 1a, 1b, and 1c and are described in Lochner et al. (1999a, 1999b). Only 30 observations were carried out, their main purpose being to monitor the five newly discovered pulsars in those regions.

Phase 2 (AO4).—Positions 1–4 were defined; position 1 overlaps most of positions 1a–1c and contained the new pulsars, positions 2 and 4 cover the rest of the bar of the SMC, while

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### Table 1

| Name       | R.A.   | Decl.   |
|------------|--------|---------|
| 1a         | 00 52.07.8 | -72 25 43.3 |
| 1b         | 00 51 04.0 | -72 13 44.0 |
| 1c (SMC X-3) | 00 54 54.8 | -72 26 40.9 |
| 1/A        | 00 53 53.0 | -72 26 42.0 |
| 2          | 01 05 00.0 | -72 06 00.0 |
| 3          | 01 15 00.0 | -73 06 00.0 |
| 4          | 00 50 44.6 | -73 16 04.8 |
| 5          | 00 50 00.0 | -73 06 00.0 |
| B          | 01 05 00.0 | -72 06 21.6 |
| C          | 01 15 00.0 | -73 24 59.8 |
| D          | 00 50 00.0 | -73 06 00.0 |
| X          | 01 05 00.0 | -72 06 00.0 |
| SMC X-2    | 00 54 33.3 | -73 41 04.2 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

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**Fig. 1.**—Map of the SMC H\textsc{i} distribution with the five main pointing positions of RXTE during the survey shown as numbered white circles. For each pointing, the inner circle has a diameter of 1', the outer has a diameter of 2'. For clarity, positions A, B, C, D, and X have not been plotted, as they are very close to positions 1, 2, 3, 4, and 2, respectively. Pulsars with known positions are marked by small circles. H\textsc{i} data are from Stanimirovic et al. (1999). [See the electronic edition of the Supplement for a color version of this figure.]
Position 3 covers the area of the wing containing SMC X-1. A continued survey began at this point in time, with ~3 ks observations being made once a week, mostly of position 1, with some occasional looks at the other positions.

**Phase 3 (AO5–AO6).**—Only position 5 was monitored, and this was done weekly so as not to create gaps in the data; the majority of the most active systems located in position 1 also fell within the field of view of position 5. Time allotted for the project was increased to an average of ~5 ks per observation, thus providing better sensitivity to longer period pulsations.

**Phase 4 (AO7–AO9).**—Weekly monitoring returned to position 1, now renamed position A, with additional observations of the other positions (B, C, and D, which are very close to 2, 3, and 4, respectively) being made once a month. These monthly pointings were ~15 ks, while the weekly ones were increased to ~6–7 ks.

**Phase 5 (AO10).**—The time available for the monthly observations of alternate positions was invested into increasing the length of the weekly observations of position A to ~10 ks, this being the only monitored position.

**Phase 6 (AO11).**—Having mainly monitored the central bar of the SMC, it was decided to move to another location at the northeastern tip of the bar, near position B. This new location, position X, was monitored for ~10 ks weekly for 18 weeks, but was abandoned due to lack of pulsar activity. Observations then changed to position D.

### 1.2. Data Reduction

Cleaning of the raw light curves was achieved via a pipeline employing various FTOOLS routines (Blackburn 1995). Initial filtering required the data to come from observations offset from the target no more than 0.004", with an elevation above the Earth's horizon of more than 5°, and not taken during times of high background. Good Xenon mode data from the top anode layer only were used, within an energy range of 3–10 keV. Data were binned at 0.01 s intervals, while background files were generated in 16 s bins. For each time step, the net flux was divided by the number of active PCUs to give the counts PCU~1 s~1.

Then, the light curves time tags were corrected to the solar system barycenter, removing timing variations caused by the satellite's motion around the Earth and Sun. Finally, short light curves belonging to the same observation (which had been split up due to South Atlantic Anomaly [SAA] passage, Earth occultation, or flares) were pieced together into a long light curve spanning the whole observation.

### 1.3. Collimator Correction

The collimator of each PCU consists of a number of hexagonal cells joined in a honeycomb structure. The hexagonal tubes are not perfectly parallel, with the result that all the PCU s are slightly off center. Hence, the resulting collimator response pattern has an elliptical hexagon shape with the maximum throughput being slightly off center.

In order to account for differences in observed flux from a pulsar when observed at different pointing positions, a collimator correction was applied to each pulsar's count rate. A look-up table approach was used, where each pulsar had a collimator response calculated for each of the pointing positions used in the survey (see Table 1).

A pulsar with unknown position cannot be collimator corrected, so significant detections may not rise above the noise level in the long-term light curve unless the outbursts are very bright and/or the pulsar is located close to the center of the field of view. Type I outbursts may only appear bright when the pulsar is close to the center of the field of view (as with SXP 59.0 in position 1/A; Fig. 17), in which case the collimator correction is small anyway. To overcome this limitation pulsars with unknown positions had coordinates “guessed” for them on the basis of which observing positions they had been detected in throughout the mission; the coordinates assigned were approximately at the center of the region formed by the overlap of the observing positions in which it had been previously detected.

### 1.4. Data Analysis

Once the cleaned light curve for an observation was obtained, it was run through a timing analysis package using the Lomb-Scargle method (Lomb 1976; Scargle 1982) and numerically implemented following the prescription by Press & Rybicki (1989). Two different power spectra were generated for each light curve, each spanning different period spaces (from Pmin to Pmax), at different timing resolutions (Δf), and pulsars were later searched for in their corresponding group according to their pulse period. The parameters used for each group are listed in Table 2. The reason for creating two groups was to obtain densely sampled periodograms at long periods without creating excessively large files. The parameters were chosen such that both groups would contain approximately the same number of independent frequencies, M.

Once the periodograms were calculated, it was necessary to establish an objective way to determine which peaks in the power spectra were real; this is covered in Appendix A.

#### 1.4.1. Pulsar Detection

Pulsars were searched for within the data using an algorithm specifically created for the task. Each light curve’s two power spectra were scanned to look for the pulsars in groups 1 and 2; the steps used were as follows.

**Step 1.**—The highest peak (at a period P) above 90% global significance in the power spectrum is found and either identified as a known pulsar or flagged as an “unknown.”

**Step 2.**—The light curve is folded at period P to produce a pulse profile.

**Step 3.**—Using the pulse profile as a template, the pulsations are then subtracted from the light curve, and a power spectrum of the cleaned light curve is produced.

**Step 4.**—This power spectrum is subtracted from the previous one to create a pulsar-specific power spectrum (or P2S2), which shows only the contribution of the individual pulsar to the power spectrum. This method allows one to see the possible harmonics that may have been lost in the noise or confused with the fundamental of another pulsar. The power of the fundamental and harmonic(s) peaks in the P2S2 is measured and a pulse amplitude

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4 See http://heasarc.gsfc.nasa.gov/ftools/.
estimated using equation (A5). The significance of the detection is taken to be the local significance of a peak of power equal to that which the detected signal would have if the power in the harmonics were concentrated in the fundamental.

**Step 5.**—Repeat previous steps until all signals with peaks above 90% significance have been removed.

**Step 6.**—To account for the remaining, dim pulsars, a stretch of the power spectrum centered on each pulsar’s nominal frequency, and with a total width which is different for each pulsar (and depends on the pulsar’s past period history), is searched for a peak. If no peak is found, then the significance of the detection is set to 0% and the amplitude to that of the average power within the region. If there is a peak, then the significance of the detection is set to the local significance and the amplitude of the pulsar calculated from the power in the peak according to equation (A4). No harmonics are searched for in this case.

1.4.2. **Light Curve Generation and \(P_{\text{orb}}\) Calculations**

Once the amplitude of the pulsed flux for every pulsar in every observation had been measured, a long-term light curve was created for each system showing its X-ray activity over the course of the survey. It is important to note that these light curves do not show the absolute flux, but rather the pulsed flux. Without knowing the pulsar’s pulse fraction for each observation, it is impossible to convert the pulsed-flux amplitude into an absolute flux value. These light curves were then searched for periodicities, as the X-ray emission could show orbital modulations. Again, the Lomb-Scargle technique was employed, searching for periods in the appropriate range for each pulsar. In cases in which type II outbursts contaminated the Lomb-Scargle periodogram, these were removed from the data. In general, all bright outbursts were initially removed and only added back into the light curve if they coincided with the calculated ephemerides and their inclusion increased the significance of the calculated orbit period. It is important to note that the collimator response correction was only applied to the data points whose local significance on detection was \(\geq 99\%\), anything below this detection threshold was considered noise and as such was not collimator corrected. Section 2 shows the results of these analyses.

1.4.3. **Orbital Profile Generation**

Based on the ideas of de Jager et al. (1988) and Carstairs (1992) we used the phase-independent folding (PIF) technique to create the orbital profiles. The method is as follows. The folded light curve is obtained from \(m\) sets of \(n\)-binned folded light curves. To begin with, the light curve is folded at the desired period and the time values converted to phase space (ranging from 0 to 1). This “raw” folded light curve is then binned into \(n\) bins (of width \(1/n\)) in the standard way, with each bin starting at phase \(a/n\) (with \(a = 0, 1, 2, \ldots, n - 1\)). This step is repeated again, but this time the bins start at phase \(a/n + 1/(n \times m)\). In this way we create \(m\) folded light curves from the same data, each consisting of \(n\) bins, and only differing in the starting phase of these bins. The general expression for the phase at which each bin begins is \(a/n + m/(n \times m)\). Now each folded light curve is further divided into \(l = n \times m\) subbins, such that in each light curve there will be \(n\) groups of \(m\) consecutive bins with the same flux value. The final folded light curve will have \(l\) bins, each of which is the average of the bins from the \(m\) sets of light curves. The error in each bin will be given by the standard error calculated from the \(m\) values that were averaged for each \(l\) bin. In the present work we have used \(n \times m = 10 \times 5\).

