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Evidence of a change in the long-term spin-down rate of the X-ray pulsar 4U 1907+09

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ABSTRACT

We analysed *RXTE* archival observations of 4U 1907+09 between 1996 February 17 and 2002 March 6. The pulse timing analysis showed that the source stayed at almost constant period around 1998 August and then started to spin-down at a rate of $(-1.887 \mp 0.042) \times 10^{-14}$ Hz s^{-1} which is ∼0.60 times lower than the long-term (∼15 yr) spin-down rate. Our pulse-frequency measurements for the first time resolved significant spin-down rate variations since the discovery of the source. We also presented orbital phase resolved X-ray spectra during two stable spin-down episodes during 1996 November–1997 December and 2001 March–2002 March. The source has been known to have two orbitally locked flares. We found that X-ray flux and spectral parameters except hydrogen column density agreed with each other during the flares. We interpreted the similar values of X-ray fluxes as an indication of the fact that the source accretes not only via transient retrograde accretion disc but also via the stellar wind of the companion, so that the variation of the accretion rate from the disc does not cause significant variation in the observed X-ray flux. Lack of significant change in spectral parameters except hydrogen column density was interpreted as a sign of the fact that the change in the spin-down rate of the source was not accompanied by a significant variation in the accretion geometry.

Key words: accretion, accretion discs – stars: neutron – X-rays: binaries – X-rays: individual: 4U 1907+09.

1 INTRODUCTION

The X-ray source 4U 1907+09 is an accretion-powered X-ray pulsar accreting plasma from a blue supergiant companion star. Since its discovery in the Uhuru survey (Giacconi et al. 1971), it has been observed by various X-ray observatories including *Ariel V* (Marshall & Rickets 1980), *Tenma* (Makishima et al. 1984), *EXOSAT* (Cook & Page 1987), *Ginga* (Makishima & Mihara 1992; Mihara 1995), *BeppoSAX* (Casumano et al. 1998), XMPC (Chitnis et al. 1993), *IXAE* (Mukerjee et al. 2001) and *RXTE* (in't Zand, Strohmayer & Baykal 1997, 1998b; in't Zand, Baykal & Strohmayer 1998a; Baykal et al. 2001; Roberts et al. 2001). Marshall & Rickets (1980) determined the orbital period to be 8.38 d using *Ariel V* observations. They also found two flares, namely a primary and a secondary occurring near periastron and apastron, and *EXOSAT* and *RXTE* observations (in't Zand et al. 1998a,b) have clearly shown that these flares are locked to orbital phases separated by half an orbital period. Using *Tenma* observations, Makishima et al. (1984) also found the pulse period of the source to be 437.5 s. Makishima et al. (1984) and Cook & Page (1987) discussed the possibility that the two flares are caused by an equatorial disc-like envelope (circumstellar disc) around the companion star. When the neutron star crosses the disc, the mass-accretion rate on to the neutron star increases temporarily. We expect to see two peaks while the neutron star passes twice through the circumstellar disc of the companion star in every cycle. We also expect a transient accretion disc formation around the neutron star while the neutron star passes through this circumstellar disc. For the formation of the circumstellar disc around the companion star, the companion must most likely be a Be-type star. Recent optical observations showed that the optical companion of 4U 1907+09 is an O8/O9 supergiant with a dense stellar wind (Cox, Kaper & Mokiem 2005). Formation of a transient accretion disc around the neutron star as a result of disruption of the dense stellar wind of a massive companion is quite possible as well (Blondin et al. 1990).

The timing measurements from *EXOSAT* (Cook & Page 1987) and *RXTE* observations (in't Zand et al. 1998a,b; Baykal et al. 2001) showed continuous spin-down of the neutron star. The source was found to be spinning down almost at a rate of $\dot{\nu} = (-3.54 \pm 0.02) \times 10^{-14}$ Hz s^{-1} for more than 15 yr (Baykal et al. 2001). Timing analysis of *RXTE* (in't Zand et al. 1998a,b) and *IXAE* (Mukerjee et al. 2001) observations of 4U 1907−09 also revealed transient oscillations with periods of about 18.2 and 14.4 s, respectively. These transient oscillations were suggested to be related to the

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Table 1. Observation list for 4U 1907+09.

