Eclipse timings of the LMXB XTE J1710-281: orbital period glitches

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ABSTRACT

We present an X-ray eclipse timing analysis of the transient low mass X-ray binary XTE J1710-281. We report observations of 57 complete X-ray eclipses, spread over more than a decade of observations, made with the proportional counter array detectors aboard the RXTE satellite. Using the eclipse timing technique, we have derived a constant orbital period of 0.136 710 9674 (3) d, during the period from MJD 52132 up to MJD 54410, and 0.2 × 10^{-12} d d^{-1}, on the period derivative, \( \dot{P}_{\text{orb}} \). This puts constraints on the minimum time-scale of secular orbital period evolution (\( P_{\text{orb}}/\dot{P}_{\text{orb}} \)) of 2.34 × 10^8 yr for a period decay and 18.7 × 10^8 yr for a period increase. We also report detection of two instances of discontinuity in the mid-eclipse time, one before and one after the above MJD range. These results are interpreted as three distinct epochs of orbital period in XTE J1710-281. We have put lower limits of 1.4 and 0.9 ms on orbital period change (\( \Delta P_{\text{orb}} \)) at successive epochs. The detection significance of the two orbital period glitches are 11σ and 4σ, respectively. The sudden changes in orbital period is very similar in nature to that observed in EXO 0748-676, though their magnitude is much smaller in XTE J1710–281.

Key words: accretion, accretion discs – binaries: eclipsing – binaries: general – stars: individual: XTE J1710-281 – stars: neutron – X-rays: stars.

1 INTRODUCTION

XTE J1710–281 is a transient low mass X-ray Binary (LMXB) which was discovered in 1998 by the Rossi X-ray Timing Explorer (RXTE), and is likely to be associated with the ROSAT source 1RXS J171012.3-2807 54 (Markwardt et al. 1998). It is a highly variable source and several bursts have been reported to occur (Markwardt, Swank & Strohmayer 2001; Galloway et al. 2008). The system has an orbital period of 3.28 h (Markwardt et al. 2001) and the light curve shows dipping phenomena which could be due to occultations in the outer regions of the accretion disc as seen in many other high inclination LMXBs (White & Swank 1982).

XTE J1710–281 is a poorly studied LMXB. Being in a binary system, the orbital period of XTE J1710–281 is expected to change, due to redistribution of the angular momentum arising from interaction between the components of the binary system. The orbit can evolve due to various mechanisms, such as, mass transfer within the system due to Roche lobe overflow, tidal interaction between the components of the binary system, gravitational wave radiation, magnetic braking, (Rappaport, Verbunt & Joss 1983; Hurley, Tout & Pols 2002) and X-ray irradiated wind outflow (Ruderman et al. 1989). The measurement of orbital period derivative and hence the orbital evolution is therefore, important to understand the physical processes occurring in the system.

Orbital evolution can be determined by several techniques. Measurement of pulse arrival time delay, is one of the methods used to determine the evolution of the binary orbits (Dee et al. 1991; Paul, Naik & Bhatt 2004; Paul et al. 2007). The method of pulse folding and \( \chi^2 \) maximization with a varying orbital ephemeris, has also been used to determine the orbital evolution (Paul et al. 2002; Jain, Dutta & Paul 2007). Both these methods are well established and statistically at par. However, to determine the pulse arrival times, the data length for each sample should be kept small so as to avoid significant smearing of pulse phase due to orbital motion. In the case of faint sources, or in the case of observation made with a small photon collection area (e.g. with focusing optics), a small integration time may be insufficient for measurement of pulse arrival time. In such a case, maximization of pulse detection by varying the orbital ephemeris is an effective technique as the entire data set is used together (Paul et al. 2002). Eclipse timing is another technique, used to determine the orbital evolution of LMXBs (Wolff et al. 2009; Jain, Paul & Dutta 2010). In some sources, in the absence of pulsations or eclipses, orbital period derivative has been measured with some stable orbital intensity modulation features (4U 1820-30: Chou & Grindlay 2001; Cyg X-3: Singh et al. 2002).

XTE J1710–281 is one of the very few LMXBs, where full, sharp X-ray eclipses have been observed. The other systems
being, EXO 0748–676 (Wolff et al. 2002), GRS J1747–312 (in’t Zand et al. 2003), MXB 1658–298 (Cominsky & Wood 1989) and AX J1745.6–2901 (Maeda et al. 1996). Among these sources, EXO 0748–676 (Parmar et al. 1986; Wolff et al. 2002) is the only system in which a large number of eclipses have been timed with high accuracy (Wolff et al. 2009). In case of GRS J1747–312 and AX J1745.6–2901, the eclipse duration is too long (~43 and ~23 min, respectively, in’t Zand et al. 2003; Porquet et al. 2007) to carry out monitoring measurements. AX J1745.6–2901 is located near a bright source, which puts strong constraints on the timing analysis. The fifth source, MXB 1658–298 has been mostly in inactive state, since its discovery (Wachter, Smale & Bailyn 2000; Oosterbroek et al. 2001). The LMXB XTE J1710–281 has a fairly small eclipse duration and has been persistently active since its discovery. This makes it an ideal source to investigate the orbital evolution.

