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Orbital Evolution Measurement of the Accreting Millisecond X-ray Pulsar SAX J1808.4–3658

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Abstract. We present results from a pulse timing analysis of the accretion-powered millisecond X-ray pulsar SAX J1808.4–3658 using X-ray data obtained during four outbursts of this source. Extensive observations were made with the proportional counter array of the Rossi X-ray Timing Explorer (RXTE) during the four outbursts that occurred in 1998, 2000, 2002 and 2005. Instead of measuring the arrival times of individual pulses or the pulse arrival time delay measurement that is commonly used to determine the orbital parameters of binary pulsars, we have determined the orbital ephemeris during each observation by optimizing the pulse detection against a range of trial ephemeris values. The source exhibits a significant pulse shape variability during the outbursts. The technique used by us does not depend on the pulse profile evolution, and is therefore, different from the standard pulse timing analysis. Using 27 measurements of orbital ephemerides during the four outbursts spread over more than 7 years and more than 31,000 binary orbits, we have derived an accurate value of the orbital period of 7249.156862(5) s (MJD = 50915) and detected an orbital period derivative of $(3.14 \pm 0.21) \times 10^{-12}$ s s^{-1}. We have included a table of the 27 mid-eclipse time measurements of this source that will be valuable for further studies of the orbital evolution of the source, especially with ASTROSAT. We point out that the measured rate of orbital period evolution is considerably faster than the most commonly discussed mechanisms of orbital period evolution like mass transfer, mass loss from the companion star and gravitational wave radiation. The present time scale of orbital period change, 73 Myr is therefore likely to be a transient high value of period evolution and similar measurements during subsequent outbursts of SAX J1808.4–3658 will help us to resolve this.

Key words. Stars: neutron stars—pulsars: individual (SAX J1808.4–3658), magnetic fields—X-rays: binaries—accretion.

1. Introduction

In accretion-powered binary X-ray pulsars, the orbital evolution can often be measured using pulse timing. Though the accretion-powered X-ray pulsars often have variable and broad pulse profiles, the uncertainties in the measurement of orbital ephemeris is usually much smaller than the rate of advancement or delay of the ephemeris in a few years time scale. In the last three decades, repeated measurements of the orbital ephemeris of many binary X-ray pulsars have led to accurate determination of the orbital evolution time scales (Cen X-3: Nagase *et al.* 1992, Paul *et al.* 2007; LMC X-4: Naik & Paul 2004; SMC X-1: Wojdowski *et al.* 1998, Paul *et al.* 2007; 4U 1538–52: Mukherjee *et al.* 2006; Her X-1: Paul *et al.* 2004). In some of the non-pulsating X-ray binaries, the orbital evolution has been measured using eclipse timing or non-eclipsing orbital modulation of the X-ray light curve (Cyg X-3: Singh *et al.* 2002; EXO 0748-676: Wolff *et al.* 2002; 4U 1822-371: Parmar *et al.* 2000). In the High Mass X-ray Binaries (HMXB), the orbital evolution time-scale is in the range of 10^5–10^6 years and in the low mass X-ray binaries it is more than 10^8 years. In HMXB sources, the orbital evolution is believed to be driven by tidal interaction and mass loss from the companion star while in LMXB sources, it is due to mass transfer or magnetic interaction between the two stellar components. In very compact X-ray binaries, like some of the millisecond X-ray pulsars with orbital period of about 40 minutes, orbital evolution due to gravitational wave radiation may also become dominant.