Time of observation start–end (yyyy mm dd–yyyy mm dd)	*RXTE* proposal ID	Number of observations
1996 February 17–1996 February 23	10155	8
1996 November 25–1997 December 14	10154–20146	24
1998 July 26–1998 October 01	30093	14
2001 March 10–2002 March 06	60061	38

presence of a transient retrograde accretion disc which is also responsible for the slowing down of the pulsar.

In this paper, we present the results of timing and spectral studies of archival *RXTE*-PCA observations of 4U 1907+09, and report a change in the spin-down rate of this system.

2 INSTRUMENT AND OBSERVATIONS

The Proportional Counter Array (PCA) (Jahoda et al. 1996) onboard the *RXTE* consists of five identical proportional counter units (PCUs) coaligned to the same point in the sky, with a total effective area of approximately 6250 cm^2, and a field of view of $\sim 1^0$ full width at half-maximum (FWHM), operating in the 2–60 keV energy range. The number of active PCUs is varied between one and five during the observations. Observations after 2000 May 13 belong to the observational epoch for which background level for one of the PCUs (PCU0) increased due to the fact that this PCU started to operate without a propane layer. Latest combined background models (CMs) were used together with FTOOLS 6.0 to estimate the appropriate background.

The *RXTE*-PCA observations used in this work are listed in Table 1.

3 ANALYSIS AND RESULTS

3.1 Timing analysis

In order to obtain background-subtracted light curves, we generated the background using the background estimator models based on the rate of very large solar events, spacecraft activation and cosmic X-ray emission with the standard PCA analysis tools. Then, we subtracted background light curves from the source light curves obtained from the event data. The background-subtracted light curves were also corrected to the barycentre of the Solar system and to the binary orbital motion of 4U 1907+09 around its companion. For the correction of binary orbital motion, we used the orbital parameters deduced by in't Zand et al. (1998a). In the timing analysis, we fold the light curve outside the intensity dips from long data string around 7–10 ks on statistically independent trial periods (Leahy et al. 1983). A template pulse profile was constructed by folding the data on the period giving the maximum χ^2. Template pulse profile was represented by its Fourier harmonics (Deeter & Boynton 1985) and cross-correlated with the harmonic representation of average pulse profiles from each observation. The pulse phases obtained from the cross-correlation analysis are presented in Fig. 1.

In order to estimate pulse-frequency derivatives, the pulse phases are fitted to the quadratic polynomial

$$\delta\phi = \phi_o + \delta\nu(t - t_o) + \frac{1}{2}\dot{\nu}(t - t_o)^2, \quad (1)$$

where $\delta\phi$ is the pulse phase offset deduced from the pulse timing analysis, t_o is the mid-time of the observation, ϕ_o is the phase offset at t_o, $\delta\nu$ is the deviation from the mean pulse frequency (or additive correction to the pulse frequency), and $\dot{\nu}$ is the pulse-frequency derivative of the source. The pulse phases and the residuals of the fit after the removal of the quadratic polynomial are also presented in Fig. 1. Table 2 presents the timing solution of 4U 1907+09.

The pulse-frequency derivative from the sequence of 19 pulse phases spread over 360 d was measured as $\dot{\nu} = (-1.887 \pm 0.042) \times 10^{-14}$ Hz s^{-1}. This value approximately $\sim$0.60 times lower than previous measurements of pulse-frequency derivatives which were measured over 383-d time-span (Baykal et al. 2001). In this and the previous observations Baykal et al. (2001), time-spans of the observations are similar ($\sim$ over an year) and in both, observations possess low-timing noise. However, the spin-down rate is lowered by a factor of 0.6 times in latter observations.

In order to see the spin-down trends clearly, we estimate the pulse-frequency histories by taking the derivatives of each pairs of pulse phases from the pulse phases of this work and previous work by Baykal et al. (2001) and presented in Table 3 and Fig. 2 along with previous frequency measurements.