The PIF method provides an efficient way of generating folded light curves from poorly sampled data as their shape will not depend on the starting point at which they are folded, and although only every \(mb\) bin will be independent, spurious flux values within bins will be evened out while real features will remain. Thus, we obtain the benefits of both wide bins (sufficient counts in each bin for good statistics) and narrow bins (sensitivity to narrow features in the profile).

### 2. RESULTS

In what follows are the results obtained from the light curves of the observed SMC X-ray pulsars. In the triple-panel plots (generally the top plots), the top panel shows the X-ray activity of each pulsar through the amplitude of the pulsed flux, with each solid line representing one observation. When an orbital period has been found, the ephemerides for the dates of maximum flux are over plotted as dashed vertical lines; where the orbital period is less than 25 days, only every other line is plotted for clarity. The middle panel shows the period at which the pulsar was detected, with the horizontal dashed line denoting the center of the pulsar’s search range (note that only significant detections have their periods plotted). Finally, the bottom panel displays the significance of the neutron star’s pulsations for each observation, with the three horizontal dashed lines marking, from bottom to top, the levels of 99%, 99.9%, and 99.999% local significance. We considered that a pulsar had been detected when its local significance was \(\geq 99\%\). In the bottom two plots we show the Lomb-Scargle periodogram of the pulsed flux light curve (middle plot) and the light curve folded at the orbital period (bottom plot). When horizontal dashed lines are plotted on the periodogram, these represent different levels of significance, which are \((\text{from bottom to top})\) 99%, 99.9%, 99.99%, and 99.999%. The coordinates given for each system are the most accurate at time or writing. When a Be/X-ray system has a confirmed optical counterpart, the coordinates of the counterpart are used. When no optical counterpart is known, but the system has been detected by the Chandra X-Ray Observatory and/or XMM-Newton, then it is the X-ray coordinates that were given. For some of the pulsars without an exact position, the coordinates provided by scans with RXTE are given; these are the least precise and have errors of up to several arcminutes.

**2.1. SXP 0.92**

PSR J0045−7319; R.A. = 00\(^h\)45\(^m\)35\(^s\), decl. = −73°19′02″.

*History.*—First discovered as a radio pulsar by Ables et al. (1987) with a period of 0.926499 ± 0.000003 s using the Parkes 64 m radio telescope. Kaspi et al. (1993) observed Doppler shifts in the pulse period which were consistent with a 51 day binary orbit with a companion star having mass \(\sim 4 M_\odot\). Optical observations of the field revealed a 16th magnitude, 11 \(M_\odot\), B1 main-sequence star, which is likely the companion (Bell 1994).

*Survey Results.*—SXP 0.92 received ~2 yr of uninterrupted coverage during A05 and A06 (see Fig. 2), during which time it was only once detected above 99% local significance (MJD 52,334). The power spectrum does not show any significant periods.

**2.2. SXP 2.16**

XTE SMC 2165; R.A. = 01\(^h\)19\(^m\)00\(^s\), decl. = −73°12′27″.

*History.*—Discovered during the course of this survey by Corbet et al. (2003d) at 2.1652 ± 0.0001 s.

*Survey Results.*—Because of its position near SMC X-1, it has only been within the field of view on three occasions: MJD 51,220,
51,263, and 51,310. It was on this last date that it was discovered (its only significant detection).

2.3. SXP 2.37

SMC X-2; R.A. = 00°54′34″, decl. = −73°41′03″.

History.—Discovered in SAS 3 observations of the SMC carried out by Clark et al. (1978). Further outbursts were also observed by HEAO 1 and ROSAT, but no pulsations were detected until it was observed in the present survey by RXTE during a long outburst lasting from 2000 January through May (Corbet et al. 2001; Laycock 2002).

Survey Results.—After the aforementioned outburst, SMC X-2 was only detected on three further occasions (MJD 51,974, 52,025, and 52,228), but at a much lower flux of $F_{X\text{pul}} < 1$ counts PCU$^{-1}$ s$^{-1}$ (see Fig. 3). Lomb-Scargle analysis of the data following the major outburst shows no clear periods.

2.4. SXP 2.76

RX J0059.2−7138; R.A. = 00°59′11.7″, decl. = −71°38′48″.

History.—First reported by Hughes (1994) from a ROSAT observation showing 2.7632 s pulsations that varied greatly with energy. In the low-energy band of the ROSAT PSPC (0.07−0.4 keV), the source appears almost unpulsed, while in the high-energy band (1.0−2.4 keV), the flux is ~50% pulsed. Its optical counterpart was confirmed as a 14th magnitude Be star by Southwell & Charles (1996). Schmidtke et al. (2006) report a period of 82.1 days with a maximum at MJD 52,188.9 from analysis of OGLE III data.

Survey Results.—This source is near the edge of the field of view of position 1A, so we would expect to detect only the brighter outbursts. Only two detections were made (MJD 52,527 and 53,327), and no orbital period can be extracted from the X-ray data (see Fig. 4). We find no power at the reported optical period and note that the two X-ray detections occurred ~10 days after and ~11 days before the optical ephemesis’s predicted maximum.

2.5. SXP 3.34

AX J0105−722; RX J0105.3−7210; R.A. = 01°05′02″, decl. = −72°11′00″.

History.—Reported as an ASCA source with 3.34300 ± 0.00003 s pulsations by Yokogawa & Koyama (1998c). Its optical counterpart is proposed to be [MA93] 1506 by Coe et al. (2005), who also find an 11.09 day modulation in MACHO data. Although this could be the orbital period of the system (as it falls within the expected range on the Corbet diagram; Corbet 1984), Schmidtke & Cowley (2005a) report the find of a strong 1.099 day period and note that the two X-ray detections occurred ~10 days after and ~11 days before the optical ephemesis’s predicted maximum.

Survey Results.—There have been no significant detections of the pulsar during this survey, and timing analysis of the light curve reveals no clear periodicities.

2.6. SXP 4.78

XTE J0052−723; R.A. = 00°52′06.6″, decl. = −72°20′44″.

History.—Discovered by the present survey in late 2000 December and reported in Laycock et al. (2003), where [MA93] 537 was proposed as the optical counterpart. Another possible counterpart is suggested in Coe et al. (2005), as the star AzV 129 is found to have a 23.9 ± 0.1 day period in both MACHO colors, which would agree with the expected orbital period inferred from the Corbet diagram.

Survey Results.—SXP 4.78 was detected on one occasion after its initial outburst (MJD 52,729) at a much weaker $F_{X\text{pul}} \approx 0.8$ counts PCU$^{-1}$ s$^{-1}$. It then began a relatively long, bright (peaking at ~1.2 counts PCU$^{-1}$ s$^{-1}$) outburst on 2005 December.
21 (MJD 53,725) that lasted ~7 weeks (see Fig. 5). Despite the long outburst, no orbital modulation is apparent. Timing analysis using all the data finds no periods, while analysis of the data outside the two bright outbursts suggests a weak period at 34.1 days. A 1 ks observation with Chandra was carried out on 2006 March 3 in an attempt to establish the pulsar’s coordinates. Unfortunately, the outburst had ended, and no source was detected within the RXTE error box provided by Laycock et al. (2003).

2.7. XTE J0103–728

XTE J0103–728; R.A. = 01\(^{\circ}\)02\(^{\prime\prime}\); decl. = −72\(^{\circ}\)44\(\prime\)33\(\prime\)"

History.—First detected in 2003 April with a pulse period of 6.8482 ± 0.0007 s (Corbet et al. 2003e). It was detected in outburst with XMM-Newton on 2006 October 2, which provided a more accurate position (Haberl et al. 2007). This allowed its optical counterpart to be identified as a Be star with V = 14.59, with a possible 24.82 day periodicity (Schmidtke & Cowley 2007a).

Survey Results.—It has been detected on three other occasions (circa MJD 52,885, 53,440, and 53,677) at varying fluxes (F\(_{\text{Xray}}\) ≈ 0.8–1.8 counts PCU\(^{-1}\) s\(^{-1}\)), but high above the noise level (see Fig. 6). Lomb-Scargle analysis of the data outside the four bright detections shows no significant period. When including these outbursts, we find a significant period of 112.5 days; this is the minimum time lapse between any two outbursts and probably drives the result. Given its pulse period, and based on the spin-orbit relation, we do not discard the possibility that the real orbital period is 2 or 4 this value. The current X-ray ephemeris is MJD 52,318.5 ± 7.9 + n(112.5 ± 0.5) days. We note that the outburst detected on 2006 October 2 (MJD 54,010) is consistent with the proposed ephemeris.

2.8. SXP 7.78

SMC X–3; R.A. = 00\(^{\circ}\)52\(^{\prime\prime}\)05.8\(^{\prime\prime}\), decl. = −72\(^{\circ}\)26′03″.

History.—Originally detected by Clark et al. (1978). It was not identified with the previously detected RXTE 7.78 s source until 2004 (Edge et al. 2004a). Corbet et al. (2003a, 2004b) proposed an orbital period from a series of recurrent X-ray outbursts (in the present survey) of 45.1 ± 0.4 days. An optical modulation in MACHO data was reported by Cowley & Schmidtke (2004; 44.86 days) and Coe et al. (2005; 44.6 ± 0.2 days); Edge (2005) also found a strong 44.8 ± 0.2 day modulation in the OGLE counterpart, present even when there was no significant X-ray activity.

Survey Results.—It has displayed in the past 10 yr three distinct periods of outbursts (F\(_{\text{Xray}}\) ≈ 0.3 counts PCU\(^{-1}\) s\(^{-1}\)), lasting ~200–400 days (see Fig. 7, top). Timing analysis of the complete light curve reveals a clear period at 44.92 days; the ephemeris we derive is MJD 52,250.9 ± 1.4 + 44.92n ± 0.06 days. The folded light curve may show evidence of detections at apastron. During the longer of the outburst episodes (circa MJD 52,500), the pulsar shows some spin-up, about \(\dot{P} = 3.7 \times 10^{-10}\) s s\(^{-1}\), implying \(L_x \geq 2.3 \times 10^{37}\) ergs s\(^{-1}\) (\(B \leq 3.6 \times 10^{12}\) G). This pulsar is unique in that, despite the spin-up observed during each of the individual outburst episodes, the overall spin evolution seems to show a long-term spin-down.

