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DISCOVERY OF 16.6 AND 25.5 SECOND PULSATIONS FROM THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We report the serendipitous detection of two previously unreported pulsars from the direction of the Small Magellanic Cloud, with periods of 16.6 and 25.5 s. The detections are based on archival Proportional Counter Array data from the *Rossi X-Ray Timing Explorer*. The observation leading to these detections occurred in 2000 September, extending over 2.1 days with an exposure of 121 ks. A possible identification of the 16.6 s pulsar with an X-ray source (RX J0051.8−7310) seen by both the *ROSAT* and *ASCA* imaging X-ray satellites is presented.

Subject headings: accretion, accretion disks — binaries: general — pulsars: general — X-rays: general

1. INTRODUCTION AND *RXTE* RESULTS

In the course of a survey of archival data from the Proportional Counter Array (PCA) of the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993), we have found evidence for two previously unreported pulsars with periods of 16.6 and 25.5 s. The evidence is based on observations taken on 2000 September 13–15 with the PCA field of view, ~1°.0 FWHM (Jahoda et al. 1996), viewing an area near the southwestern edge of the Small Magellanic Cloud (SMC) centered on $00^h50^m44^s.64$, $-73°16'04''.8$.

The observation in question extended for 2.1 days with minimal interruptions, leading to 68% of the time devoted to source region coverage. Such extended "dense" observations are well suited for sensitive searches for periodic phenomena from relatively faint sources.

The PCA observations used the so-called Good Xenon data mode, in which the arrival of each photon at the detector is time tagged to an accuracy of better than 1 μs. For the timing analysis, the electrical pulses were required to originate in either one of the top two layers (of three) of the PCA, with pulse heights in the X-ray energy range of 2–15 keV. Such an energy and layer selection is effective in improving the signal-to-noise ratio for pulsar detection.

The times of arrival were corrected to the barycenter of the solar system, and a discrete fast Fourier transform (FFT) of these times was performed. The portion of this transform from 0.02 to 0.2 Hz is shown in Figure 1.

There are four distinct frequencies and one second harmonic that are evident in the spectrum of Figure 1. The frequencies, corresponding periods, and Fourier power (normalized to 1) are listed in Table 1. Two of the periods are consistent with those that have been previously reported from this region of the SMC. The 8.9 s period is identified with the same-period pulsation from the Be transient RX J0051.8−7231 (Israel et al. 1997). The 15.7 s period may be identified with the reported 15.3 s period from the SMC transient RX J0052.1−7319 (Finger et al. 2001). The observations reported by Finger et al. for this object occurred 3.8 yr earlier than the *RXTE* observation of Figure 1. The difference in period (2.5%) can be accounted for by a spin-down episode(s), consistent with spin histories of other Be transients (Bildsten et al. 1997); therefore, we regard this identification as reasonable. As for the remaining periods, 16.6 and 25.5 s, we have found no previous reports covering this portion of the sky.

In what follows we present the pulse profiles for both the 16.6 and 25.5 s pulsars and discuss evidence for a possible identification of the 16.6 s pulsar with a *ROSAT* source, RX J0051.8−7310. In the concluding section we discuss the luminosities of sources. If these pulsars are associated with the SMC, as is likely, their discovery further accentuates the remarkable overdensity of binary pulsars in the SMC relative to our own galaxy.

2. PULSE PROFILES

There is evidence for a significant spin-down of the frequency of the 16.6 s pulsar during the course of the *RXTE* observation. We find that the time derivative of the frequency, $\dot{f}$, which maximizes the sum of the power at the fundamental and second harmonics (~0.12 Hz), is $(-4.6 \pm 1.0) \times 10^{-11}$ Hz s^{-1} at a frequency of 0.0603435 Hz. With these values, the sum of the power at the fundamental and second harmonics is 265; with no frequency derivative, the power sum is 218. The pulse profile resulting from these values of f and $\dot{f}$ is shown in top panel of Figure 2. Using the lowest bin of the pulse profile to establish an unpulsed level, we find a pulsed counting rate of 0.60 ± 0.08 photons s^{-1}.