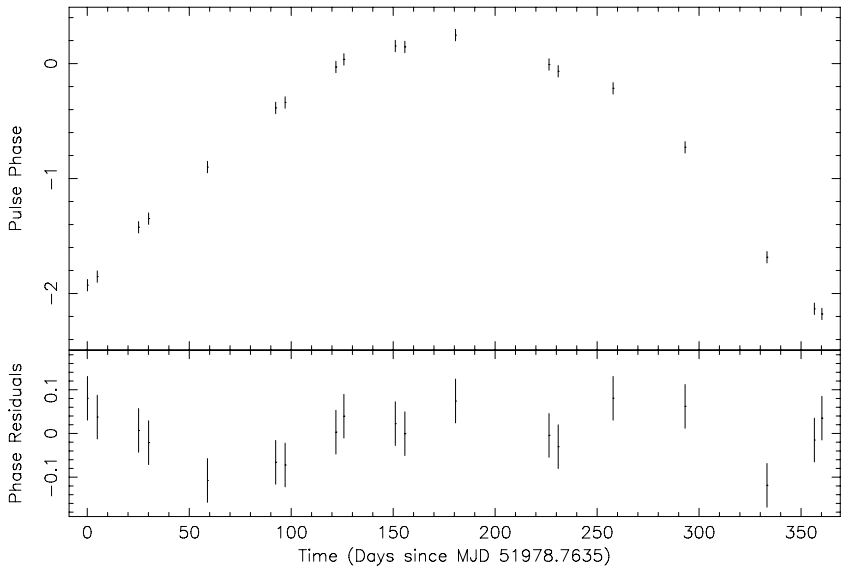

Figure 1. Pulse phase and its residuals fitted to the orbital model presented in Table 2.

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Table 2. Timing solution of 4U 1907+09.[a]

$T_{\pi/2}$ (orbital epoch) (MJD)	501 34.76 ∓ 0.06[b]
$P_{\rm orb}(d)$	8.3753 ∓ 0.0001[b]
$a_x \sin i$ (lt s)	83 ∓ 2[b]
e	0.28 ∓ 0.04[b]
w	330 ∓ 7[b]
t_0 (MJD)[c]	521 54.6183 ∓ 0.0005
Pulse period (s)	441.0932 ∓ 0.0003
Pulse-period derivative (s s^{-1})	(3.653 ∓ 0.081) × 10^{-9}
Pulse-frequency derivative (Hz s^{-1})	(−1.887 ∓ 0.042) × 10^{-14}

[a]Confidence intervals are quoted at 1σ level; [b]orbital parameters are taken from in't Zand et al. (1998a). $P_{\rm orb}$: orbital period, a_x sin i: projected semimajor axis, e: eccentricity and w: longitude of periastron; [c]mid-time of the observation used in pulse timing (see equation 1 in the text).

Table 3. *RXTE* pulse-period measurements of 4U 1907+09.

Epoch (MJD)	Pulse period (s)	Reference
455 76	437.483 ± 0.004	Makishima et al. (1984)
458 50	437.649 ± 0.019	Cook & Page (1987)
481 56.6	439.19 ± 0.02	Mihara (1995)
501 34	440.341 ± 0.014	in't Zand et al. (1998)
504 24.3	440.4854 ± 0.0109	This work
504 40.4	440.4877 ± 0.0085	Baykal et al. (2001)
504 60.9	440.5116 ± 0.0075	This work
505 02.1	440.5518 ± 0.0053	This work
505 47.1	440.5681 ± 0.0064	This work
505 81.1	440.5794 ± 0.0097	This work
506 06.0	440.6003 ± 0.0115	This work
506 31.9	440.6189 ± 0.0089	This work
506 65.5	440.6323 ± 0.0069	This work
506 99.4	440.6460 ± 0.0087	This work
507 26.8	440.6595 ± 0.0105	This work
507 54.1	440.6785 ± 0.0088	This work
507 82.5	440.6910 ± 0.0097	This work
510 21.9	440.7045 ± 0.0032	Baykal et al. (2001)
510 80.9	440.7598 ± 0.0010	Baykal et al. (2001)
519 93.8	441.0484 ± 0.0072	This work
520 16.8	441.0583 ± 0.0071	This work
520 61.5	441.0595 ± 0.0063	This work
520 88.0	441.0650 ± 0.0063	This work
521 17.4	441.0821 ± 0.0062	This work
521 41.2	441.0853 ± 0.0082	This work
521 91.4	441.1067 ± 0.0046	This work
522 17.2	441.1072 ± 0.0077	This work
522 54.3	441.1259 ± 0.0074	This work
522 92.0	441.1468 ± 0.0065	This work
523 28.8	441.1353 ± 0.0090	This work