All the X-ray sources mentioned above are persistent X-ray pulsars while all the millisecond accreting X-ray pulsars are transient X-ray sources. It is therefore difficult to measure the orbital evolution of the later class of sources. Only one of the eight accreting millisecond X-ray pulsars, SAX J1808.4–3658 has shown repeated outbursts that makes it suitable for investigation of orbital evolution. SAX J1808.4–3658 is the first of the eight known accretion-powered millisecond pulsars. It was discovered during an outburst in 1996 by the *Beppo*SAX Wide Field Camera (in 't Zand *et al.* 1998). The X-ray transient was again detected during an outburst in April 1998 (Marshall 1998) with the Proportional Counter Array (PCA) on-board the Rossi X-ray Timing Explorer (RXTE). During this outburst, coherent millisecond X-ray pulsations at 401 Hz were detected, first in any accretion-powered X-ray pulsar (Wijnands & van der Klis 1998). From the same observation a binary period of 2 h was also measured (Chakrabarty & Morgan 1998). Outbursts were again detected from SAX J1808.4–3658 in 2000 (van der Klis *et al.* 2000; Wijnands *et al.* 2001), 2002 (Wijnands 2004 for a review) and 2005 (Wijnands 2005).

Chakrabarty & Morgan (1998) had measured the orbital parameters using the observations made by the RXTE during the 1998 outbursts. The orbital parameters were subsequently revised by Papitto *et al.* (2005), who reduced the error in the earlier reported orbital period by an order of magnitude. Papitto *et al.* (2005) performed the timing analysis for observations spanning 5 years, covering the outbursts that occurred in 1998, 2000 and 2002. However, the data from these three outbursts were insufficient for the determination of orbital period derivative and Papitto *et al.* (2005) reported an orbital period derivative in the range of -6.6×10^{-12} s s^{-1} to 0.8×10^{-12} s s^{-1}.

In the present work described in the following chapters, we have analyzed all the long RXTE–PCA observations of this source during the four outbursts. We have made an accurate measurement of the orbital period evolution of this compact X-ray binary system during the period 1998–2005.

2. Observations and analysis

We have analyzed all the sufficiently long archival data from observations of the millisecond pulsar SAX J1808.4–3658 using the RXTE–PCA. The PCA consists of an array of five collimated xenon/methane multi-anode proportional counter units (PCU) with a total photon collection area of 6500 cm^2 (Jahoda *et al.* 1996). Data used in the present analysis were taken from the event mode of PCA with a time resolution of 122 μs and 64 channel energy information in the entire PCA energy band of 2–60 keV. Table 1 lists all the observation IDs used in the present work along with the average number of PCUs available during each observation and the good exposure time for each of the observations.

Table 1. Log of RXTE observations analyzed in the present work.

Outburst	Data range (MJD)	Observation IDs	Average number of PCU ON	Exposure time (ks)
1998	50914–50932	30411-01-05-00	4–5	15.8
		30411-01-06-00	3–4	24.9
		30411-01-07-00	3–4	5.5
		30411-01-08-00	3–4	17.9
		30411-01-09-00	3–4	17.2
		30411-01-09-02	3–4	14.4
		30411-01-09-04	3–4	13.5
		30411-01-10-00	3–4	8.9
		30411-01-10-01	3–4	7.3
2000	51585–51593	40035-01-02-08	3–4	6.5
		40035-01-03-00	4–5	8.2
2002	52564–52573	70080-01-01-020	2–3	20.1
		70080-01-01-02	3.0	
		70080-01-02-04	3–4	17.3
		70080-01-02-06	3–4	17.2
		70080-01-02-08	3–4	17.2
		70080-01-02-14	2–3	13.8
		70080-01-03-02	3–4	17.4
2005	53524–53537	91056-01-02-01	2–3	17.5
		91056-01-02-02	3–4	13.9
		91056-01-02-03	3–4	20.4
		91056-01-02-04	2–3	13.8
		91056-01-02-05	2–3	17.2
		91056-01-02-06	3–4	10.2
		91056-01-02-08	3–4	13.8
		91056-01-03-00	3–4	13.2
		91056-01-03-06	2–3	13.8
		91056-01-03-10	3–4	13.5

The source count rate during most of the observations varied from 500–900 counts/s. But during the 2000 outburst, the count rate was lower, about 270 counts/s. Observations shorter than a duration of 5 ks were not used in this analysis, as they would not provide a good measurement of the orbital ephemeris.