The observed spin-down rate for the 16.6 s pulsar has a characteristic timescale, $f/\dot{f}$, of 41 yr. This value is approximately 60 times shorter than the same quantity for the isolated pulsar with the largest known spin-down rate, the Crab pulsar. It is therefore likely that the observed change in frequency of the 16.6 s pulsar is due to a combination of binary motion of the neutron star around its companion and accretion torques. Further discussion of this point is given in § 4.

The upper limit for a nonzero $\dot{f}$ for the 25.5 s pulsar is 3×10^{-11} Hz s^{-1}. Its pulse profile is shown in bottom panel of Figure 2. Its pulsed counting rate is 0.49 ± 0.08 photons s^{-1}.

3. POSSIBLE IDENTIFICATION OF THE 16.6 s PULSAR

We have examined the public archive of the *ROSAT* satellite for data relevant to the possible identification of either of these newly discovered pulsars. There are four observations taken by the *ROSAT* Position Sensitive Proportional Counter (PSPC) that are within 30′ of the center of the *RXTE* PCA's field of view. Two of the four observations have insufficient exposure (≲2 ks) for a sensitive search for pulsations from any of the relatively faint sources in the field. Both the remaining obser-

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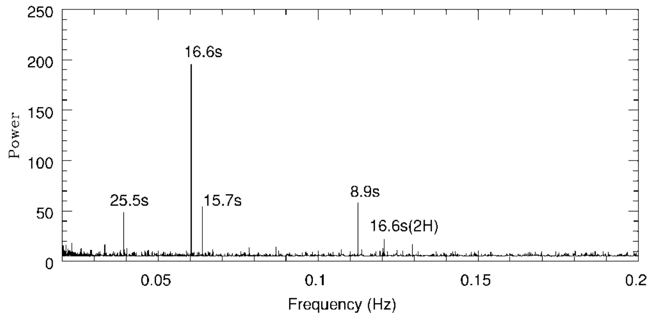

FIG. 1.—FFT of the *RXTE* observation

TABLE 1
FREQUENCIES WITH POWER GREATER THAN 20

Frequency (Hz)	Normalized Power	Period (s)
0.0392305(5)	48	25.5
0.0603395(5)	196	16.6
0.0638610(5)	54	15.7
0.1124010(5)	58	8.90
0.1206855(10)	22	16.6 (2Harm)

vations have similar deep exposures, ∼20 ks. However, one of these (rp500249n00) is significantly more useful than the other (rp600196a01), since the latter observation has a duration more than 3 times as long. For a fixed number of pulsed photons, the detection sensitivity for a pulsar will decline as the length of the observation is increased. This is because the number of independent frequencies required to cover a given frequency range increases with T, where T is the total observation duration. Also, the frequency variations that are to be expected (on the basis of the *RXTE* observations for the 16.6 s pulsar) will further vitiate the sensitivity of long observations. Therefore, we have examined only rp500249n00 for possible counterparts to the *RXTE* sources.

In the field of rp500249n00 there are five sources with counting rates greater than 0.01 counts s^{-1}. None of these five *ROSAT* sources are identified with previously reported pulsars. However, an *ASCA* source, AX J0051.6−7311 (Yokogawa et al. 2000b), which may or may not be the same source as one of the five *ROSAT* sources, RX J0051.8−7310, has reported a 172 s pulsation.

We have Fourier transformed the arrival times of the photons from each of the five *ROSAT* sources with the view of establishing the identity and precise location of either the 16.6 or 25.5 s pulsar. The *ROSAT* observation began on 1992 April 15, 6.8 yr earlier than the *RXTE* observation. In order to account for possible episodes of spin-up and spin-down over that interval, we have searched a range of $\pm 5\%$ around the signal frequencies of 0.06034 and 0.03923 Hz.