The whole data set of 4U 1907+09 mentioned in previous sections was also analysed for possible detection of any transient oscillations around ∼14–18 s, similar to those reported from previous *RXTE* (in't Zand et al. 1998a) and *IXAE* (Mukerjee et al. 2001) observations. In the power spectra of 3–25 keV *RXTE*-PCA light curve, we searched for transient oscillations around ∼0.06 Hz in the 0.50-s binned ∼170 light curve segments of length of 512 s. In order to test the significance of these oscillations, we used the approach of van der Klis (1989). As the result of this search, we found only three 512-s segments in the whole data set with the transient oscillations of significance exceeding 5σ at MJD ∼501 36, ∼510 79 and ∼510 87. Our results about transient oscillations are marginal, and therefore inconclusive. Future observations may be useful to observe and analyse possible transient oscillations of the source.

3.2 Analysis of the energy spectrum

The complete data set of 4U 1907+09 mentioned in Section 2.1 were also analysed to investigate whether there is any significant spectral evolution accompanied with the change in the spin-down rate of the pulsar or not. Spectra, background and response matrix files were created using FTOOLS 6.0 data analysis software. Background spectra were generated using the background estimator models based on the rate of very large events, spacecraft activation and cosmic X-ray emission.

Spectral analysis and error estimation of the spectral parameters were performed using XSPEC version 11.3.2. We extracted individual 3–25 keV PCA spectra each corresponding to a single pulse period. For these spectra, energies lower than 3 keV were ignored due to uncertainties in background modelling while energies higher than 25 keV were ignored as a result of poor-counting statistics. In order to take into account the X-ray background from the Galactic ridge and the nearby supernova remnant W49B, we followed the approach used by Roberts et al. (2001). We extracted overall 'dip'-state spectra of the source for each of the proposal IDs listed in Table 1 and the corresponding background spectra. We found that the count rate and the spectral shape of the dip-state spectra were consistent with the models of the diffuse emission from the Galactic ridge (Valinia & Marshall 1998). So, these dip-state observations were used as additional background spectra in spectral fits of the source spectrum. These additional background spectra were created by subtracting the corresponding dip-state model background spectrum from the dip-state source spectrum using 'mathpha' FTOOL.

A power-law model with low-energy absorption (Morrison & McCammon 1983), multiplied by an exponential high-energy cut-off function (White, Swank & Holt 1983) was used to model 3–25 keV spectra of the source. We found no evidence of a statistically significant iron line emission at ∼6.4 keV which is consistent with the previous *RXTE* spectral fits (Roberts et al. 2001). An additional cyclotron resonance absorption line (Makishima et al. 1990) component at ∼19 keV was required to fit the spectra. The parameters of cyclotron absorption line were found to be consistent with the fundamental cyclotron line parameters found from *BeppoSAX* observations of the source (Casumano et al. 1998). Obtaining the spectral fits, we fixed the cyclotron absorption line energy at 19 keV. The results of the spectral fits as a function of orbital phase were presented in Fig. 3. Sample model parameters were listed in Table 4.

4 CONCLUSION

The spin-down rate of 4U 1907+09 obtained from the pulse arrival times between 2001 March and 2002 March was found to be ∼0.60 times lower than both the previous *RXTE* measurements of spin-down rate between 1996 November and 1997 December by Baykal et al. (2001) and the long-term spin-down trend of the source between 1983 and 1997 (See Fig. 1 in Baykal et al. 2001). In this and the previous *RXTE* observations, time-spans of the observations were similar (∼ over an year) and in both, observations posses low-timing noise. However, spin-down rate is lowered by a factor of 0.6 in latter observations. It is also interesting to observe that the spin-down rate is consistent with zero around MJD 510 00 before this significant change in spin-down rate. Our pulse-frequency measurements for the first time resolved significant spin-down rate variations since the discovery of the source.