In this work, we have used the sharp eclipses of XTE J1710–281 as timing markers to determine the orbital period of the system. By measuring the mid-eclipse times, over a long time baseline of ~11 yr, we can determine the change in the orbital period and hence estimate the orbital evolution of the system.

2 OBSERVATIONS AND ANALYSIS

Data for the present analysis were obtained from observations made with the Proportional Counter Array (PCA) on board the RXTE satellite (Bradt, Rothschild & Swank 1993). The RXTE-PCA consists of an array of five collimated xenon/methane multianode proportional counter units (PCU) with a total photon collection area of 6500 cm² (Jahoda et al. 1996, 2006), depending on the number of PCUs ON. The entire analysis was done using ftools from the astronomy software package HEASOFT ver. 6.10. The PCA data collected in the event mode and the Good Xenon mode, were used to generate the light curves, using the ftool SEEXTRACT. The analysis was done in the energy band 2–20 keV. The background was estimated using the ftool PCABACKEST. Faint source model was taken from the RXTE website (http://heasarc.gsfc.nasa.gov/docs/xte/pca-news.html). Thereafter, the background subtracted light curves were barycentre corrected using the ftool FXBARY.

We have analysed all the RXTE-PCA archival data, which covered a full X-ray eclipse. However, since this is a bursting source, we ignored few eclipses, where bursts occurred close to the ingress and egress phase of the eclipse. From data spread over ~11 yr (1999–2010), we have found 57 complete eclipses. Table 1 gives the observation IDs of all the 57 eclipses, observed with RXTE-PCA. In Fig. 1, we have shown a sample background subtracted light curve of XTE J1710-281 (Obs ID: 91045-01-01-02), binned with 2 s and including an eclipse lasting for ~420 s, excluding the ingress and egress phase.

For most of the observations, apart from a few type-I X-ray bursts, the out-of-eclipse count rate did not seem to have any significant variability. Therefore, the variable components of the light curve around the eclipse phase are, the pre-ingress (C_{pre-ingress}), eclipse (C_{eclipse}) and post-egress (C_{post-egress}) count rates; the ingress (\Delta t_{in}) and egress (\Delta t_{eg}) duration, the eclipse duration (\Delta t_{ecl}) and the mid-eclipse time. Considering all the components to be freely variable, we first fitted a seven-parameter ramp and step model to the eclipse phase (similar to Wolff et al. 2009). It was found that the value of C_{pre-ingress} and C_{post-egress} were similar and the eclipse ingress and egress duration were also similar withing errors. The parameter space, thus got reduced to five; the pre-ingress and the post-egress count rate (C_{pre-ingress}, C_{post-egress}), the eclipse count rate, the ingress and egress duration (\Delta t_{in}, \Delta t_{eg}), the eclipse duration (\Delta t_{ecl}) and the mid-eclipse time. The average eclipse duration in XTE J1710-281 is ~420 s; and for the model fitting, ~150 s of data were taken before and after the eclipse phase. It was also seen that the error in the mid-eclipse time measurement was smaller when the five-parameter

| RXTE observation ID | Orbital cycle | Mid-eclipse time (MJD) | 1σ uncertainty (d) |
|---------------------|--------------|-----------------------|-------------------|
| 40407-01-03-00      | 1            | 51251.061141           | 0.000 006         |
| 40135-01-04-00      | 728          | 51350.450003           | 0.000 035         |
| 60049-01-01-03      | 6452         | 52132.938718           | 0.000 046         |
| 60049-01-03-00      | 7118         | 52224.033183           | 0.000 012         |
| 60049-01-04-00      | 7567         | 52285.416436           | 0.000 029         |
| 60049-01-05-00      | 7623         | 52939.072343           | 0.000 006         |
| 60049-01-06-00      | 7667         | 52299.087534           | 0.000 012         |
| 60049-01-07-010     | 9431         | 52540.245711           | 0.000 064         |
| 60049-01-07-01      | 9432         | 52540.382406           | 0.000 030         |
| 80045-01-01-00      | 11732        | 52854.817626           | 0.000 006         |
| 80045-01-01-01      | 11733        | 52854.954339           | 0.000 010         |
| 80045-01-01-03      | 11756        | 52858.096861           | 0.000 009         |
| 80045-01-01-04      | 11757        | 52859.235396           | 0.000 010         |
| 80045-01-01-05      | 11760        | 52858.645512           | 0.000 009         |
| 80045-01-02-00      | 12432        | 52952.515726           | 0.000 009         |
| 80045-01-02-01      | 12444        | 52952.155841           | 0.000 012         |
| 80045-01-02-02      | 12454        | 52953.522899           | 0.000 014         |
| 80045-01-02-04      | 12455        | 52953.696494           | 0.000 019         |
| 80045-01-02-05      | 12456        | 52953.796342           | 0.000 008         |

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model was used. The best-fitting model for the eclipse profile in Fig. 1, is shown with a solid line. The best fit had a $\chi^2$ of 381 for 375 degrees of freedom (d.o.f.).