2.9. SXP 8.02

CXOU J010042.8−721132; R.A. = 01\(^{\circ}\)00\(^{\prime\prime}\)41.8\(^{\prime\prime}\), decl. = −72°11′36″.

History.—Proposed as the first anomalous X-ray pulsar (AXP) in the SMC by Lamb et al. (2002a). They found the source to have displayed little variability in the past 20 yr. It is characterized by a very soft spectrum and low luminosity (~1.5 × 10\(^{35}\) ergs s\(^{-1}\)).

Survey Results.—During AO5 and AO6 it was outside the field of view of our observations. Coverage from AO7 onward has
been good, and timing analysis of these dates shows a possible periodicity at $C24^{23.2\text{ days}}$, which is likely driven by the only two clear detections, separated by that time range (see Fig. 8). This period disappears when removing these two detections from the data. If SXP 8.02 is truly an anomalous pulsar, it is not expected to show periodicity in its X-ray emission. The two significant detections were observed at around $L_X = 5.0 \times 10^{36} \text{ ergs s}^{-1}$ (unabsorbed, assuming a 50% pulse fraction and a power-law spectrum of $\gamma = 1$).

2.10. SXP 8.88
RX J0051.8–7231, 1E0050.1–7247, 1WGA J0051.8–7231; R.A. = $00^h51^m52.0^s$, decl. = $-72^\circ31'51.7''.$

**History.**—Detected several times between 1979 and 1993 by Israel et al. (1997). A number of optical counterparts have been proposed, and Haberl & Sasaki (2000) believe [MA93] 506 to be the correct one. From a number of outbursts during 2003 July–2004 May, Corbet et al. (2004a) derived an orbital ephemeris of MJD 52,850 ± 2 + 28.0n ± 0.3 days. Schmidtke & Cowley (2006) find an optical period of 33.4 days in OGLE and MACHO data. Note that this system was incorrectly named SXP 8.80 in Coe et al. (2005).

**Survey Results.**—Two type II outbursts together with the aforementioned series of type I outbursts have been detected (see Fig. 9). A period of $\sim 28$ days is found using Lomb-Scargle analysis on the data not containing the type II outbursts, similar to the value from Corbet et al. (2004a). The new ephemeris from the survey data is MJD 52,392.2 ± 0.9 + 28.47n ± 0.04 days. We note that the two type II outbursts began roughly at the times of expected maximum flux, lasted about 1 orbit, and peaked 0.5 $P_{\text{orb}}$ later. This could be explained by a number of scenarios. (1) The neutron...
star forms an accretion disk around periastron, which it consumes throughout the orbit. (2) An accretion disk is formed around periastron which is accreted onto the neutron star along the orbit at the same time as wind accretion (which would peak around apastron) is taking place. (3) The Be star ejects material forcefully at the same time as wind accretion (which would peak around periastron which is accreted onto the neutron star along the orbit). Scenario (2) would require a very dense wind in order for its accretion to become greatest at apastron on both occasions. Scenario (3) suffers a similar drawback, as it would require the annulus to move at similar speeds on both outbursts.

There has been much debate as to which is the correct optical counterpart to this source. Schmidttke et al. (2004) and Filipović et al. (2000) identify it with the ROSAT source RX J0049.5−7310, but Coe et al. (2005) conclude that it is a Hα source coincident with RX J0049.2−7311. Timing analysis of the OGLE data shows a peak at 40.17 days and its probable harmonic at 20.08 days (Edge 2005). It should be noted that Schmidttke et al. (2004) find a 91.5 day or possibly an ~187 day period for RX J0049.5−7310. It was detected by ASCA on one further occasion on MJD 51,645 at $L_X = 1.9 \times 10^{35}$ erg s$^{-1}$ (Yokogawa et al. 2003).

**Survey Results.**—Although coverage of this source has been very complete, it has only been detected in outburst three times (circa MJD 53,545, 53,700, and 53,780). Lomb-Scargle analysis of data prior to this date shows power at a period of 77.4 days; when analyzing the whole data set, the most significant peak is at 77.2 days (Fig. 10, middle and bottom). In both cases the ephemerides agree with the three outbursts (Fig. 10, top), which strongly suggests this could be the orbital period of the system. However, it should be noted that this value is different from the reported optical periods. The ephemeris we derive is MJD 52,380.5 ± 2.3 ± 77.2n ± 0.3 days. The above reported ASCA detections did not find the system in outburst and cannot be used to ratify this ephemeris.

**2.12. SXP 15.3**

RX J0052.1−7319; R.A. = 00°52′14″, decl. = −73°19′19″.

**History.**—Pulsations were found at 15.3 s in ROSAT and CGRO Burst and Transient Source Experiment (BATSE) data from 1996 by Lamb et al. (1999). They estimate the luminosity to be $\sim 10^{37}$ ergs s$^{-1}$ with a pulse fraction of $\sim 27\%$. Edge (2005) finds an ephemeris of MJD 50,376.1 + 75.1n ± 0.5 days describes the modulation in the MACHO and OGLE light curves. It should be noted that this ephemeris is likely driven by the large 1996 X-ray outburst which is clearly visible in the OGLE data; this type II outburst peaked around MJD 50,375.

**Survey Results.**—There was a very minor detection of SXP 15.3 in 2000 February (MJD 51,592), and a more significant one in 2003 August (MJD 52,883) at $F_X \simeq 1.6$ counts PCU$^{-1}$ s$^{-1}$ (see Fig. 11). Two more bright detections separated by 13 days occurred in 2005 March (circa MJD 53,445); then, on July 12 (MJD 53,564) a very bright outburst began, lasting until October 17 (MJD 53,661; ~100 days long). During this time the pulsed flux oscillated between ~2.0 and ~5.6 counts PCU$^{-1}$ s$^{-1}$. A clear spin-up is detected up until September 15, when the period...
started increasing. The maximum period change was \( \Delta P = 3.3 \times 10^{-2} \) over the course of 56.68 days, giving \( P = 6.74 \times 10^{-9} \text{ s}^{-1} \). We derive the expected luminosity (see Appendix B for the method) from such a level of spin-up (if it were all intrinsic with no orbital contribution) to be \( L_X \geq 8.6 \times 10^{37} \text{ ergs s}^{-1} \) (\( B \leq 1.5 \times 10^{13} \text{ G} \)). It is likely this outburst lasted for more than one orbital cycle (expected to be \( \sim 30 \)–50 days from the Corbet diagram), so some orbital modulation might be visible in the period data. An attempt was made to fit these data to an orbital model with constant global spin-up and also with a piecewise approach in which the spin-up varies throughout the outburst (following the method outlined in Wilson et al. 2003). Although no definite value was found, variations in the period curve suggest a period of \( \sim 28 \) days. Timing analysis of the data outside the long outburst revealed no periodicities. Furthermore, the optical ephemeris proposed by Edge (2005) does not agree with any of the detections for this source.

2.13. SXP 16.6

XTE J0050–731; No position available.

*History.*—Discovered with a deep 121 ks observation taken for this survey in 2000 September. It was initially misidentified as RXJ0051.8–7310 but later disproved Yokogawa et al. (2002), and so SXP 16.6 remains unassociated with any known source, although it is often still mistakenly referred to as RXJ0051.8–7310.

**Survey Results.**—There have been a large number of detections of SXP 16.6, and Lomb-Scargle analysis finds a strong modulation at 33.72 days (see Fig. 12, middle and bottom), which we propose as the orbital period of the system. The ephemeris is MJD 52,373.5 \( \pm 1.0 + 33.72n \pm 0.05 \) days.

2.14. SXP 18.3

XTE J0055–727; R.A. = 00\(^{h}\)50\(^{m}\), decl. = \(-72^\circ\)42\(^{\prime}\).

*History.*—Reported by Corbet et al. (2003c) from observations in 2003 November/December. An approximate position was established from scans with the RXTE PCA (Corbet et al. 2003c). No optical counterpart has yet been identified. A number of further outbursts between 2004 May and October provide an ephemeris of MJD 53,145.7 \( \pm 1.3 + 34.6n \pm 0.4 \) days from O-C (observed vs. calculated) orbital calculations (Corbet et al. 2004d).

**Survey Results.**—A long, bright outburst began around MJD \( \sim 53,925 \) (2006 July), which was ongoing as of 2007 January (see Fig. 13, top). Lomb-Scargle analysis of data prior to this outburst finds a peak at 17.73 days, which is \( \sim 1 \) the period proposed by Corbet et al. (2004d). We find no significant power at this period and note that some of the significant detections do not agree with it. Thus, the new ephemeris for this system is MJD 52,275.6 \( \pm 0.9 + 17.73n \pm 0.01 \) days.
2.15. SXP 22.1

RX J0117.6–7330; R.A. = 01°17′40.5″, decl. = −73°30′52.0″.

History.—Discovered with ROSAT as an X-ray transient in 1992 September (Clark et al. 1996). Its companion was identified as a 14.2 mag OB star by Charles et al. (1996). It was observed with ROSAT again in October, but no pulsations were detected (Clark et al. 1997). The companion’s classification as a Be (B1–2) star was confirmed by Coe et al. (1998). There were 22 s pulsations finally detected in ROSAT and BATSE data by Macomb et al. (1999).

Survey Results.—There are only three observations of this pulsar’s region, and it was not significantly detected in any of them.

2.16. SXP 31.0

XTE J0111.2–7317, AX J0111.1–7316; R.A. = 01°11′09.0″, decl. = −73°16′46.0″.

History.—Simultaneously discovered by RXTE and BATSE during a giant outburst that began late October 1998 (Chakrabarty et al. 1998; Wilson & Finger 1998). Schmidtke et al. (2006) report a 90.4 day periodicity in OGLE III data.

