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The steady spin-down rate of 4U 1907+09

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ABSTRACT

Using X-ray data from the *Rossi X-ray Timing Explorer*, we report the pulse timing results of the accretion-powered, high-mass X-ray binary pulsar 4U 1907+09, covering a time-span of almost two years. We measured three new pulse periods in addition to the previously measured four pulse periods. We are able to connect pulse arrival times in phase for more than a year. The source has been spinning down almost at a constant rate, with a spin-down rate of $\dot{\nu} = (-3.54 \pm 0.02) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ for more than 15 yr. Residuals of pulse arrival times yield a very low level of random-walk noise, with a strength of $\sim 2 \times 10^{-20}\,\mathrm{rad^2\,s^{-3}}$ on a time-scale of 383 d, which is 40 times lower than that of the high-mass X-ray binary pulsar Vela X-1. The noise strength is only a factor of 5 greater than that of the low-mass X-ray binary pulsar 4U 1626−67. The low level of the timing noise and the very stable spin-down rate of 4U 1907+09 make this source unique among the high-mass X-ray binary pulsars, providing another example, in addition to 4U 1626−67, of long-term quiet spin down from an accreting source. These examples show that the extended quiet spin-down episodes observed in the anomalous X-ray pulsars 1RXS J170849.0−400910 and 1E 2259+586 do not necessarily imply that these sources are not accreting pulsars.

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

1 INTRODUCTION

4U 1907+09 is an accretion-powered X-ray binary pulsar that is accreting plasma from a blue supergiant companion star. It was discovered as an X-ray source by Giacconi et al. (1971) and has been studied using instruments on board *Ariel V* (Marshall & Ricketts 1980), *Tenma* (Makishima et al. 1984), *EXOSAT* (Cook & Page 1987), *Ginga* (Makishima & Mihara 1992; Mihara 1995), and *RXTE* (in ’t Zand, Baykal & Strohmayer 1998a; in ’t Zand, Strohmayer & Baykal 1997, 1998b). Marshall & Ricketts (1980) determined the orbital period as 8.38 d by analysing the data taken by *Ariel V.* They also found two flares, a primary and a secondary, each occurring at the same orbital phase. Subsequent *Tenma* observations of this source have shown a pulse period at 437.5 sec (Maksihima et al. 1984). Later *EXOSAT* (Cook & Page 1987) and recent *RXTE* observations (in ’t Zand et al. 1998a,b) have shown that these flares are locked to orbital phases separated by half an orbital period. Makishima et al. (1984) and Cook & Page (1987) suggested that the two flares are caused by an equatorial disc-like envelope around a companion star which is inclined with respect to the orbital plane. When the neutron star crosses the disc, the mass accretion rate onto the neutron star (and, therefore, the X-ray flux) increases temporarily. Transient ∼18-s oscillations have appeared during the secondary flare (in ’t Zand et al. 1998a). These oscillations may be interpreted as Keplerian motion of an accretion disc near the magnetospheric radius. Owing to the long spin period, the co-rotation radius is much larger than the magnetospheric radius corresponding to the magnetic field of 2.1×10^{12} Gauss implied by a cyclotron feature in the X-ray spectrum (Cusumano et al. 1998). Therefore, 4U 1907+09 is not likely to be spinning near equilibrium, like some other wind fed X-ray pulsars such as Vela X-1 (Waters & van Kerkwijk 1989). The 18-s quasi-periodic oscillation at the flare suggests the formation of transient accretion discs from the wind accretion (in ’t Zand et al. 1998a).

Vela X-1 and 4U 1907+09 have similar pulse periods (283 s for Vela X-1, 440 s for 4U 1907+09) and orbital periods (8.96 d for Vela X-1, 8.38 d for 4U 1907+09), and both have supergiant companions. Vela X-1 has shown several spin up/down episodes (Nagase 1989) and its pulse frequency time series has been modelled by a random walk model (Deeter et al. 1989). Continuous monitoring of more than 15 accreting pulsars with the Burst and Transient Source Experiment (BATSE) has shown that all of them exhibit stochastic variations in their spin frequencies (Bildsten et al.