Orbital parameters of binary X-ray pulsars are usually determined by measuring the delay in arrival times of individual or a group of pulses due to orbital motion. The maximum group length is kept small so as to avoid smearing of the pulses due to orbital motion. In the case of millisecond accreting pulsars, especially when the source is in low intensity state, folding very short data segments may lead to non-detection of pulses or significant error in determination of the pulse phase (or arrival time). Therefore, to detect the pulsations even in the low state and also to simultaneously measure the local orbital ephemeris from data stretches comparable to the orbital period, we adopted a technique in which the photon arrival times are corrected for the binary motion. For this correction, a range of trial ephemerides were taken around the value extrapolated from earlier measurements (Chakrabarty & Morgan 1998; Papitto *et al.* 2005) and the folded pulse profiles were analyzed to determine the most appropriate orbital ephemeris. The orbital period (7249.1569 s) which was initially taken to be a constant and the orbital semi-amplitude values (62.809 lt–ms) were also taken from the same earlier reports. Though the orbital period is evolving, the rate of evolution is too small to affect the local orbital motion correction. We developed this technique for orbital evolution studies of X-ray pulsars and a similar technique has also been applied to *Beppo*-SAX, ASCA and IXAE observations of several sources like LMC X-4, SMC X-1 and XTE J1946 + 27 (Paul *et al.* 2001, 2002; Naik & Paul 2004).

From each observation listed in Table 1, we generated energy resolved pulse folded light curves using the FASEBIN tool in the Ftools version 5.2. This tool corrects the photon arrival times for the orbital motion of the pulsar as described above and also converts the photon arrival times to the solar system barycenter. The output is a two-dimensional histogram of photon count rate against the pulse phase and energy. It applies all the known RXTE clock corrections and converts the photon arrival times to the solar system barycenter using JPL DE-200 ephemeris. The position coordinates used were R.A. $= 18^h\ 08^m\ 27^s.6$ and dec $= -36^\circ\ 58'\ 43''.3$. This is the best estimate for the source position and is compatible with the optical counterpart (Rupen *et al.* 2002; Giles *et al.* 1999).

We have then used another Ftool – FBSSUM, which enables us to use the output of FASEBIN and integrate the pulse profiles over different energy ranges. Figure 1 shows a sample of the pulse profiles in the 2–10 keV energy band during each of the four outbursts obtained with the ephemerides determined from the present analysis. The technique used in this analysis is independent of the pulse profile changes that are seen in this pulsar. The pulse profiles thus obtained were fitted with a constant and the χ^2 was measured as a function of the orbital ephemeris (or the time of passage of the neutron star at the ascending node T^*). This variation of χ^2 with the orbital ephemeris is shown in Fig. 2 for one of the observations. We made a Gaussian fit to this χ^2 distribution and the best value of the orbital ephemeris (T^*) and its error were determined for each set of observations. We took a long dataset from one of the 1998 observations and measured T^* and its error using the pulse profiles in different energy ranges. The energy range of 2–10 keV was chosen for all further analysis because this energy gave us the minimum error in measurement of T^*. We also independently measured the spin period of the pulsar during each of the outbursts. The T^* obtained for each of the dataset and