Survey Results.—Being in the same field as SMC X-1, it was only observed three times; the first during the end of the aforementioned giant outburst. The two detections are ~43 days apart, and a spin-up of 0.4 s is measured, which implies a luminosity of $L_X \geq 2.7 \times 10^{38}$ erg s$^{-1}$. As Laycock et al. (2005) in an in-depth spectral analysis of these observations derive a value of $L_X \geq 4.6 \times 10^{37}$ erg s$^{-1}$, we can assume we are seeing Doppler-shifted periods due to orbital motion. No further information can be derived from these observations.

2.17. SXP 34.1

RX J0055.4–7210; R.A. = 00°55′26.9″, decl. = −72°10′59.9″.

History.—Discovered in archival Chandra data at 34.08 ± 0.03 s and lying 0.6″ from a known ROSAT source (Edge et al. 2004c, 2004d).

Survey Results.—Only two significant detections are seen (MJD 50,777 and 53,690), and no clear periods can be found with timing analysis (see Fig. 14).

2.18. SXP 46.6

XTE J0053.7–7226; R.A. = 00°53′58.5″, decl. = −72°26′35″.

History.—Discovered in the first observation of this survey (1998 November 25) with a period of 46.63 ± 0.04 s while it was undergoing a long outburst (Corbet et al. 1998). Laycock et al. (2005) derive a period of 139 ± 6 days from six X-ray outbursts in the earlier part of this survey. Two candidates for the optical counterpart were proposed by Buckley et al. (2001). Schmidtke et al. (2007) confirm it is star B and find two periods in OGLE data: 69.2 ± 0.3 and 138.4 ± 0.9 days; they suggest the possibility that the orbital period is the shorter or the two values.

Survey Results.—The source was thought to be inactive after 2002 January. In the meantime a new SMC pulsar with a 46.4 s period was announced (Corbet et al. 2002). Lomb-Scargle analysis of both pulsars revealed the same orbital periods and very similar ephemeris, suggesting they were the same pulsar which has been slowly spinning up (Galache et al. 2005). The estimated luminosity required for a spin-up of $P = 1.05 \times 10^{-8}$ s s$^{-1}$ during MJD 50,800–51,900 is $L_X \geq 9.9 \times 10^{35}$ erg s$^{-1}$ ($B \leq 6.0 \times 10^{32}$ G), and for $P = 4.68 \times 10^{-10}$ s s$^{-1}$ during the same time period, $L_X \geq 4.4 \times 10^{35}$ erg s$^{-1}$ ($B \leq 4.0 \times 10^{32}$ G). The ephemeris of the outbursts is now best described by MJD 52,293.9 ± 1.4 + 137.36n ± 0.35 days (see Fig. 15, top). Although the folded light curve shows a small increase in flux half a phase away from maximum, we do not believe this is evidence that the orbital period is half the calculated value. Given the clear, regular outbursts experienced by this system throughout the survey, we believe the true orbital period is ~137 days.
2.19. SXP 51.0

SMC 51; No position available.

History.—Erroneously proposed as a new 25.5 s pulsar in Lamb et al. (2002b) from a deep 121 ks observation. Laycock (2002) identifies the 25.5 s peaks in the power spectrum as harmonics of the SXP 51.0 true pulse period. No position is available; it lies within position 4, most likely in the overlap between positions 1/A and 4.

Survey Results.—Despite numerous significant detections (see Fig. 16), timing analysis finds no strong periodicities in the light curve.

2.20. SXP 59.0

XTE J0055−724, RX J0054.9−7226, 1WGA J0054.9−7226
R.A. = 00h54m56s, decl. = −72°26′50″.

History.—Discovered in RXTE observations of the vicinity of SMC X-3 (Marshall et al. 1998). It showed four bright, very similar, outbursts during 1998 January–1999 September from which Laycock et al. (2005) derived an orbital period of 123 ± 1 days. The optical counterpart was established by Stevens et al. (1999); Schmidtke & Cowley (2005b) found a 60 s period associated with these spin-ups are, respectively, $P = 4.7 \times 10^{-9}$ s s$^{-1}$ and again throughout the five outbursts of 2002–2003, with a value of $P = 5.9 \times 10^{-9}$ s s$^{-1}$. The luminosities associated with these spin-ups are, respectively, $L_X \geq 2.6 \times 10^{36}$ ergs s$^{-1}$ ($B \leq 1.3 \times 10^{13}$ G) and $L_X \geq 3.3 \times 10^{36}$ ergs s$^{-1}$ ($B \leq 1.4 \times 10^{13}$ G). In between both groups of outbursts, SXP 59.0 was observed to have spun down during the ∼1100 days it was undetected. The average spin-down was $P = -4.2 \times 10^{-9}$ s s$^{-1}$, which would be associated with an estimated $L_X \geq 2.9 \times 10^{36}$ ergs s$^{-1}$. Although SXP 59.0 was further away from the center of the field of view during AO5–AO6 (MJD 51,600–52,300), it should have been picked up as a number of the detections during the second outburst season were made when $P = 122.10$ days.

RXTE was pointing at position D (essentially the same coordinates as position 5). In view of this, the spin-down mechanism for SXP 59.0 must be something other than reverse accretion torque and is likely due to the propeller effect.

2.22. SXP 74.7

RX J0049.1−7250, AX J0049−729; R.A. = 00h49m04″, decl. = −72°50′54″.

History.—Discovered in the first observation of this survey with a period of 74.8 ± 0.4 s (Corbet et al. 1998). Kahabka & Pietsch
(1998) identified it with the ROSAT source RX J0049.1—7250, and Stevens et al. (1999) found a single Be star within the ROSAT error radius which they proposed as the optical counterpart. Only three X-ray outbursts were observed in the early stages of this survey (before MJD 52,300), from which Laycock et al. (2005) derived a possible orbital period of 642 ± 59 days based on the separation between the outbursts. Schmidtke & Cowley (2005b) and Edge (2005) find a 33.4 day periodicity in OGLE data.

**Survery Results.**—Lomb-Scargle analysis of the data finds a period at 62 days, which although not strong, shows a convincing profile (see Fig. 18, middle); its ephemeris is MJD 52,319.0 ± 3.1 + 61.6n ± 0.2 days. There is a weak peak in the power spectrum at 33.2 days, close to the reported optical period, but folding the light curve at this period does not produce a clear modulation.

### 2.23. SXP 82.4

**XTE J0052—725; R.A. = 00h52m09.5s, decl. = −72°38′03″.**

**History.**—First observed by RXTE in this survey (Corbet et al. 2002). Its position was determined from archival Chandra observations (Edge et al. 2004b). OGLE data show a strong modulation at ~380 days (W. R. T. Edge 2006, private communication).

**Survey Results.**—The Lomb-Scargle periodogram for the light curve shows a very significant peak at ~362 days with a number of harmonics (see Fig. 19, middle); the ephemeris derived is MJD 52,089.0 ± 3.6 + n × 362.3 ± 4.1 days. Although this period is longer than would be expected given its $P_o$ position in the Corbet diagram, its similarity to the optical period would seem to confirm it is the actual orbital period of the system. We note that in the aforementioned Chandra observation of this pulsar on MJD 52,459, it was detected at $L_X = 3.4 \times 10^{36}$ ergs s$^{-1}$ (Edge et al. 2004c); this date is 8 days after our predicted periastron passage, and the luminosity exhibited is consistent with a type I outburst (which was also detected with RXTE; see Fig. 19, top).

### 2.24. SXP 89.0

**XTE SMC pulsar; No position available.**

**History.**—Reported by Corbet et al. (2004b) from observations in 2002 March. It is located within the field of view of position 1/A.

**Survey Results.**—The first outburst is a single detection in 2000 February (MJD 51,592), 2 yr before the official discovery; four others occurred 2 yr later in a short space of time, within ~260 days (see Fig. 20, top). They follow a high-low-high-low brightness pattern, with very similar high/low count rates. The separation between them is ~88 days, which could be expected to be the orbital period. In fact, timing analysis finds a strong period at 87.6 days, with an ephemeris of MJD 52,337.5 ± 6.1 + 87.6n ± 0.3 days.
2.25. SXP 91.1

AX J0051$-$722, RX J0051.3$-$7216; R.A. = 00h50m55s, decl. = $-72^\circ13'38''$.

History.—Discovered in the first observation in this survey with a period of 92 ± 1.5 s (Marshall et al. 1997). Further analysis improved this measurement to 91.12 ± 0.05 s (Corbet et al. 1998). An orbital period of 115 ± 5 days was derived by Laycock et al. (2005) from early survey data (before MJD 52,200). Stevens et al. (1999) identified the optical counterpart; Schmidtke et al. (2004) find an 88.25 day period in their analysis of MACHO data for this star.

Survey Results.—Corbet et al. (2004b) reported the discovery of a new 89 s pulsar from XTE observations in 2002 March, it was located within the field of view of position 1/A. After studying the long-term light curves of these two pulsars, we believe SXP 89.0 is actually SXP 91.1 after having spun up (see Fig. 21, top). The Lomb-Scargle periodogram of the whole light curve returns a period of ~101 days, which is slightly shorter than the period found by Laycock et al. (2005). Timing analysis of the light curve post MJD 52,300 shows no clear periods. The ephemeris we derive is MJD 52,197.9 ± 8.2 + 117.8n ± 0.5 days. The average spin-up during MJD 50,750$-$51,550 is calculated to be $\dot{P} = 1.8 \times 10^{-8}$ s s$^{-1}$, with a luminosity of $L_X \geq 3.6 \times 10^{36}$ ergs s$^{-1}$ ($B \leq 2.5 \times 10^{13}$ G). Given the proximity in spin period between SXP 91.1 and SXP 89.0, and the fact that the optical orbital period of SXP 91.1 is so similar to the X-ray period of SXP 89.0, it is possible that they may be one and the same pulsar. In the top plot of Figure 22 we show the consolidated light curve for both pulsars showing the possibility that SXP 91.1 spun up sufficiently to be later detected as a separate pulsar. We are hesitant to claim they are one single system, because the orbital ephemeris of this consolidated data set does not coincide with either system’s ephemeris: MJD 52,301.2 ± 3.0 + n × 101.3 ± 0.4 days. However, the orbital profile (see Fig. 22, middle and bottom) is convincing and appears similar to that of SXP 8.88 (Fig. 9, middle and bottom) or SXP 18.3 (Fig. 13, middle and bottom).