To assess the significance of any possible detection, we use a formula first derived by Fisher (1929). This formula gives the probability that a given Fourier power P, taken from a range of n-independent values of power, will be exceeded by chance. Equation (4) of Fisher gives that probability as a series whose leading term $n(1-g)^{n-1}$ is the only term that is significant for our values of P and n. The parameter g is the fraction of the power contained in the term in question. We have used normalized values of power, and thus $g = P/n$. However, since we have used a frequency digitization finer than the independent frequency spacing, $1/T$, we must multiply Fisher's expression by an oversampling factor. For the FFT's we have used a frequency spacing of $\sim 1/5T$, for which an appropriate value of the oversampling factor is 3 (Lewis 1994).

For the 0.039 Hz search region, there are 1060 independent frequencies. None of the five sources showed any power greater than 8 over that region. The probability of a power of 8 or more occurring by chance is therefore (3 oversampling) (5 sources)(1060)$(1-8/1060)^{1059} > 1$. Thus, there is no evidence for the 25.5 s pulsar in this data set.

For the 16.6 s search range it is a somewhat different story. The largest power occurring in the search range for any of the five sources was 14.0. In the search range there are 1630 independent frequencies. The probability that any one of these sources would give a power greater than 14 is therefore (3)(5)(1630) $(1-14/1630)^{1629} = 1.9\%$. Therefore, the source RX J0051.8−7310 is a candidate for identification with the 16.6 s pulsar. The

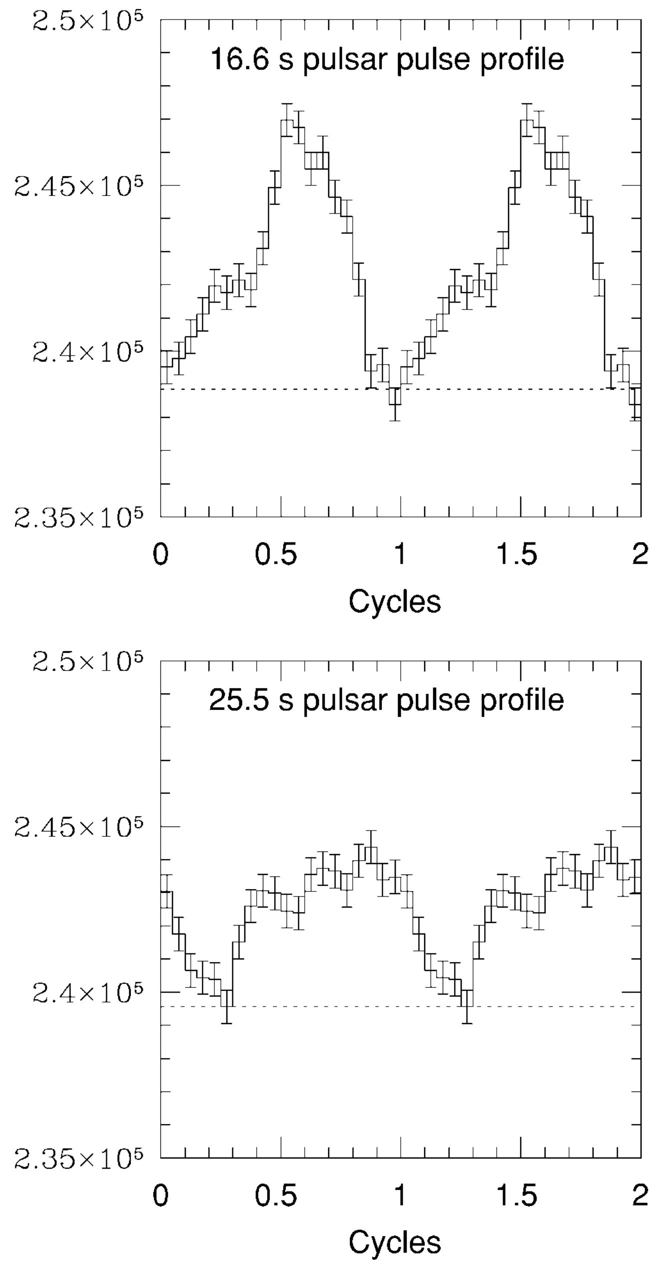

FIG. 2.—Pulse profiles for the 16.6 s (*top panel*) and 25.5 s (*bottom panel*) pulsars, 2–15 keV.