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1997). Their time series displays several spin up/down trends on time-scales changing from days to years. 4U 1907+09 was not included in this study because it has no significant emission in the BATSE instrument bandpass.

4U 1907+09 has shown spin-down rate changes of less than ~8 per cent within 12 yr (in 't Zand et al. 1998b). In the present work, we investigate the stability of the spin-down rate. Using the archival *RXTE* observations, we measured three new pulse periods covering a time-span of over 2 yr in addition to the previous four pulse period measurements. With $\sim 10^3$–10^4 s observations separated by intervals of the order of a month we have been able to connect the pulses in phase and to construct the timing solution extending over a year. The residuals of pulse arrival times yielded a very low noise strength. Our findings imply that the source has a very stable spin-down rate even over short time intervals, in contrast to the noise seen in other high-mass X-ray binary pulsars (HMXRBs).

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

Time of observation (day/month/year)	Exposure (s)
25/11/1996	9163
19–27/12/1996	35102
29/01/1997	849
19/03/1997	7430
29/04/1997	13908
26/05/1997	8352
18/06/1997	11695
17/07/1997	724
24/08/1997	6976
23/09/1997	5811
18/10/1997	7913
17/11/1997	7787
14/12/1997	645
26–29/07/1998	33211
18/09–01/10/1998	175382

2 OBSERVATIONS AND ANALYSIS

The observations used in this work are listed in Table 1. The results presented here are based on data collected with the Proportional Counter Array (PCA; see Jahoda et al. 1996). The PCA instrument consists of an array of five proportional counters operating in the 2–60 keV energy range, with a total effective area of approximately 7000 cm^2 and a field of view of ~1° full width at half-maximum.

Background light curves were generated 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 and were subtracted from the source light curve obtained from the event data. The background subtracted light curves were corrected to the barycentre of the solar system. Using the binary orbital parameters of 4U 1907+09 from *RXTE* observations (in 't Zand et al. 1998a), the light curves are also corrected for binary motion of 4U 1907+09 (see Table 3, later). From the long archival data string outside the intensity dips, pulse periods for 4U 1907+09 were found by folding the time series on statistically independent trial periods (Leahy et al. 1983). Master pulses were constructed from these observations by folding the data on the period giving the maximum χ^2. The master pulses were arranged in 20 phase bins and represented by their Fourier harmonics (Deeter & Boynton 1985) and cross-correlated with the harmonic representation of average pulse profiles from each observation. The pulse arrival times are obtained from the cross-correlation analysis. We have measured three new pulse periods from the longer observations. These are presented in Fig. 1 and listed in Table 2. We have found that the rate of change of the pulse period of 4U 1907+09 is stable. Therefore, we have been able to connect all pulse arrival times in phase over a 383-d time-span. The