2.26. SXP 95.2

SMC 95; R.A. = 00h52m, decl. = $-72^\circ45'$.  

History.—Was discovered in 1999 March in data from this survey (Laycock et al. 2002). An approximate position was obtained with PCA scans over the source and has a large uncertainty. The X-ray orbital period suggested from the two bright outbursts before MJD 52,300 is 283 ± 8 days (Laycock et al. 2005).

Survey Results.—Only three other marginal detections are available in the data (see Fig. 23). Lomb-Scargle analysis does not return any clear period, either including or excluding the two bright outbursts, although the former has its highest power at 71.3 days, an ephemeris that is consistent with the source’s significant detections and may reflect its orbital period.
2.27. SXP 101

RX J0057.3−7325, AX J0057.4−7325; R.A. = 00°57′26.8″, decl. = −73°25′02″.

History.—Discovered in an ASCA observation at a period of 101.45 ± 0.07 s (Yokogawa et al. 2000c) and identified also as a ROSAT source. Two optical counterparts were suggested by Edge & Coe (2003); from a Chandra observation McGowan et al. (2007) pinpoint the counterpart as a $V = 14.9$ star that exhibits a 21.9 day periodicity in both OGLE III and MACHO data. Schmidtke & Cowley (2007b) find the same period.

Survey Results.—This pulsar lies in the southeast edge of the wing and was in the field of view of positions 4 and 5, so coverage is only continuous throughout AO5 and AO6 (see Fig. 24); during this time only three outbursts of low brightness were observed (MJD 51,814, 51,863, and 52,137). Timing analysis returns no significant periods, although the highest peak in the periodogram is at 25.2 days, similar to the optical period.

2.28. SXP 138

CXOU J005323.8−722715; R.A. = 00°53′23.8″, decl. = −72°27′15.0″.

History.—Discovered in archival Chandra data (Edge et al. 2004b). The optical counterpart is [MA93] 667 (Edge 2005). The MACHO light curves for the companion star reveal peaks at ~125.1 day intervals (stronger in the red band). Schmidtke & Cowley (2006) report finding a weak periodicity in the 122−123 s region in MACHO data.

Survey Results.—X-ray data from this survey show two brighter detections ~112 days apart (see Fig. 25, top). Lomb-Scargle analysis finds no significant periods; however, if these two detections are removed from the data, a period of 103.6 days appears in the power spectrum. Its ephemerides (shown by the vertical dashed lines in Fig. 25, top) do not correspond with the two detections, and the profile (Fig. 25, bottom) looks almost sinusoidal, unlike the profiles exhibited by other systems in the SMC. The maxima for this period occur at MJD 52,400.2 ± 5.2 + 103.6n ± 5 days.

2.29. SXP 140

XMMU J005605.2−722200, 2E0054.4−7237; R.A. = 00°56′05.7″, decl. = −72°22′00″.

History.—Discovered in XMM-Newton observations by Sasaki et al. (2003). The optical counterpart is believed to be [MA93] 904 (Haberl & Pietsch 2004). Schmidtke & Cowley (2006) find a 197 ± 5 day period in MACHO data.

Survey Results.—None of the detections has been longer than 1 week, with only two of them showing significant brightness (see Fig. 26). Timing analysis returns no clear periods, although the periodogram of the data, excluding the two bright detections,
does show some power at $\sim 197$ days. As a number of different periods have similar power, this may only be a coincidence. The folded light curve at 197 days does not show a typical orbital profile.

2.30. SXP 144

XTE SMC pulsar; No position available.

History.—Detected in observations from this survey in 2003 April by Corbet et al. (2003e), who later reported an ephemeris of MJD 52,779.2 $\pm$ 2.9 + 61.2$n$ $\pm$ 1.6 days (Corbet et al. 2003b).

Survey Results.—Although there are a few minor detections before the initial discovery, 2003 April (~ MJD 52,750) saw the beginning of a regular pattern of outbursts which continued until 2006 February (~MJD 53,800; see Fig. 27, top). The neutron star has displayed an extremely linear and constant spin-down during this time, with an average $P = 1.6 \times 10^{-8}$ s s$^{-1}$, from which we derive a $L_X \geq 1.1 \times 10^{36}$ ergs s$^{-1}$ ($B \leq 2.4 \times 10^{13}$ G). The improved outburst ephemeris from Lomb-Scargle analysis is MJD 52,368.9 $\pm$ 1.8 + $n$ $\times$ 59.38 $\pm$ 0.09 days. This period is shorter than might have expected from the pulse-orbit relationship, but what is most unusual about this pulsar is that it is spinning down, moving it even further away from the Be group on the Corbet diagram.

2.31. SXP 152

CXOU J005750.3$-$720756; R.A. = 00$^{h}$57$^{m}$49$,^{s}$, decl. = $-72^\circ$07$'$59$''$.

History.—Suggested to be a Be binary pulsar (Haberl & Sasaki [2000] based on the H$\alpha$-emitting object [MA93] 1038, although
ROSAT observations of this source had not detected any pulsations. These were found in a long Chandra observation by Macomb et al. (2003) at a period of 152.098 ± 0.016 s (they report a very high pulse fraction of 64% ± 3% and $L_X = 2.6 \times 10^{33}$ ergs s$^{-1}$), and in an XMM-Newton observation by Sasaki et al. (2003) at 152.34 ± 0.05 s.

Survey Results.—The observational history is shown in Figure 28. The periodogram of the light curve shows no clear orbital period, although the highest power peak is at ~107 days, which would agree with the expected value from the Corbet diagram. The lack of periodic outbursts, despite its clear X-ray activity, may imply a low-eccentricity system. This would limit accretion onto the neutron star to times when the Be star ejecta are dense enough and would be independent of the orbital phase. Analysis of the optical light curve of the companion Be star is needed.

2.32. SXP 169

XTE J0054−720, AX J0052.9−7158, RX J0052.9−7158; R.A. = 00°52′54.0″, decl. = −71°58′08.0″.

History.—First detected by RXTE in 1998 December at a period of 169.30 s (Lochner et al. 1998). Laycock et al. (2005) suggested a possible orbital period of 200 ± 40 days. Galache et al. (2005) reported an orbital period of 68.6 ± 0.2 days based on data from this survey, while Schmidtke et al. (2006) found a period of 67.6 ± 0.3 days in OGLE III data.

Survey Results.—Corbet et al. (2004b) announced a new SMC pulsar at 164.7 s with an unknown position. After comparing the long-term light curves and the ephemerides from timing analysis, it became apparent that SXP 165 and SXP 169 were the same source. A consolidated light curve is presented here (Fig. 29, top), where the spin-up of SXP 169 throughout the survey is apparent. The estimated spin-up during MJD 50,800–51,500 is $\dot{P} = 2.5 \times 10^{-8}$ s s$^{-1}$, implying $L_X \geq 1.2 \times 10^{36}$ ergs s$^{-1}$ ($B \leq 3.0 \times 10^{13}$ G); for the remaining data the spin-up is $\dot{P} = 2.0 \times 10^{-8}$ s s$^{-1}$, implying $L_X \geq 9.6 \times 10^{35}$ ergs s$^{-1}$ ($B \leq 2.6 \times 10^{13}$ G). Lomb-Scargle analysis provides a clear period, and the outbursts are described by the ephemeris MJD 52,240.1 ± 2.1 + 68.54 $n$ ± 0.15 days, in agreement with the reported optical period.

2.33. SXP 172

AX J0051.6−7311, RX J0051.9−7311; R.A. = 00°51′52″, decl. = −73°10′35″.

History.—Found in an ASCA observation (Torii et al. 2000). It was identified with the ROSAT source RX J0051.9−7311, which has a Be optical counterpart (Cowley et al. 1997). Laycock et al. (2005) suggest a possible orbital period of ~67 days based on the X-ray activity up until MJD 52,350. Schmidtke & Cowley (2006) report an optical period of 69.9 ± 0.6 days in OGLE II data. This pulsar has been detected on 17 occasions by Einstein, ROSAT and ASCA, but never above $L_X = 7.8 \times 10^{35}$ ergs s$^{-1}$ (Yokogawa et al. 2000b).

Survey Results.—SXP 172 underwent a phase of intense, semiregular activity during MJD 51,600−52,400 (see Fig. 30). Lomb-Scargle analysis was carried using data from only this period and also from the whole data set with no conclusive outcome. However, it is clear that the series of outbursts during the aforementioned dates are separated by ~70 days (consistent with the optical period). It is possible we are seeing contamination from another pulsar of similar pulse period, maybe located within a different pointing position. As past missions did not detect this pulsar in outburst, it is hard to confirm an X-ray ephemeris.

2.34. SXP 202

XMMU J005920.8−722316; R.A. = 00°59′20.8″, decl. = −72°23′16″.

History.—Detected in a number of archival XMM-Newton observations and reported in Majid et al. (2004). The authors found an early B-type star at the X-ray coordinates and classified it as a HMXB.
Survey Results.—This source has shown little bright activity throughout the survey, except for the outburst in 2006 January (circa MJD 53,740; see Fig. 31). Lomb-Scargle analysis of the data returns no clear period, but we note that a ∼91 day orbital period would agree with the six outburst detections since MJD 53,000.