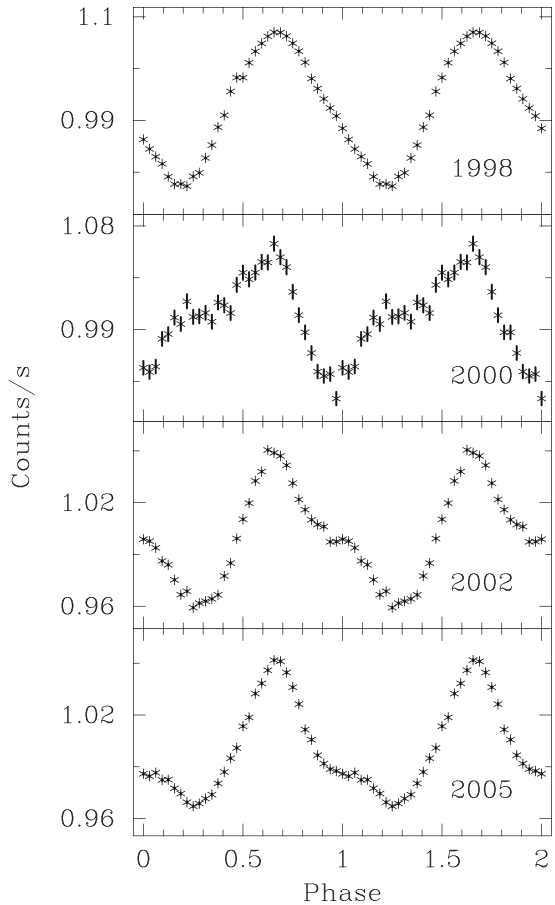

Figure 1. X-ray pulse profile of the millisecond pulsar SAX J1808.4–3658 obtained from observations with RXTE during the four outbursts are shown here in the energy band of 2–10 keV.

the corresponding 1σ measurement uncertainty are shown in Table 2 against the corresponding binary orbit number $N (N = \mathrm{int}[(T^*–T_0^*)/P_{\mathrm{orb}}]$, where T_0^* is the time of passage of the neutron star at the ascending node at the reference time (start of the 1998 observation). The orbital ephemerides history clearly shows a quadratic nature. To estimate the orbital period and the period derivative valid through the entire outburst history of the millisecond pulsar, we fitted a quadratic curve to the ephemerides history. The parameters obtained for the best fitted curve are given in Table 3. We have obtained an orbital period of 7249.156862(5) s on MJD = 50914.878425(1) and an orbital period derivative of $(3.14 \pm 0.21) \times 10^{-12}$ s s^{-1}. We subtracted the best fitted linear component from the ephemerides history and the residual is plotted in Fig. 3. It clearly shows the quadratic component.

3. Discussion

We have performed a pulse timing analysis of the accretion-powered millisecond pulsar SAX J1808.4–3658 during the four X-ray outbursts. The RXTE–PCA observations

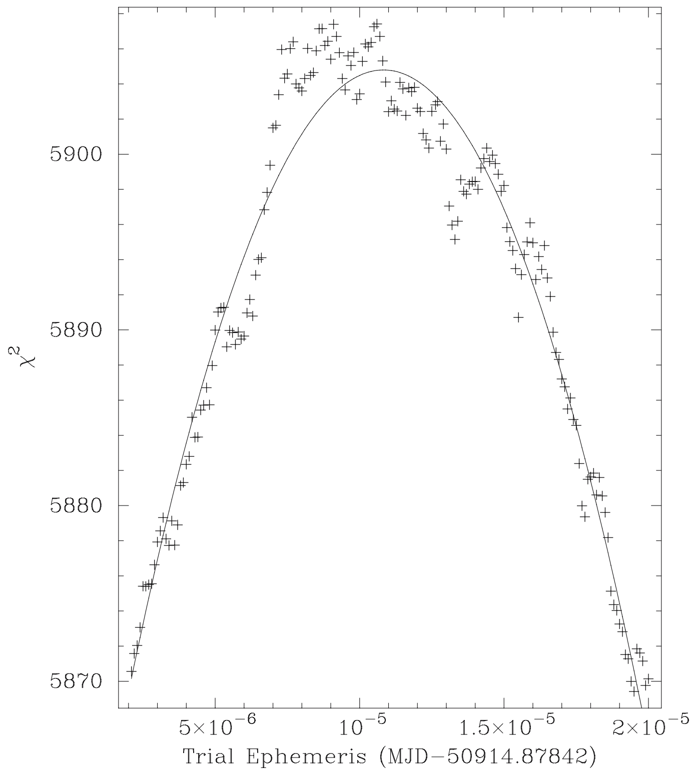

Figure 2. The variation of χ^2 as a function of the trial ephemeris for one of the RXTE observations of the 1998 outburst from SAX J1808.4–3658.