The steady spin-down rate (Baykal et al. 2001) and the presence of occasional transient oscillations (in't Zand et al. 1998a; Mukerjee et al. 2001) in 4U 1907+09 support the idea that the source

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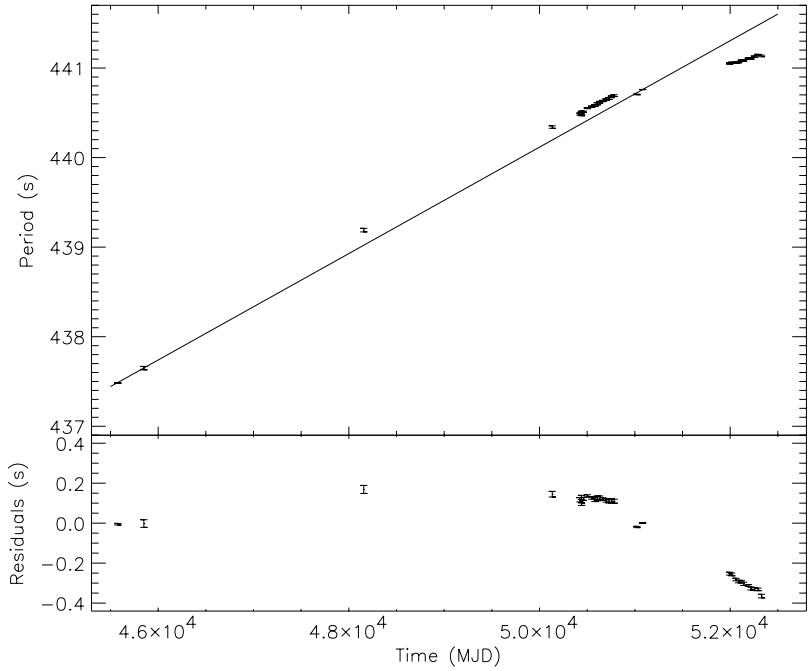

Figure 2. Plot of pulse-period history listed in Table 3 (Makishima et al. 1984; Cook & Page 1987; Mihara 1995; in't Zand et al. 1998; Baykal et al. 2001, and this work). Solid line and the residuals correspond to the previous spin-down rate found by Baykal et al. (2001).