2.35. SXP 264
XMMU J004723.7−731226, RX J0047.3−7312, AX J0047.3−7312; R.A. = 00h47m23.7s, decl. = −73°12′25″.

History.—Initially reported by Yokogawa et al. (2003) from ASCA observations, although it had previously been detected (yet remained undiscovered) in earlier XMM-Newton observations (Ueno et al. 2004). It had originally been proposed as a Be/X-ray binary candidate by Haberl & Sasaki (2000) based on its X-ray variability. Edge et al. (2005a) identified the companion as the emission-line star [MA93] 172 and found an optical period of 48.8 ± 0.6 days, which they propose as the orbital period of the system. Further analysis of the OGLE light curve finds an ephemeris of MJD 50,592 ± 2 + 49.2n days (Edge 2005). Schmidtke & Cowley (2005b) found a 49.1 day period in OGLE data.

Survey Results.—Because of its location, this pulsar was only observed consistently during AO5 and AO6 (see Fig. 32). No major outbursts were detected, and the power spectrum shows no significant peak at the optical period, nor at any other. We note that the optical ephemeris does not agree with the X-ray activity.

2.36. SXP 280
RX J0057.8−7202, AX J0058−72.0; R.A. = 00h57m48.2s, decl. = −72°02′40″.

History.—Discovered in 1998 March in an ASCA observation by Yokogawa & Koyama (1998a) at a period of 280.4 ± 0.3 s. It is identified with the Be star [MA93] 1036, and Schmidtke et al. (2006) find a 127.3 day period in its OGLE data with an epoch of maximum brightness at MJD 52,194.7. This pulsar was observed on 15 occasions by Einstein, ROSAT, and ASCA, but never detected above $L_X = 6.0 \times 10^{33}$ ergs s$^{-1}$ (Tsujimoto et al. 1999).

Survey Results.—There are only five clear detections of this source throughout the survey, and the power spectrum shows no significant periods, although the highest peak is at 64.8 days, which is $\sim \frac{1}{3}$ of the optical period. For this reason, the ephemeris lines and folded light curve are shown in Figure 33. The tentative ephemeris of the X-ray period is MJD 52,312 ± 6 + 64.8n days, which is within $\sim$12 days of the epoch of peak optical flux. A lack of earlier detections of this system in outburst makes it difficult to firmly establish an X-ray ephemeris.

2.37. SXP 293
XTE J0051−727; No position available.

History.—Reported by Corbet et al. (2004c) from observations during this survey of the outburst at MJD 53,097.

Survey Results.—Only one of the six outbursts lasts longer than 1 week (Fig. 34, top), which could imply that this is a type II outburst and thus is not expected to coincide with periastron passage. For this reason, it was removed from the data after initial timing analysis produced no results. The resulting power spectrum, while not showing any significant periods, does have its strongest peak at 151 days, an ephemeris that agrees well with the remaining five detections. We suggest this is the likely orbital period of the system, with an ephemeris of MJD 52,327.3 ± 4.5 + 151n ± 1 days.

2.38. SXP 304
RX J0101.0−7206, CXOU J010102.7−720658; R.A. = 01h01m01.7s, decl. = −72°07′02″.

History.—Discovered in Chandra observations at 304.49 ± 0.13 s. The optical counterpart is identified as the emission-line
The authors measured an unusually high pulse fraction of 90% at a luminosity of $L_X = 1.1 \times 10^{34}$ ergs s$^{-1}$. Schmidtke & Cowley (2006) suggest there may be a 520 day period in MACHO data of the optical counterpart [MA93] 1240.

**Survey Results.**—This source was out of the field of view during AO5 and AO6, so it has only been adequately covered from AO7 onward. A number of small outbursts were detected during MJD 52,600–53,000 (see Fig. 35), and it was not detected again until recently, in MJD 53,747, when it began a 2.39 week outburst, the longest and brightest observed so far in this survey. Lomb-Scargle analysis of the data outside of this outburst finds moderate power at 50 days and no significant power at the optical period. It should be noted that this source displays X-ray activity on timescales much shorter than the reported 520 day optical period.

**2.39. SXP 323**

RX J0050.7–7316, AX J0051–733; R.A. = 00h50m44s, decl. = −73°16’06.0’’.

**History.**—Detected in 1997 November (Yokogawa & Koyama 1998a) at the coordinates of the ROSAT source RX J0050.7–7316 with pulsations at 323.2 ± 0.4 s. Cowley et al. (1997) identified the optical counterpart as a Be star. This system has been found to exhibit optical and infrared variability at periods of ~0.7 and 1.4 days (Coe et al. 2002) and 1.695 days (Coe et al. 2005). These periods are too short to be the orbital period of the system and are most likely nonradial pulsations in the Be star. Laycock et al. (2005) suggest an orbital period of 109 ± 18 days from X-ray data earlier in this survey.

**Survey Results.**—This pulsar showed quite regular, bright activity during the survey (see Fig. 36, top). We found that the...
outburst circa MJD 52,960 skewed the timing analysis results, which we attribute to it being a type II outburst; for this reason it was excluded from the analysis. The ephemeris found for the remaining outbursts is MJD 52336.9/C60.6 days, which is consistent with the orbital period proposed by Laycock et al. (2005).

2.40. SXP 348

RX J0102−722, SAX J0103.2−7209, AX J0103.2−7209; R.A. = 01h03m13.0s, decl. = −72°09′18.0″.

History.—Detected in BeppoSAX observations in 1998 July with pulsations at 345.2 ± 0.1 s (Israel et al. 1998). Subsequently, pulsations at 348.9 ± 0.1 s were found in archival ASCA data from 1996 May, implying \( P = 5.39 \times 10^{-8} \) s s\(^{-1}\) (Yokogawa & Koyama 1998b). The ROSAT source lies in a supernova remnant with a Be counterpart; a weak 93.9 day periodicity has been reported from OGLE data (Schmidtke & Cowley 2006). Israel et al. (2000) suggest this is a persistent, low-luminosity X-ray system.

Survey Results.—Although this source has been detected by a number of different instruments, it was always at low luminosities (≤10\(^{36}\) ergs s\(^{-1}\)), so it is not surprising that there are not many detections in the survey (Fig. 37). Furthermore, it has also been detected at a wider range of periods than other pulsars (from 340 to 348 s), which makes it more difficult to pick out in the periodograms from weekly observations. Timing analysis reveals no significant periods.

2.41. SXP 452

RX J0101.3−7211; R.A. = 01h01m19.5s, decl. = −72°11′22″.

History.—Initially proposed as an X-ray binary by Haberl et al. (2000). Pulsations were detected in XMM-Newton observations during 2001 at 455 ± 2 s and in 1993 ROSAT data at 450−452 s (Sasaki et al. 2001), implying \( P = 2.3 \times 10^{-8} \) s s\(^{-1}\); the optical counterpart was identified as a Be star (Sasaki et al. 2001). Schmidtke et al. (2004) propose an orbital period of 74.7 days for this system based on its optical variability.

Survey Results.—With only five detections throughout the survey (Fig. 38), this source's periodogram shows no periodicities, and there is no evidence for the reported 74.7 day optical period.

2.42. SXP 504

RX J0054.9−7245, AX J0054.87244, CXOU J005455.6−724510; R.A. = 00h54m55.6s, decl. = −72°45′10″.

History.—Discovered in archival Chandra data with 503.5 ± 6.7 s pulsations (Edge et al. 2004c, 2004d). It was also reported by Haberl et al. (2004) from an XMM-Newton observation at 499.2 ± 0.7 s and \( L_X = 4.3 \times 10^{35} \) ergs s\(^{-1}\). An orbital period of 268.0 ± 1.4 days was determined from optical (OGLE) data.
and corroborated by preliminary X-ray data from the present survey (Edge et al. 2005b). The optical ephemeris was later refined to MJD 50\,556 + 3 + 268.0n ± 0.6 days (Edge et al. 2005c). Schmidtke & Cowley (2005b) found a period of 273 days in OGLE data.

**Survey Results.**—The light curve for this system can be seen in the top plot of Figure 39. Lomb-Scargle analysis of the entire survey (with or without the bright outbursts circa MJD 52,440 and 52,980) returns a slightly shorter orbital period to the optical one previously reported, but is consistent within errors. Furthermore, Edge et al. (2005c) find that the epochs of maximum X-ray flux are coincident with the optical outbursts. The ephemeris we find is MJD 52\,219:0 + 151.8n ± 0.6 days. We note there is no power at the reported optical period nor does the optical ephemeris agree with the brightest X-ray detections of this source. In view of this, it is possible that the optical counterpart has been misidentified; however, there is no other bright candidate star within 10 00 of the very precise Chandra position. The folded light curve has a unique shape, showing significant activity around periastron. The asymmetry of the periastron peak is likely due to the presence of an accretion disk around the neutron star that is not completely consumed by the time it reaches apastron, where its lower orbital velocity allows it to “top up” its disk from the Be star’s wind.

**2.43. SXP 565**

CXOU J005736.2−721934; R.A. = 00h57m36.2s, decl. = −72°19′34″.

**History.**—Discovered in Chandra observations at 564.81 ± 0.41 s with a pulse fraction of 48% ± 5% ($L_X = 5.6 \times 10^{33}$ ergs s$^{-1}$). The optical counterpart is identified as the emission-line star [MA93] 1020 (Macomb et al. 2003). An optical period of 95.3 days has been reported for this system (Schmidtke et al. 2004), but this period is not seen in OGLE data (Edge 2005).

**Survey Results.**—This source shows a lot of variability, but no clear outbursts (see Fig. 40, top). The power spectrum returns two significant peaks, with only the higher one providing a convincing orbital profile. The ephemeris for this period is MJD 52,219.0 ± 13.7 + 151.8n ± 1.0 days. We note there is no power at the reported optical period nor does the optical ephemeris agree with the brightest X-ray detections of this source. In view of this, it is possible that the optical counterpart has been misidentified; however, there is no other bright candidate star within 10 00 of the very precise Chandra position. The folded light curve has a unique shape, showing significant activity around periastron. The asymmetry of the periastron peak is likely due to the presence of an accretion disk around the neutron star that is not completely consumed by the time it reaches apastron, where its lower orbital velocity allows it to “top up” its disk from the Be star’s wind.

**2.44. SXP 700**

CXOU J010206.6−714115; R.A. = 01h02m06.69s, decl. = −71°41′15.8″.