portion of the FFT from 0.02 to 0.2 Hz for this source is shown in Figures 3*a* and 3*b*.

The four peaks evident in the figure near 0.0615 Hz are due to the sparse sampling of the *ROSAT* data, which extended for 270 ks with only 19 ks of exposure. The spacing of the four peaks (0.174 mHz between peaks) is due to the orbital period of the *ROSAT* spacecraft (~95 minutes). We have verified this behavior using a simulation of the observation with an artificial 0.06 Hz signal arranged to mimic the exposure time of the *ROSAT* observation. In the simulation, a "picket fence" of power peaks around 0.06 Hz similar to that in Figure 3*b* was seen, with the separation between adjacent power peaks given by 0.174 mHz.

We have searched for evidence for a possible frequency derivative of the putative signal and find none. Further support for the identification comes from an analysis of the *ASCA* observation (48003010) in which a source, AX J0051.6−7311, is observed. Yokogawa et al. (2000b) identify this source with the *ROSAT* source RX J0051.8−7310 because its location is consistent with that of the *ROSAT* source. They find a significant 172 s pulsation for this source in the *ASCA* data set with no such pulsations seen in the *ROSAT* data. However, the *ASCA* instrument used for the observation, the Gas Imagining Spectrometer, has an angular resolution greater than 1′ (FWHM) in the vicinity of this source, and the position given by Yokogawa et al. (2000b) has an uncertainty of $1'.5$. This raises the possibility of source confusion, particularly given the large number of X-ray sources observed in the SMC. We therefore proceeded to analyze photons from this position with the view of finding (or not finding) confirmation for the *ROSAT* identification of the 16.6 s pulsar.

The *ASCA* observation extended for 2.8 days beginning on 2000 April 11. Again we use a search range of $\pm 5\%$ around the *RXTE* frequency of 0.06034 Hz. Although the *ASCA* observation occurred less than 6 months prior to the *RXTE* observations, episodes of appreciable spin-up or spin-down may occur on rather short timescales (Bildsten et al. 1997). We selected photons from the region of RX J0051.8−7310 and performed an FFT. In the search range, the highest power was 10.1. There were 1450 independent frequencies in the search range, and again we use an oversampling factor of 3. The probability of a power exceeding this value in the search range is therefore (3)(1450) $(1 - 10.1/1450)^{1449} = 17\%$.

We then added a search on a possible frequency derivative, varying it from -1.0×10^{-9} to $+1.0 \times 10^{-9}$ Hz s^{-1}. The spacing between independent values of the frequency derivative is given by $1/2T^2$. Thus, to cover this search range, 230 trials with an additional factor of 3 for oversampling are required. From this search, a power of 19.5 occurred at a frequency of 0.06028 Hz and a frequency derivative of $(9.0 \pm 0.5) \times 10^{-11}$ Hz s^{-1}. The number of independent frequencies searched is therefore $1450 \times 230 = 333{,}500$. The probability of a power of 19.5 being exceeded by chance is therefore (3)(3)(333,500) $(1 - 19.5/333{,}500)^{333{,}499} = 1.0 \times 10^{-2}$. Figures 3*c* and 3*d* show a portion of the FFT from the *ASCA* observation.

We may combine the probabilities of the *ROSAT* and *ASCA* observations to arrive at an overall probability that these two observations are due to chance. That probability is 2×10^{-4}. This number is sufficiently small to suggest that the identification is correct. However, in view of the reported 172 s pulsation seen by Yokogawa et al. (2000b) from nearly the same location, we regard this identification as tentative until it is supported by further imaging X-ray satellite observations.