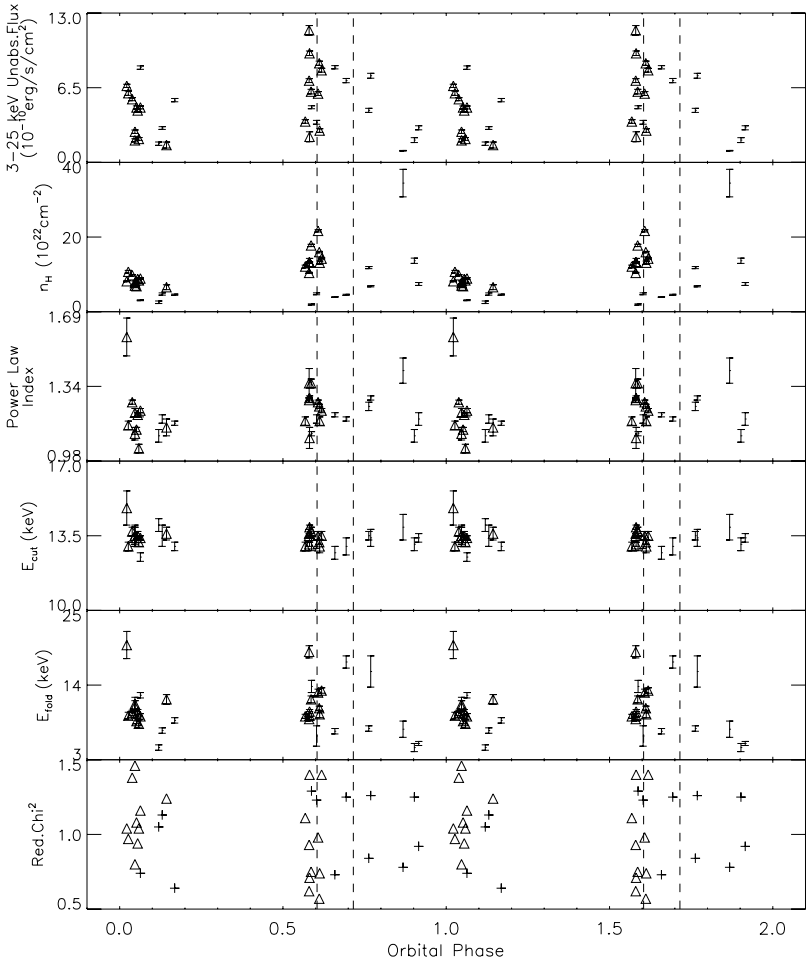

Figure 3. Evolution of 3–25 keV unabsorbed flux, hydrogen column density, power-law index, cut-off energy, e-folding energy, and reduced χ^2 in orbital phase. Vertical dashed lines indicate the orbital phase corresponding to periastron passages. Points marked with triangles indicate observations between 2001 March and 2002 March (proposal ID 60061) for which spin-down rate of the source was lower. The dotted lines indicate $\pm\sigma$ from the periastron.

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Table 4. Sample spectral parameters of individual PCA observations of 4U 1907+09.

Parameter	MJD 505 47	MJD 520 61
Hydrogen column density (10^{22} cm^{-2})	5.51 ∓ 0.50	9.13 ∓ 0.23
Power-law photon index	1.20 ∓ 0.04	1.21 ∓ 0.03
Power-law normalization (10^{-2} cts cm^{-2} s^{-1})	4.04 ∓ 0.09	2.83 ∓ 0.15
Cut-off energy (keV)	12.9 ∓ 0.2	13.7 ∓ 0.3
e-folding energy (keV)	7.0 ∓ 0.5	9.6 ∓ 0.5
Cyclotron depth	0.14 ∓ 0.05	0.20 ∓ 0.02
Cyclotron energy (keV)	19.0 (fixed)	19.0 (fixed)
Cyclotron width (keV)	1.12 ∓ 0.10	1.71 ∓ 0.34
3–25 keV unabsorbed X-ray flux (10^{-10} erg cm^{-2} s^{-1})	6.36 ∓ 0.14	4.69 ∓ 0.25
Reduced χ^2 (43 d.o.f.)	0.74	0.98

accretes from retrograde transient accretion disc. The possibility of a prograde disc for which the magnetospheric radius should be close to the corotation radius so that the magnetic torque overcomes material torque is not likely to be the case for this system (in't Zand et al. 1998a). If the disc is retrograde and the material torque is dominant, using Ghosh & Lamb (1979) accretion disc model, a decrease in spin-down rate of the neutron star should be a sign of a decrease in the mass-accretion rate coming from the accretion disc. If the disc accretion is the only accretion mechanism, then this decrease in mass-accretion rate should also lead to a decrease in X-ray flux of the system.

From the X-ray spectral analysis of the source, we found no clear evidence of a correlation between 3- and 25-keV flux and the change in spin-down rate (see Fig. 3). The flux levels were about the same for latter observations with low spin-down rate compared to the rest of the observations. This was not our expectation if we only consider disc accretion and may be because of the fact that the total mass-accretion rate is not only due to only disc accretion, but also due to accretion from stellar wind may contribute to the total mass-accretion rate (see also Roberts et al. 2001). In the case of accretion from both transient disc and wind, the change in mass-accretion rate from the accretion disc might not cause a substantial change in X-ray flux. However, it is important to note that the orbital coverage of the latter (proposal ID 60061) observations is poor and limited to the phase-locked flares in orbital phases $\sim$0.05 and $\sim$0.6 as seen in Fig. 3. Future observations of the source may be helpful to have a better understanding of a possible relation between spin-down rate and X-ray flux.