**History.**—Discovered as part of the aforementioned Chandra survey of the SMC wing reported in McGowan et al. (2007). They detected a source with $L_X = 6.0 \times 10^{35}$ ergs s$^{-1}$ (35% ± 5%
pulse fraction) with pulsations at 700.54 ± 34.53 s and found its position to coincide with the emission-line star [MA93] 1301, a \( V = 14.6 \) O9 star. The OGLE data available for this object show a periodic modulation at 267.38 ± 15.10 days (McGowan et al. 2007).

**Survey Results.**—Because of its proximity in period to SXP 701, limitations of the current analysis script (which cannot work on two pulsars of such similar spin periods) have not allowed the extraction of an X-ray light curve for this pulsar. However, it has not contaminated the data presented for SXP 701, because even though they are \( \sim 66\' \) away from each other, they were never within the same field of view.

2.45. **SXP 701**

RX J0055.2−7238, XMMU J005517.9−723853; R.A. = 00^h^55^m^17.9^s^, decl. = −72°38′53″

**History.**—First observed during an XMM-Newton Target of Opportunity (ToO) observation at 701.6 ± 1.4 s and located within the error circle of a ROSAT object (Haberl et al. 2004). Fabrycky (2005) finds optical periods of 6.832 and 15.587 hr, which are attributed to stellar pulsations. A weak 412 day period has been seen in MACHO data (Schmidtke & Cowley 2005b).

**Survey Results.**—Similar to SXP 565, it displays much X-ray variability with no bright outbursts (see Fig. 41). Unfortunately, timing analysis provides no clear periodicities.

2.46. **SXP 756**

RX J0049.6−7323, AX J0049.4−7323; R.A. = 00^h^49^m^42.42^s^, decl. = −73°23′15.9″

**History.**—Detected in a very long (\( \sim 177 \) ks) ASCA observation of the SMC in 2000 April with pulsations at 755.5 ± 0.6 s. The source was detected at a luminosity of \( L_x = 5 \times 10^{35} \) ergs s⁻¹ (Yokogawa et al. 2000a). The optical counterpart was later established as a \( V = 15 \) Be star (Edge & Coe 2003). Laycock (2002) and Laycock et al. (2005) find an X-ray period of 396 ± 5 days, while Cowley & Schmidtke (2003) and Schmidtke et al. (2004) report recurring outbursts at \( \sim 394 \) day intervals in \( R \)- and \( I \)-band MACHO data.

**Survey Results.**—Coverage of this pulsar has been sparse due to its southern location in the SMC, only visible to observations of positions 4 and 5. Despite this, it has been detected various times in outburst, the brightest of which was a 3 week outburst (Fig. 42, top). We decided to remove the brightest point from this outburst so as not to skew the Lomb-Scargle power spectrum. A strong period is found at 194.9 days, which we believe to be the first harmonic of the orbital period. Looking at the light curve, it is evident that the bright detections are spaced \( \sim 400 \) days apart. Moreover, this would be in agreement with the optical period of the system, so we use twice the value of the harmonic as the orbital period and derive the ephemeris MJD 52,196.1 \( \pm 3.9 \) + 389.9n \( \pm 7.0 \) days. This ephemeris places the first outburst in the data at MJD 51,416, which is consistent with the last optical outburst available in the MACHO data (Cowley & Schmidtke 2003).

2.47. **SXP 1323**

RX J0103.6−7201; R.A. = 01^h^03^m^37.5^s^, decl. = −72°01′33.2″

**History.**—Source with the longest known pulse period in the SMC. It was reported by Haberl & Pietsch (2005) in a number of archival XMM-Newton observations. The authors identify the emission-line star [MA93] 1393 (\( V \approx 14.6 \)) as the optical counterpart. Schmidtke & Cowley (2006) report three strong periods for this source from OGLE II data: 0.41, 0.88, and 26.16 days; they attribute the first two to nonradial pulsations of the Be star, but suggest the latter might be the orbital period.

\[^6\] Also note that only one peak appears in the orbital profile in the bottom plot of Fig. 42. If 194.9 days were the actual orbital period, the plot would show two peaks per orbital cycle.
Survey Results.—This source is difficult to detect due to its long period (requiring observations with a baseline longer than ~4 ks) and its location near the edge of position 1/A. Despite these limitations, a number of bright outbursts have been detected, but no periodicities can be found in the sparse data (see Fig. 43).

3. DISCUSSION

Table 3 presents a summary of the timing analysis results for the SMC pulsars, providing orbital periods and ephemerides where available, together with periods observed at other wavelengths. In cases in which there is only weak evidence for an orbital period in the X-ray data, the number is given in parentheses.

Those systems with unequivocal orbital periods have allowed us to study and compare a selection of well-defined orbital profiles. In particular, we consider the profiles of the following systems that have shown regular activity at or around, periastron passage: SXP 6.85, SXP 7.78, SXP 46.6, SXP 59.0, SXP 82.4, SXP 144, SXP 169, and SXP 756. It is notable that their profiles all share a similar shape, even though their orbital periods cover a range of 1.7 s. It would seem that factors other than just the orbital and spin periods govern the behavior and evolution of these binary systems, and they need to be taken into account. Orbital eccentricity and/or the magnetic field strength are likely to be important factors in determining the relationship between the spin and orbital periods.

4. CONCLUSION

We have presented the most comprehensive collection of pulsed light curves for 41 probable Be/X-ray systems in the SMC.
TABLE 3
X-RAY Binary Systems in the SMC

| Object     | \(P_x\) (s) | R.A.  | Decl.  | X-Ray \(T_P\) (MJD) | X-Ray \(P_{\text{orb}}\) (days) | Other \(P_{\text{orb}}\) (days) |
|------------|-------------|-------|--------|----------------------|-------------------------------|-------------------------------|
| SXP 0.09   | 0.087       | 00 42 35.0 | −73 40 30.0 | ...                  | ...                           | ...                           |
| SXP 0.72   | 0.716       | 01 17 05.2 | −73 26 36.0 | ...                  | ...                           | ...                           |
| SXP 0.92   | 0.92        | 00 45 35.0 | −73 19 02.0 | ...                  | ...                           | 51a                           |
| SXP 2.16   | 2.165       | 01 19 00  | −73 12 27  | ...                  | ...                           | ...                           |
| SXP 2.37   | 2.374       | 00 54 34.0 | −73 41 03.0 | ...                  | ...                           | ...                           |
| SXP 2.76   | 2.763       | 00 59 11.7 | −71 38 48.0 | ...                  | ...                           | 82.1b                         |
| SXP 3.34   | 3.34        | 01 05 02.0 | −72 11 00.0 | ...                  | ...                           | ...                           |
| SXP 4.78   | 4.782       | 00 52 06.6 | −72 20 44  | ...                  | (34.1)                        | 23.9g                         |
| SXP 6.85   | 6.848       | 01 02 53.1 | −72 44 33  | 52,318.5 ± 7.9       | 112.5 ± 0.5                   | 24.8g, 44.8g                  |
| SXP 7.78   | 7.780       | 01 52 06  | −72 26 06  | 52,250.9 ± 1.4       | 44.92 ± 0.06                  | 44.86g, 44.6g, 44.8g          |
| SXP 8.02   | 8.020       | 01 00 41.8 | −72 11 36  | ...                  | ...                           | ...                           |
| SXP 8.88   | 8.880       | 00 51 52.0 | −72 31 51  | 52,392.2 ± 0.9       | 28.47 ± 0.04                  | 33.4h                         |
| SXP 9.13   | 9.130       | 00 49 13.6 | −73 11 39  | 52,380.5 ± 2.3       | 77.2 ± 0.3                    | 40.17g, 91.5g                 |
| SXP 15.3   | 15.30       | 00 52 14   | −73 19 19  | ...                  | (28)                          | 75.1j                         |
| SXP 16.6   | 16.52       | ...       | ...      | 52,373.5 ± 1.0       | 33.72 ± 0.05                  | ...                           |
| SXP 18.3   | 18.37       | 00 50      | −72 42   | 52,275.6 ± 0.9       | 17.73 ± 0.01                  | 3.6k                          |
| SXP 22.1   | 22.07       | 01 17 40.5 | −73 30 52.0 | ...                  | ...                           | ...                           |
| SXP 31.0   | 31.01       | 01 11 09.0 | −73 16 46.0 | ...                  | ...                           | ...                           |
| SXP 34.1   | 34.08       | 00 55 26.9 | −72 20 59.9 | ...                  | ...                           | ...                           |
| SXP 46.6   | 46.59       | 00 53 58.5 | −72 26 35.0 | 52,293.9 ± 1.4       | 137.36 ± 0.35                 | 69.2j, 138.4d                 |
| SXP 51.0   | 51.00       | ...       | ...      | ...                  | ...                           | ...                           |
| SXP 59.0   | 58.86       | 00 54 56.6 | −72 26 50  | 52,306.1 ± 3.7       | 122.10 ± 0.38                 | 60.2h                         |
| SXP 65.8   | 65.78       | 01 07 12.6 | −72 35 33.8 | ...                  | ...                           | 110.6a                        |
| SXP 74.7   | 74.70       | 00 49 04  | −72 50 54  | 52,319.0 ± 3.1       | 61.6 ± 0.2                    | 33.4a                         |
| SXP 82.4   | 82.40       | 00 52 09   | −72 38 03  | 52,089.0 ± 3.6       | 362.3 ± 4.1                   | 380.9p                        |
| SXP 89.0   | 89.00       | ...       | ...      | 52,337.5 ± 6.1       | 87.6 ± 0.3                    | ...                           |
| SXP 91.1   | 91.10       | 00 50 55   | −72 13 38  | 52,197.9 ± 8.2       | 117.8 ± 0.5                   | 88.25d                        |
| SXP 95.2   | 95.20       | 00 52 00   | −72 45 00  | ...                  | (71.3)                        | ...                           |
| SXP 101.1  | 101.40      | 00 57 26.3 | −73 25 02  | ...                  | (25.2)                        | 21.9g                         |
| SXP 138.0  | 138.00      | 00 53 23.8 | −72 27 15.0 | 52,400.5 ± 5.2       | 103.6 ± 0.5                   | 125.9, 122–123f               |
| SXP 140.0  | 140.99      | 00 56 05.7 | −72 22 00.0 | ...                  | ...                           | 197g                          |
| SXP 144.0  | 144.00      | ...       | ...      | 52,368.9 ± 1.8       | 59.38 ± 0.09                  | ...                           |
| SXP 152.0  | 152.10      | 00 57 49   | −72 07 59  | ...                  | ...                           | ...                           |
| SXP 169.0  | 167.35      | 00 52 54.0 | −71 58 08.0 | 52,240.1 ± 2.1       | 68.54 ± 0.15                  | 67.6g                         |
| SXP 172.0  | 172.40      | 00 51 52   | −73 10 35  | ...                  | (70)                          | 69.9g                         |
| SXP 202.0  | 202.00      | 00 59 20.8 | −72 23 17  | ...                  | (91)                          | ...                           |
| SXP 264.0  | 263.60      | 00 47 23.7 | −73 12 25  | ...                  | ...                           | 49.25, 49.1w                  |
| SXP 280.0  | 280.40      | 00 57 48.2 | −72 02 40  | 52,312 ± 6           | 64.8 ± 0.2                    | 127.3w                        |
| SXP 293.0  | 293.00      | ...       | ...      | 52,327.3 ± 4.5       | 151 ± 1                       | ...                           |
| SXP 304.0  | 304.49      | 01 01 01.7 | −72 07 02  | ...                  | ...                           | 520f                          |
| SXP 323.0  | 323.20      | 00 50 44.8 | −73 16 06.0 | 52,336.9 ± 3.5       | 116.6 ± 0.6                   | ...                           |
| SXP 348.0  | 348.75      | 01 03 13.0 | −72 09 18.0 | ...                  | ...                           | 93.9g                         |
| SXP 452.0  | 452.01      | 01 01 19.5 | −72 11 22  | ...                  | ...                           | 74.7g                         |
| SXP 504.0  | 503.50      | 00 54 55.6 | −72 45 10.0 | 52,167.4 ± 8.0       | 265.3 ± 2.9                   | 268.0d, 273w                  |
and have determined an X-ray (likely orbital) ephemeris for 21 of them while presenting possible periods for six others. Ten of these ephemerides are from new X-ray periods, while six others are improvements of previously known ephemerides. Of the systems exhibiting periodicities in the X-rays, 19 also show optical periodicities, although it is noteworthy that the optical and X-ray periods only agree on seven occasions. Of the remaining 12, three have proven to be the most successful method of study.

