## The Steady Spin Down Rate of 4U 1907+09

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Received <u>\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_;</u> accepted \_

### ABSTRACT

Using X-ray data from the Rossi X-Ray Timing Explorer (RXTE), we report the pulse timing results of the accretion powered high mass X-ray binary (HMXRB) 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  $\dot{\nu} = (-3.54 \pm 0.02) \times 10^{-14}$  Hz s<sup>-1</sup> for more than 15 years. Residuals of pulse arrival times yield a very low level of random walk noise strengths  $\sim 2 \times 10^{-20}$  rad<sup>2</sup> sec<sup>-3</sup> on a time scale of 383 days, which is four decades lower than that of the HMXRB pulsar Vela X-1. The noise strength is only a factor of 5 greater than that of the low mass X-ray binary pulsar (LMXRB) 4U 1626-67. The low level of the timing noise and the very stable spin down rate of 4U 1907+09 makes this source unique among the HMXRBs, 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 (AXPs) pulsars 1RXS J170849.0-400910 and 1E 2259+586 do not necessarly imply that these sources are not accreting pulsars.

#### 1. Introduction

4U 1907+09 is an accretion powered X-ray binary pulsar which 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, Strohmayer & Baykal 1997, In 't Zand, Baykal & Strohmayer 1998, In 't Zand, Strohmayer & Baykal 1998). Marshall & Ricketts (1980) first determined the orbital period of the binary at 8.38 days by analysing the data taken between 1974 and 1980 from a survey instrument on board Ariel V. Folding the light curve of these data, they 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 obsevations (In 't Zand, Baykal & Strohmayer 1998, In 't Zand, Strohmayer & Baykal 1998) 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 due to an equatorial disk-like envelope around a companion star which is inclined with respect to the orbital plane. When the neutron star crosses the disk, the mass accretion rate onto the neutron star, therefore the X-ray flux, increases temporarily. Transient  $\sim$  18 sec oscillations have appeared during the secondary flare (In 't Zand, Baykal & Strohmayer 1998). These oscillations may be interpreted as Keplerian motion of an accretion disk near the magnetospheric radius. Due to the long spin period the co-rotation radius is much larger than the magnetospheric radius corresponding to the magnetic field of  $2.1 \times 10^{12}$  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, unlike other accretion powered X-ray pulsars. The 18 second quasi periodic oscillation at the flare suggests the formation of transient accretion disks from the wind accretion (In 't Zand, Baykal & Strohmayer 1998). Another interesting feature of the source is the sudden decrease in X-ray intensity by a factor of  $\sim 10^2$ , during time intervals ranging from a few minutes to ∼ 1.5 hour (In 't Zand, Strohmayer & Baykal 1997). The spectra at the dipping activity and outside the dip periods were similar with no indication of large changes in the column density of cold circumstellar matter (i.e.  $N_H$  remains below

10<sup>23</sup> cm<sup>−</sup><sup>2</sup> ). It is suggested that the mass accretion rate ceased due to the inhomogeneous spherical wind from the companion.

In this work, we have investigated the stability of the spin down rate. This source has shown spin down rate changes less than ∼ 8 % within 12 years (In 't Zand, Strohmayer & Baykal 1998). Using the archival RXTE observations, we measured three new pulse periods covering a time span of over 2 years in addition to the previous four pulse period measurements. With  $\sim 10^3 - 10^4$  sec 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 HMXRBs.

#### 2. Observations and Results

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, Jahoda et al., 1996). The PCA instrument consists of an array of 5 proportional counters operating in the 2-60 keV energy range, with a total effective area of approximately 7000 cm<sup>2</sup> and a field of view of  $\sim$  1° full width half half maximum.