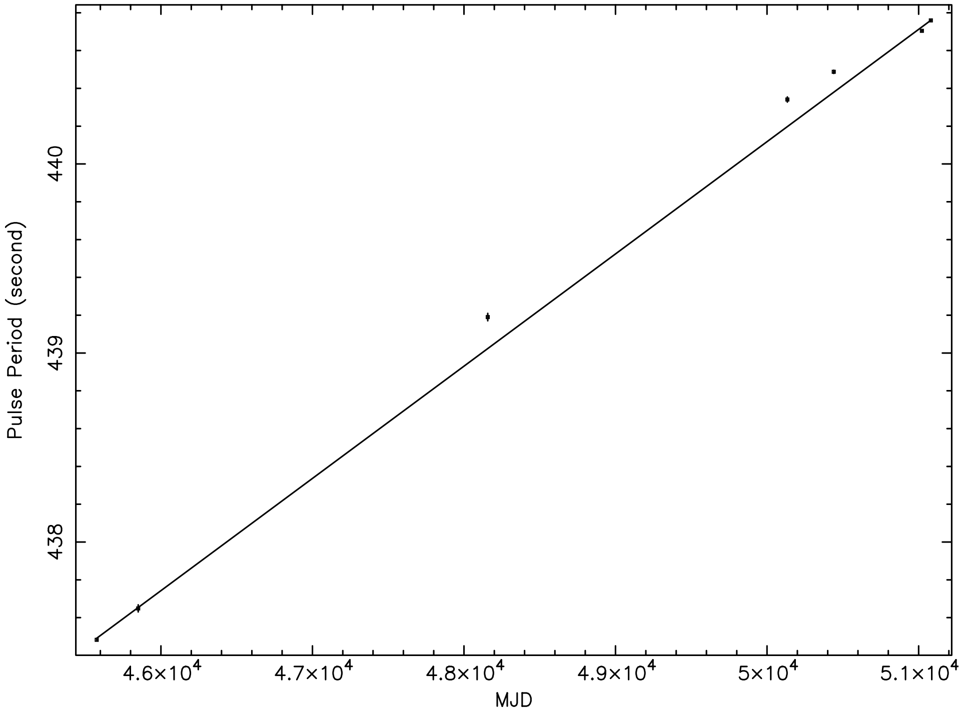

Figure 1. Pulse period history of 4U 1907+09.

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pulse arrival times are fitted to the quadratic polynomial

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

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 arrival times (pulse cycles) and the residuals of the fit after the removal of the quadratic polynomial are presented in the Fig. 2. Table 3 presents the timing solution of 4U 1907+09. The pulse frequency derivative $\dot{\nu} = (-3.188 \pm 0.006) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ is measured from the pulse arrival times obtained in a sequence of 19 observations spread over 383 d.

3 RESULTS

The value of the pulse frequency derivative based on data spanning 383 d is close (within 10 per cent) to the long term value obtained from the data displayed in Fig. 1, $\dot{\nu} = (-3.54 \pm 0.02) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$. The residuals of the fit give a random walk noise strengths at $T_{\mathrm{observation}} \sim 383$ d, $S \approx (2\pi)^2\langle\delta\phi^2\rangle/T^3_{\mathrm{observation}} \approx (2\pi)^2\langle\delta\nu^2\rangle/T_{\mathrm{observation}} \sim 2 \times 10^{-20}\,\mathrm{rad^2\,s^{-3}}$, where $\langle\delta\phi^2\rangle$ and $\langle\delta\nu^2\rangle$ are the normalized variances of pulse arrival times and residual pulse frequencies (see Cordes 1980 for further definitions of noise strength). This value is 40 times lower than that of Vela X-1 ($S \sim 8.0 \times 10^{-19}\,\mathrm{rad^2\,s^{-3}}$; see Deeter et al. 1989, Bildsten et al. 1997) and it is only a factor 5 greater than that of the low mass X-ray binary pulsar 4U 1626 − 67 ($S \sim 3.94 \times 10^{-21}\,\mathrm{rad^2\,s^{-3}}$; Chakrabarty et al. 1997). The noise strength of 4U 1626 − 67 was considered the smallest ever measured for an accretion-powered X-ray source. The stable spin-down rate of 4U 1907+09 over the 15 yr period and the low level of noise strength is a unique property of this source among the HMXRBs.

Table 2. *RXTE* pulse period measurements of 4U 1907+09.

Epoch (MJD)	Pulse period (s)	Reference
45576	437.483 ± 0.004	Makishima et al. 1984
45850	437.649 ± 0.019	Cook & Page 1987
48156.6	439.19 ± 0.02	Mihara 1995
50134	440.341 ± 0.014	in ’t Zand et al. 1998
50440.4	440.4877 ± 0.0085	This work
51021.9	440.7045 ± 0.0032	This work
51080.9	440.7598 ± 0.0010	This work

Furthermore, this noise strength is lower than the noise strength deduced from the 15-yr pulse frequency history of the anomalous X-ray pulsar (AXP) 1E 2259+586 ($S \sim 1.5 \times 10^{-19}\,\mathrm{rad^2\,s^{-3}}$; Baykal & Swank 1986). For AXPs in general, and for 1E