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**Facilities:** RXTE(PCA)

## APPENDIX A

### DETERMINING SIGNAL SIGNIFICANCE

Scargle (1982) proposes the normalization of the periodogram to the variance \( \sigma^2 \) of the signal-free data, where \( \sigma^2 \) is the standard deviation; as such, Gaussian noise will have a power of 1.\(^7\) Furthermore, the probability function Prob associated with the periodogram will be exponentially distributed,\(^8\) and it can be shown that the probability that a periodic signal with power of Z is due to noise is

\[
FAP = 1 - (1 - e^{-Z})^M, \tag{A1}
\]

\(^7\) It is clear that most of the data from observations made by RXTE during the survey contain contributions from a number of sources in the field of view, and their variance should not be used in the calculations. However, after analyzing a large number of observations, it was found that the average power within the calculated power spectra was essentially 1 (likely due to the low signal-to-noise ratio), which justifies our use of the light curve variance (including all the pulsar signals) instead of the variance of the noise, which would have been difficult to obtain.

\(^8\) It will be of the form \( \text{Prob} = e^{-Z} \), which is the probability of detecting a peak in the periodogram above a certain power Z.
which is the false-alarm probability, with \( M \) being the number of independent frequencies, which we (rather conservatively) define as

\[
M = 2n_f \Delta f \tau,
\]  
(A2)

where \( n_f \) is the number of scanned frequencies, \( \Delta f \) is the frequency interval used when calculating the periodogram, and \( \tau \) is the duration of the observation.

A more useful number may be the significance of a detection, or how sure we are that it is real; this is simply \( 1 - \text{FAP} \), expressed as a percentage. This is the value that will be used throughout this paper to estimate the importance and believability of a signal, and is given by

\[
\text{Sig}(\%) = 100(1 - e^{-Z^M} ).
\]  
(A3)

In the Lomb-Scargle periodogram, the peak-to-trough amplitude \( A \) of the modulation in the signal is related to the power \( P_{LS} \) through

\[
A = 4 \sqrt{\frac{P_{LS} \sigma_n^2}{N}},
\]  
(A4)

where \( N \) is the number of data points (Scargle 1982).

If the signal detected has any harmonics, its total power will be divided between the individual harmonic peaks in the power spectrum. Using only the fundamental to estimate the amplitude of the signal’s pulsations could then severely underestimate it if there were considerable power in any of the harmonics (which is often the case). If the amplitude of all the harmonics is known, it can be shown that the total amplitude of the signal will be given by

\[
A_{\text{tot}} = \sqrt{\sum_i A_i^2}.
\]  
(A5)

From the error in the angular frequency detected at a certain power in the Lomb-Scargle periodogram (Horne & Baliunas 1986), we derive the error on the period as

\[
dP = \frac{3}{4} \left( \frac{P^2 \sigma_n}{\sqrt{N \pi A}} \right),
\]  
(A6)

where \( A \) is the Lomb-Scargle amplitude given by equation (A5), and \( \sigma_n \) is the standard deviation of the noise, although the standard deviation of the actual data is used, as explained earlier.

Apart from the global significance of a detection, we define an additional quantity, the local significance, as the significance of a peak at frequency \( f \), within a region of frequency space extending 5% of \( f \) to either side of it.

**APPENDIX B**

**LUMINOSITY AND MAGNETIC FIELD ESTIMATION**

If all the matter accreting onto a neutron star is converted into energy, the luminosity that will result is simply the gravitational energy lost by the infalling mass (Frank et al. 2002),

\[
L_X = \frac{GM \dot{M}}{R},
\]  
(B1)

where \( \dot{M} \) is the mass transfer rate. Some manipulation and substitution can provide a more manageable expression,

\[
L_{X,77} = 8.4 \times 10^9 \left( \frac{M_\odot \dot{M}}{R_n} \right),
\]  
(B2)

which will give us the luminosity in terms of \( 10^{37} \) ergs s\(^{-1}\), and where \( M_\odot \) is the mass of the neutron star in units of \( M_\odot \), \( \dot{M} \) is the mass accretion rate in units of \( M_\odot \) yr\(^{-1}\), and \( R_n \) is the radius of the neutron star in kilometers.

The angular momentum of a neutron star is given by

\[
L_n = \frac{2\pi I_n}{P_s},
\]  
(B3)

where \( P_s \) is the spin period, and the moment of inertia is given by

\[
I_n = \frac{2}{5} M_n R_n^2,
\]  
(B4)

where \( M_n \) and \( R_n \) are the mass and radius of the neutron star in standard units.
The torque experienced by a neutron star spinning up or down is given by

$$|\tau| = \left| \frac{dL_n}{dt} \right| = 2\pi I_n \frac{\dot{P}_s}{P_s^2}, \quad (B5)$$

where $\dot{P}_s$ is the rate of change of the spin period (Frank et al. 2002).

For an accreting pulsar undergoing steady spin-up/down, the applied torque will depend on the mass accretion rate $\dot{M}$ and the angular momentum of matter in the accretion disk at the magnetospheric radius $r_m$. This torque is given by

$$\tau = \dot{M} \sqrt{GM_n r_m}. \quad (B6)$$

The maximum torque possible will occur when $r_m = r_{co}$, where the corotation radius$^9$ is given by

$$r_{co} = \left( \frac{GM_n P_s^2}{4\pi^2} \right)^{1/3}. \quad (B7)$$

Substituting this value in equation (B6) will provide the expression for the maximum torque possible,

$$\tau_{\text{max}} = \dot{M} \left( \frac{G^2 M_n^2 P_s}{2\pi} \right)^{1/3}. \quad (B8)$$

Clearly, $|\tau| \leq \tau_{\text{max}}$, so using equations (B5) and (B8) and substituting the expression for the moment of inertia from equation (B4), we find the accretion rate will be

$$\dot{M} \geq \frac{2}{5} R_n^2 \dot{P}_s \left( \frac{16\pi^4 M_n}{P_s^3 G^2} \right)^{1/3} \text{ kg s}^{-1}, \quad (B9)$$

substituting this value in equation (B1), we finally obtain the lower limit on the luminosity that will be produced through accretion,

$$L_{X,17} \geq \frac{2R_n \dot{P}_s}{5 \times 10^{16}} \left( \frac{16\pi^4 GM_n^4}{P_s^3} \right)^{1/3}, \quad (B10)$$

which will be in units of $10^{37}$ erg s$^{-1}$ if SI units are used (and the neutron star mass is in $M_\odot$). This equation will allow the estimation of the luminosity associated with an outburst if the average spin-up/down is measured.

One further value that can be estimated is the magnetic field of the neutron star. Rearranging equation (6.24) of Frank et al. (2002) and using the period in place of the frequency, a constraint can be placed on its value,

$$B_{12} \leq \left( 3.4 \times 10^{-4} R_n^{-2} M_n^{-10/7} L_{X,17}^{6/7} \frac{P_s^2}{P_n} \right)^{-7/2}, \quad (B11)$$

where the magnetic field will be in units of $10^{12}$ G if $M_n$ is in $M_\odot$ and $R_n$ in meters. In the present work we assume values for the neutron star’s radius and mass of $R_n = 10^4$ m and $M_n = 1.4 M_\odot$, respectively.

$^9$ The corotation radius is defined as the radius at which matter in the disk is moving at the same speed as the neutron star’s surface.

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