Background light curves were generated using the background estimator models based on the rate of very large events (VLE), spacecraft activation and cosmic X-ray emission with the standard PCA analysis tools (ftools) and were subtracted from the source light curve obtained from the event data. The background subtracted light curves were corrected with respect to the barycenter of the solar system. Using the binary orbital parameters of 4U 1907+09 from RXTE observations (In 't Zand, Baykal & Strohmayer 1998), the light

curves are also corrected for binary motion of 4U 1907+09 (see Table 3). 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  $\chi^2$ . 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 Figure 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 day time span. The pulse arrival times are fitted to the quadratic polynomial

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

where  $\delta\phi$  is the pulse phase offset deduced from the pulse timing analysis,  $t_o$  is the mid-time of the observation,  $\phi_o$  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 Figure 2 and Figure 3 respectively. Table 3 presents the timing solution of 4U 1907+09. The pulse frequency derivative  $\dot{\nu} = (-3.188 \pm 0.006) \times 10^{-14}$  Hz s<sup>-1</sup> is measured from the pulse arrival times obtained in a sequence of 19 observations spread over 383 days. This value is consistent within 10 % with the long term value obtained from the data displayed in Figure 1,  $\dot{\nu} = (-3.54 \pm 0.02) \times 10^{-14}$ Hz s<sup>-1</sup>. The residuals of the fit give a random walk noise strengths at  $T_{observation} \sim 383$ days,  $S \approx (2\pi)^2 < \delta\phi^2 > /T_{observation}^3 \approx (2\pi)^2 < \delta\nu^2 > /T_{observation} \sim 2 \times 10^{-20}$  rad<sup>2</sup> sec<sup>-3</sup>, 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 4

decades lower than that of Vela X-1 (Bildsten et al., 1997) and it is only a factor 5 greater than that of the LMXRB pulsar 4U 1626-67 (Chakrabarty et al., 1997). The noise strength of 4U 1626-67 was considered the smallest ever measured for an accretion powered X-ray source. This noise strength is indeed very low for a HMXRB pulsar. The stable spin down rate over the 15 years and the low level of noise strength is a unique property of this source among the HMXRBs. The spin down rate of 4U 1907+09 is only a factor four greater than that of the AXP source 1E 2259+586. Furthermore the long term noise strength is one order of magnitude lower than the AXP 1E 2259+586 (Baykal & Swank 1986). The quiet and persistent spin down rate of 4U 1907+09 shows that an accreting pulsar can spin down quietly, for extended periods. For the AXPs as well as 1E 2259+586, 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.

#### Acknowledgements :

We thank Dr. Jean Swank for the helpful comments.

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This manuscript was prepared with the AAS I4T<sub>E</sub>X macros v5.0.

Time of Observation	Exposure	
day/month/year	sec	
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	

Table 1: Observation List for 4U 1907+09

# Figure Caption

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

Fig. 2 Pulse phase (Pulse Cycles) of 4U 1907+09 with respect to the constant pulse period of 440.5738 sec.

Fig. 3 Pulse phase residuals of 4U 1907+09 with respect to the constant pulse period of 440.5738 sec after the derivative of pulse period  $6.18 \times 10^{-9}$  s s<sup>-1</sup> is removed.

Epoch(MJD)	Pulse Period (sec)	Ref.
45576	$437.483 + 0.004$	Makishima et al., 1984
45850	$437.649 + 0.019$	Cook $& Page 1987$
48156.6	$439.19 \pm 0.02$	Mihara 1995
50134	$440.341 + 0.014$	in't Zand et al., 1998
50440.4	$440.4877 \pm 0.0085$	This work
51021.9	$440.7045 \pm 0.0032$	This work
51080.9	440.7598±0.0010	This work

Table 2: RXTE Pulse Period Measurements of 4U 1907+09

Table 3: Timing Solution of 4U 1907+09 for RXTE Observations<sup> $a$ </sup>:

Orbital Epoch (MJD)	$50134.76(6)^b$
$P_{orb}$ (days)	$8.3753(1)^b$
$a_x \sin i$ (lt-sec)	$83(2)^b$
е	$0.28(4)^b$
W	$330(7)^{b}$
Epoch(MJD)	50559.5011(3)
Pulse Period (sec)	440.5738(2)
Pulse Period Derivative (s $s^{-1}$ )	$6.18(1) \times 10^{-9}$
Pulse Freq. Derivative $(Hz s^{-1})$	$-3.188(6)\times10^{-14}$

 $^a$  Confidence intervals are quoted at the 1  $\sigma$  level.

<sup>b</sup> Orbital parameters are taken from in't Zand et al., 1998 et al., (1997).  $P_{orb}=$ orbital period,  $a_x$  sin i=projected semimajor axis, e=eccentricity, w=longitude of periastron.