Table 3. Timing solution of 4U 1907+09 for *RXTE* observations.[a]

Orbital Epoch (MJD)	50134.76(6)[b]
P_{orb} (d)	8.3753(1)[b]
$a_x \sin i$ (lt s)	83(2)[b]
e	0.28(4)[b]
w	330(7)[b]
Epoch (MJD)	50559.5011(3)
Pulse period (s)	440.5738(2)
Pulse period derivative ($\mathrm{s\,s^{-1}}$)	$6.18(1) \times 10^{-9}$
Pulse freq. derivative ($\mathrm{Hz\,s^{-1}}$)	$-3.188(6) \times 10^{-14}$

[a] Confidence intervals are quoted at the 1 σ level.
[b] Orbital parameters are taken from in ’t Zand et al. (1997). P_{orb} = orbital period, $a_x \sin i$ = projected semimajor axis, e = eccentricity, w = longitude of periastron.

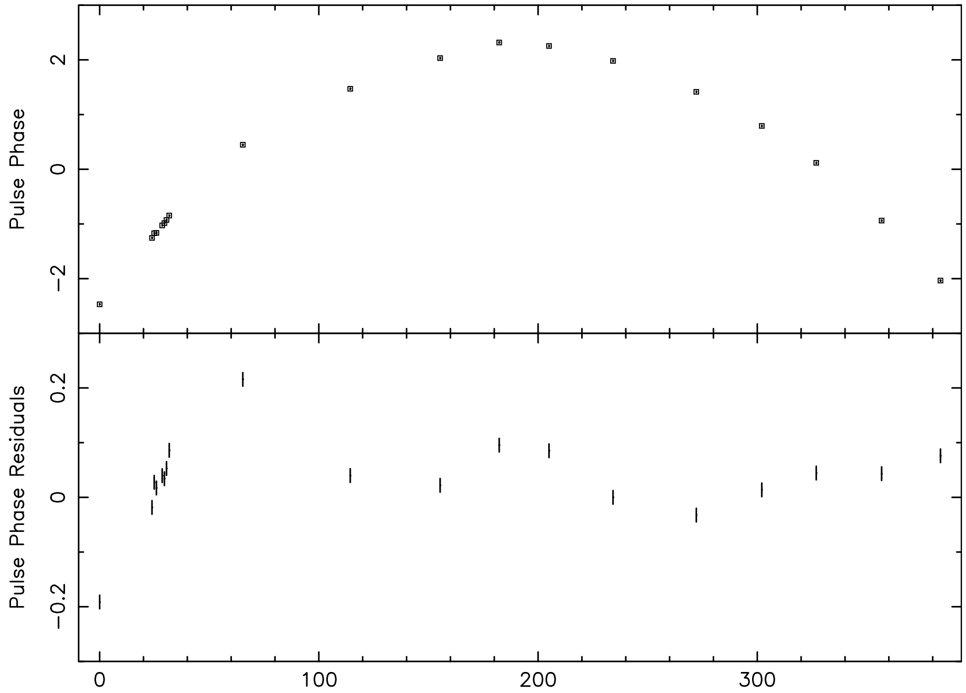

Figure 2. Pulse arrival phase residual for constant pulse period of 440.5738 sec. *Lower panel*: pulse arrival phase residual for constant spin-down model with a pulse period of 440.5738 s at MJD 50559.5011 and a spin-down rate of $6.18 \times 10^{-9}\,\mathrm{s\,s^{-1}}$. Note that the error in pulse phase is 0.0125.

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2259+586 in particular (Kaspi, Chakrabarty & Steinberger 1999), the existence of long epochs of spin down has been interpreted as evidence that these sources are isolated pulsars in dipole spin down, in which case the large spin-down rates and periods would indicate large (10^{14}–10^{15} Gauss) magnetic fields (Thompson & Duncan 1993). The existence of known accreting sources with quiet and persistent spin down, as observed from 4U 1626−67 and now 4U 1907+09, shows that quiet spin down does not necessarily imply that the source is not accreting.

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