If the identification is correct, then we may use *ROSAT* HRI data to establish an accurate position under the assumption that the HRI source is identical to the PSPC source. Using a 27 ks exposure from 1996 November (rh600811n00) that produced ~80 signal photons on a background of 10, we find a position of R.A. = $00^{h}51^{m}51^{s}.2$, decl. = $73°10'32''$ with an error of $7''$. We note that this position agrees, within errors, with the position derived from PSPC data alone by Kahabka et al. (1999).

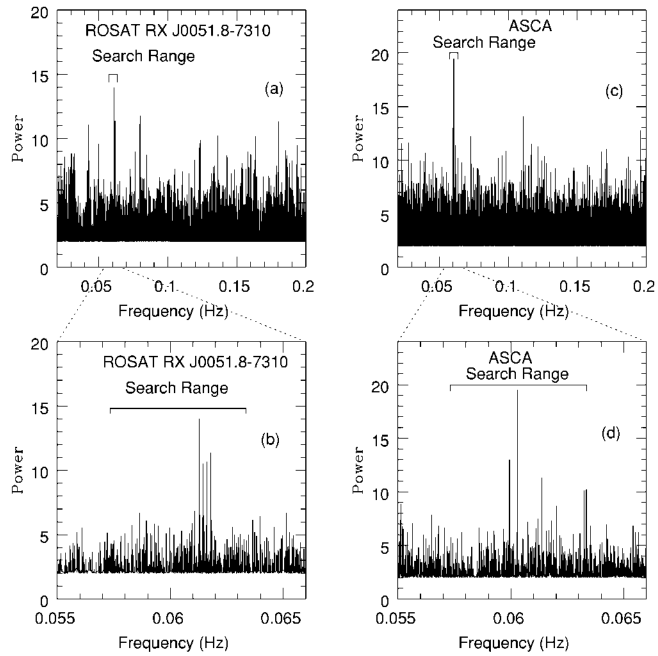

FIG. 3.—*ROSAT* and *ASCA* observations of a possible counterpart to the 16.6 s pulsar. For the *ROSAT* FFT in (*a*) and (*b*), no frequency derivative is used. For the *ASCA* FFT in (*c*) and (*d*), a frequency derivative of $(9.0 \pm 0.5) \times 10^{-11}$ Hz s^{-1} is used.

4. DISCUSSION

For the 25.5 s pulsar we derive a pulsed flux value of $(6.9 \pm 0.8) \times 10^{-12}$ (2–15 keV) under model assumptions of a power-law spectrum with an energy index of −2.0 and a hydrogen column density of 1.0×10^{21} atoms cm^{-2}. Under the same assumptions, the 16.6 pulsar flux is $(8.5 \pm 1.1) \times 10^{-12}$ (2–15 keV). At the distance of the SMC (nominally 60 kpc), these pulsed fluxes correspond to isotropic luminosities of 3.0×10^{36} and 3.7×10^{36} ergs s^{-1}. These fluxes are a few percent of the Eddington luminosity (2×10^{38} ergs s^{-1}) for a 1.4 $M_\odot$ object.

Two arguments can be made to support the idea that at least one if not both of these pulsars are binary. Isolated pulsars with periods greater than 10 s have yet to be seen. In addition, there is a significant nonzero period derivative for the 16.6 s pulsar with a spin-up timescale of 41 yr. Further analysis of existing and future *RXTE* observations may be able to constrain possible orbital parameters for this object. If these objects are Be transients, we may use the empirical correlation first noted by Corbet (1986) between spin period and orbital period for such objects. For spin periods in the range 15–20 s, orbital periods in the range 30–50 days are indicated by this correlation. Known Be transients with these orbital periods (see Bildsten et al. 1997) have an orbital size ($a \sin i$) in the range 50–200 lt-s. With these parameters, values of $|\dot{f}|$ as large as several times 10^{-10} Hz s^{-1} are obtained, easily accommodating the range of $\dot{f}$-values seen in the *RXTE*, *ROSAT*, and *ASCA* data sets.