used for the present work covered a span of more than 7 years and more than 31,000 binary orbits. The orbital parameters were measured by correcting the light curves for the binary motion of the pulsar and then optimizing the pulse detection. We have obtained an orbital period of 7249.156862(5) s and a significant orbital period derivative of $(3.14 \pm 0.21) \times 10^{-12}$ s s^{-1}. We have been able to reduce the error in the measurement of the orbital period by 2 orders of magnitude as compared to the published reports (Papitto *et al.* 2005). The observed orbital period derivative implies an orbital evolution time-scale of $(P_{\rm orb}/\dot{P}_{\rm orb})$ 73 Myr. Analysing the same set of RXTE-PCA observations with different/independent analysis techniques, Di Salvo *et al.* (2007) and Hartman *et al.* (2007) have also obtained a large orbital period derivative. Hartman *et al.* (2007) have used the technique of measuring the arrival times of individual pulses to determine the orbital evolution. But, the standard pulse timing analysis has inherent limitations when there is a pulse profile evolution, as in the case with SAX J1808.4–3658. The present work is independent of the pulse profile evolution observed in this pulsar.

The evolution of close binaries crucially depends on the exchange of mass and the exchange of angular momentum between the components of the interacting binaries. A change in the orbital angular momentum results in the orbital evolution of the binary system. A significant mass loss may occur from the binary system through stellar winds or a sudden catastrophic event like a supernova explosion on one of the components of

Table 2. Variation of T^* as a function of the orbit cycle.

Orbit no.	T^* (MJD)	1σ uncertainty in measurement of T^*
0	50914.8784309	0.0000026
0	50914.8784342	0.0000047
107	50923.8559762	0.0000041
140	50926.6247502	0.0000033
153	50927.7154825	0.0000043
164	50928.6384020	0.0000045
176	50929.6452306	0.0000045
188	50930.6520566	0.0000053
211	50932.5818133	0.0000054
7997	51585.8449364	0.0000068
8089	51593.5639393	0.0000036
19657	52564.1454912	0.0000056
19680	52566.0752480	0.0000039
19692	52567.0820713	0.0000044
19704	52568.0888978	0.0000037
19739	52571.0254824	0.0000046
19774	52573.9620552	0.0000055
31105	53524.6588101	0.0000042
31117	53525.6656400	0.0000038
31128	53526.5885608	0.0000047
31141	53527.6792960	0.0000062
31152	53528.6022180	0.0000055
31164	53529.6090365	0.0000033
31176	53530.6158673	0.0000052
31186	53531.4548906	0.0000052
31235	53535.5661091	0.0000068
31257	53537.4119610	0.0000106

the binary. This could result in a change in the energy of the binary system. A stellar wind from the co-rotating companion star carries away the angular momentum which can cause an evolution of the orbit of the binary system on a time-scale of a few Myr (Kelley 1986).

The total energy of the system may also decrease due to tidal friction. The time-scales of orbital evolution due to tidal interaction between the stars' rotation and their mutual orbit, ranges from a few Myr to more than a Hubble time ($\sim 10^{10}$ yr) which is much greater than the observed orbital evolution time-scale of 73 Myr. But tides do not always lead to rapid circularization during the early phase of mass transfer. Thus, phases of episodic mass transfer may occur at the periastron passages and may persist for a longer period. But since the source is observed to be active for a short period of time, therefore, mass transfer cannot be the decisive factor for the observed orbital evolution.

Table 3. Orbital parameters of SAX J1808.4–3658.