Examining spectral parameters plotted in Fig. 3 especially for flare parts, we also found an evidence of an increase in hydrogen column density ($n_{\rm H}$) for the latter observation with lower spin-down rate. On the other hand, there is no clear evidence of a variation of the other spectral parameters in the flares after the spin-down rate decreased. Change in $n_{\rm H}$ may be related to a change in the accretion geometry of the source. However, if there had been an accretion-geometry change accompanied with the change in the spin-down rate of the source, we would expect other spectral parameters to vary as well, especially the power-law index as in the *RXTE* observations of SAX J2103.5+4545 (Baykal et al. 2002), and 2S 1417−62 (Inam et al. 2004). New X-ray observations of the source will be useful to monitor any possible changes in the spin-down rate and its consequences.

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REFERENCES

Baykal A., Inam C., Alpar M. A., in't Z and J., Strohmayer T., 2001, MNRAS, 327, 1269
Baykal A., Stark M., Swank J., 2002, ApJ, 569, 903
Blondin J. M., Kallman T. R., Fryxell B. A., Taam R. E., 1990, ApJ, 356, 591
Casumano G., Salvo T. D., Burderi L., Orlandini M., Piraino S., Robba N., Santangelo A., 1998, A&A, 338, L79
Chitnis V. R., Rao A. R., Agrawal P. C., Manchanda R. K., 1993, A&A, 268, 609
Cook M. C., Page C. G., 1987, MNRAS, 225, 381
Cox N. L., Kaper L., Mokiem M. R., 2005, A&A, 436, 661
Deeter J. E., Boynton P. E., 1985, in Hayakawa S., Nagase F., eds, Proc. Inuyama Workshop, Timing Studies of X-ray Sources. Nagoya Univ., Nagoya, p. 29
Ghosh P., Lamb F. K., 1979, ApJ, 234, 296
Giacconi R., Kellogg E., Gorenstein P., Gursky H., Tananbaum H., 1971, ApJ, 165, L27
Inam S. C., Baykal A., Scott D. M., Finger M., Swank J., 2004, MNRAS, 349, 173
Jahoda K., Swank J., Giles A. B., Stark M. J., Strohmayer T., Zhang W., 1996, Proc. SPIE, 2808, 59
Leahy D. A., Darbro W., Elsner R. F., Weisskopf M. C., Sutherland P. G., Kahn S., Grindlay J. E., 1983, ApJ, 266, 160
Makishima K., Mihara T., 1992, in Tanaka Y., Koyama K., eds, Proc. XXVIII Yamada Conf., Frontiers of X-ray Astronomy. Universal Academy Press, Tokyo, p. 23
Makishima K., Kawai N., Koyama K., Shibazaki N., Nagase F., Nakagawa M., 1984, PASJ, 36, 679
Makishima K. et al., 1990, PASJ, 42, 295
Marshall N., Rickets M. J., 1980, MNRAS, 193, 7
Mihara T., 1995, PhD thesis, Univ. Tokyo
Morrison R., McCammon D., 1983, ApJ, 270, 119
Mukerjee K., Agrawal P. C., Paul B., Rao A. R., Yadav J. S., Seetha S., Kasturirangan K., 2001, ApJ, 548, 368
Roberts M. S. E., Michelson P. F., Leahy D. A., Hall T. A., Finley J. P., Cominsky L. R., Srinivasan R., 2001, ApJ, 555, 967
in't Zand J. J. M., Strohmayer T. E., Baykal A., 1997, ApJ, 479, L47
in't Zand J. J. M., Baykal A., Strohmayer T. E., 1998a, ApJ, 496, 386
in't Zand J. J. M., Strohmayer T. E., Baykal A., 1998b, Nucl. Phys. B, 69, 224
Valinia A., Marshall F. E., 1998, ApJ, 505, 134
van der Klis M., 1989, in Ogelman H., van den Heuvel E. P. J., eds, Timing Neutron Stars. Kluwer, Dordrecht, p. 27
White N. E., Swank J. H., Holt S. S., 1983, 270, 711

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