We may use the theoretical relation between spin-up rate $\dot{P}$, spin period P, and luminosity L, derived by Ghosh & Lamb (1979), to derive a characteristic value of the equilibrium spin-up rate due to an accretion torque. From Figure 9 of Ghosh & Lamb (1979), with $L = 3.7 \times 10^{36}$ ergs s^{-1}, a spin-up rate $\dot{f}$ of 1.1×10^{-12} Hz s^{-1} results. This spin-up rate in absolute value is only about one-quarter the spin-down rate observed for the 16.6 s pulsar in the *RXTE* data. This supports the idea that much of the frequency change observed for the 16.6 s pulsar on a timescale of a few days is due to orbital motion.

If these pulsars are binaries in the SMC, their discovery further accentuates the dramatic difference between the SMC and our Galaxy with regard to the population of such systems. This fact has been noted by several authors (Schmidtke et al. 1999; Yokogawa et al. 2000a).

In a recent compilation of known X-ray pulsars,[4] there are 18 X-ray pulsar binaries listed for the SMC, all of which are either high mass or transient and are therefore likely to be high-mass systems. We cannot say whether these newly discovered pulsars are of high or low mass. However, if they are high-mass pulsars, then this increases the number of such systems in the SMC to 20. For the Galaxy, the corresponding number is 40. Therefore, using a mass ratio of the SMC to the Galaxy of 1/100, this suggests that such systems are overabundant by a factor of ~50 relative to the Galaxy. This simple analysis ignores important issues regarding the uncertain coverage of the Galaxy for transient X-ray binaries versus the relatively complete coverage of the SMC. It also ignores differences in X-ray absorption effects. Nevertheless, pending careful analysis of such issues, there appears to be a significant overabundance of high-mass binaries in the SMC relative to the Galaxy. Since high-mass X-ray binaries have lifetimes of $\sim 10^{-3}$ the age of the Galaxy and possibly the SMC, this difference between the SMC and the Galaxy may point to a rather recent outburst of star formation in the SMC within the past $\sim 10^{7}$ yr. Yokogawa et al. (2000a) reach a similar conclusion.

[4] See http://gammaray.msfc.nasa.gov/batse/pulsar/asm.pulsars.html.

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REFERENCES

Bildsten, L., et al. 1997, ApJS, 113, 367
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Corbet, R. H. D. 1986, MNRAS, 220, 1047
Finger, M. H., Macomb, D. J., Lamb, R. C., Prince, T. A., Coe, M. J., & Haigh, N. J. 2001, ApJ, 560, 378
Fisher, R. A. 1929, Proc. R. Soc. London A, 125, 54
Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296
Israel, G. L., Stella, L., Angelini, L., White, N. E., Giommi, P., & Covino, S. 1997, ApJ, 484, L141
Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., & Morgan, E. H. 1996, Proc. SPIE, 2808, 59
Kahabka, P., Pietsch, W., Filipovic, M. D., & Haber, F. 1999, A&AS, 136, 81
Lewis, D. A. 1994, in Statistical Methods for Physical Science, ed. J. L. Stanford & S. B. Vardeman (San Diego: Academic), 367
Schmidtke, P. C., Cowley, A. P., Crane, J. D., Taylor, V. A., McGrath, T. K., Hutchings, J. B., & Crampton, D. 1999, AJ, 117, 927
Yokogawa, J., Imanishi, K., Tsujimoto, M., Nishiushi, M., Koyama, K., Nagase, F., & Corbet, R. H. D. 2000a, ApJS, 128, 491
Yokogawa, J., Imanishi, K., Ueno, M., & Koyama, K. 2000b, PASJ, 52, L73