Parameter	Chakrabarty & Morgan (1998)	Papitto *et al.* (2005)	Best fit value from the present analysis
$P_{\rm orb}$ (s)	7249.119(1)	7249.1569(1)	7249.156862(5)
$\dot{P}_{\rm orb}(10^{-12}$ s s$^{-1})$	–	$-6.6 \leq \dot{P}_{\rm orb} \leq 0.8$	3.14(0.21)
T_0^* (MJD)	50914.899440(1)^a	50914.878468(4)	50914.878425(1)

$^a T_{pi/2}$ value.

Note: The numbers in parentheses are the 1σ uncertainties in the last significant figure.

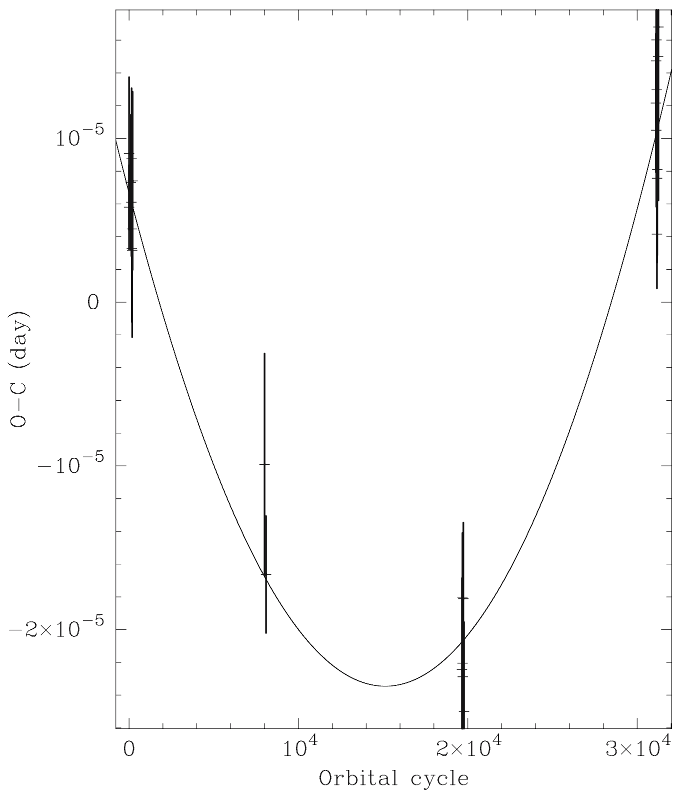

Figure 3. The time of ascending node of SAX J1808.4–3658 has been plotted here as a function of the orbital cycle, relative to an orbital period of 0.083902278 d. The curvature of the O–C curve is a measure of the orbital period derivative of the binary system.

The orbital energy of a binary is also expected to diminish through gravitational wave radiation, thus decreasing the orbital period. The rate of change of the orbital period due to the gravitational wave radiation, in a binary system with a conservative mass transfer, is of the order of 10^{-13} s s^{-1} (Verbunt 1993). But from the present analysis, we have obtained an orbital period derivative of $(3.14 \pm 0.21) \times 10^{-12}$ s s^{-1}, which is higher by more than a factor of 10. It implies that the gravitational wave radiation is not enough to explain the observed parameters.

Further, Chakrabarty & Morgan (1998), have proposed that SAX J1808.4–3658 behaves as a black widow pulsar during the periods of X-ray quiescence and is evaporating its companion star. But the time-scales of the orbital evolution due to conservative mass transfer is of the order of a few Gyr. Therefore, mass loss during quiescence is not sufficient to explain the rapid orbital evolution of the system.

In view of the results presented here, it can be proposed that either the tidal effect in the system is strong or the rapid orbital evolution is a transient high value and an analysis of any further episode of an outburst from SAX J1808.4–3658 can explain the observed evolutionary scenarios.

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References

Chakrabarty, D., Morgan, E. H. 1998, *Nature*, **394**, 346.

Di Salvo, T., Burderi, L., Riggio, A., Papitto, A., Menna, M. T. 2007, *MNRAS*, submitted (astro–ph/0708.0498).

Giles, A. B., Hill, K. M., Greenhill, J. G. 1999, *MNRAS*, **304**, 47.

Hartman, J. M., Patruno, A., Chakrabarty, D., Kaplan, D. L., Markwardt, C. B., Morgan, E. H., Ray, P. S., van der Klis, M., Wijnands, R. 2007, *ApJ*, submitted (astro–ph/0708.0211).

in 't Zand, J. J. M., Heise, J., Muller, J. M., Bazzano, A., Cocchi, M., Natalucci, L., Ubertini, P. 1998, *A&A*, **331**, L25.

Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayor, T., Zhang, W., Morgan, E. H. 1996, *Proc. SPIE*, **2808**, 59.

Kelley, R. L. 1986, In: The Evolution of Galactic X-ray Binaries (eds) Trumper, J., Lewin, W. H. G., Brinkmann, W. (Dordrecht, Reidel) 75.

Marshall, F. E. 1998, *IAUC*, 6876.

Mukherjee, U., Raichur, H., Paul, B., Naik, S., Bhatt, N. 2006, *JApA*, **27**, 411.

Nagase, F., Corbet, R. H. D., Day, C. S. R., Inoue, H., Takeshima, T., Yoshida, K., Mihara, T. 1992, *ApJ*, **396**, 147.

Naik, S., Paul, B. 2004, *ApJ*, **600**, 351.

Papitto, A., Menna, M. T., Burderi, L., Di Salvo, T., D'Antona, F., Robba, N. R. 2005, *ApJ*, **621**, L113.

Parmar, A. N., Oosterbroek, T., DelSordo, S., Segreto, A., Santangelo, A., Dal Fiume, O., Orlandini, M. 2000, *A&A*, **356**, 175.

Paul, B., Agrawal, P. C., Mukerjee, K., Rao, A. R., Seetha, S., Kasturirangan, K. 2001, *A&A*, **370**, 529.

Paul, B., Nagase, F., Endo, T., Dotani, T., Yokogawa, J., Nishiuchi, M. 2002, *ApJ*, **579**, 411.

Paul, B., Naik, S., Bhatt, N. 2004, *Nuclear Physics B – Proceedings Supplements*, **132**, 548.

Paul, B., Raichur, H., Naik, S., Bhatt, N. 2007, The Extreme Universe in the Suzaku Era, 2006, Kyoto (ed.) K. Hayashida.

Rupen, M. P., Dhawan, V., Mioduszewski, A. J., Stappers, B. W., Gaensler, B. M. 2002, *IAUC*, **7997**, 2.

Singh, N. S., Naik, S., Paul, B., Agrawal, P. C., Rao, A. R., Singh, K. Y. 2002, *A&A*, **392**, 161S.

van der Klis, M., Chakrabarty, D., Lee, J. C., Morgan, E. H., Wijnands, R., Markwadt, C. B., Swank, J. H. 2000, *IAUC*, 7358.

Verbunt, F. 1993, *ARA & A*, **31**, 93.

Wijnands R., van der Klis, M. 1998, *Nature*, **394**, 344.

Wijnands, R., Mendez M., Markwadt, C., van der Klis, M., Chakrabarty, D., Morgan, E. 2001, *ApJ*, **560**, 892.
Wijnands, R. 2004, In: *AIP Conf Proc.*, **714**, 209.
Wijnands, R. 2005, In: *Pulsar New Research*, Nova Science Publishers (NY).
Wojdowski, P., Clark, G. W., Levine, A. M., Woo, J. W., Zhang, S. N. 1998, *ApJ*, **502**, 253.
Wolff, M. T., Hertz, P., Wood, K. S., Ray, P. S., Bandhopadhyay, R. M. 2002, *ApJ*, **575**, 384.