All the 57 X-ray eclipse light curves were fitted with a five-parameter ramp function, as described above. The mid-eclipse times and the corresponding 1σ errors were determined. The results are given in Table 1. The errors in the mid-eclipse times vary between 0.000 006 and 0.000 064 d, i.e. 0.5–5.5 s. This is mainly due to differences in the relative count rates of the source and the background, and partly due to the number of detectors ON. The orbit numbers are with respect to the first eclipse detected in the RXTE-PCA data. We fitted a constant and a linear model to the eclipse measurements between MJD 52132 and MJD 54410. The results of the fit are given in Table 2. We obtained an orbital period of 0.136 710 9674 (3) d and limits on the period derivative of $689 \pm 180$ (3) d yr$^{-1}$ between MJD 52132 and MJD 54410. The results of the fit are given in Table 2. The folded profiles are shown in the top panel of Fig. 3. The best-fitting ramp function is also shown for the eclipse profile of epoch 2. The best fit had a $\chi^2$ of 689 for 650 d.o.f. The bottom panels of the same figure show the eclipse ingress and egress profiles. It is clear from Fig. 3 that the time of ingress and egress of eclipse, during the three epochs is shifted in phase while the eclipse duration has remained nearly same.

3 DISCUSSION

Measurements of change in orbital period of an LMXB, is a crucial diagnostic to understand the accretion processes occurring in a binary system and their effect on the system parameters. And the orbital period can be very well determined by time connecting a stable fiducial marker in the light curve of the binary system. We have analysed 57 full X-ray eclipses of XTE J1710-281, observed by the RXTE satellite. The observations cover more than 30 000 binary orbits spread over ~11 yr. A five-component model was fit to each eclipse profile and the mid-eclipse times and the corresponding errors determined. We have determined an orbital period of 0.136 710 9674 (3) d and limits on the period derivative of $689 \pm 180$ (3) d yr$^{-1}$, i.e. limits on the time-scale of secular orbital period evolution, $P_{\text{orb}}/P_{\text{orb}}$, of $2.34 \times 10^{-8}$ yr for a period decay and $18.7 \times 10^{-8}$ yr for a period increase, respectively, during the period from MJD 52132 to MJD 54410.

The variation in the orbital ephemerides of XTE J1710-281, is significantly different from that seen in most of the other LMXBs, such as, 4U 1820-303 (Chou & Grindlay 2001), SAX J1808.4-3658 (Jain et al. 2007), Her X-1 (Paul et al. 2007), X 2127+119 (Homer & Charles 1998) and 4U 1822-37 (Jain et al. 2010). During the period from MJD 52132 to MJD 54410, the limits on the orbital period derivative of XTE J1710-281, is more than an order of magnitude smaller than those measured in the other LMXBs [4U 1820-303 ($3.5 \times 10^{-8}$ yr$^{-1}$), SAX J1808.4-3658 ($1.3 \times 10^{-8}$ yr$^{-1}$), Her X-1 ($2 \times 10^{-7}$ yr$^{-1}$), X 2127+119 ($9 \times 10^{-7}$ yr$^{-1}$) and 4U 1822-37 ($2.0 \times 10^{-7}$ yr$^{-1}$)].
Figure 3. A sample of 2–20 keV folded light curves of XTE J1710-281. The light curves were folded with a period of 0.1367109674 d at an epoch of MJD 51250.924540. The normalized intensities during epoch 1 and epoch 2 have been rescaled, by adding constant numbers to the curves. The solid line in the middle light curve (epoch 2) shows the best-fitting five-parameter model to the X-ray eclipse. The best fit had a reduced $\chi^2$ of 689 for 650 d.o.f. The top panel shows the complete eclipse, whereas, the bottom panels show the ingress and egress of the eclipse phase.

MJD range, the observed trend in the residual (O − C) behaviour of XTE J1710-281, is also different from that seen in the aforementioned LMXBs.

The observed O − C variation strongly resemble the one seen in EXO 0748-676 (Wolff et al. 2009). Interestingly, of the known LMXBs with well-determined eclipse times, EXO 0748-676 and XTE J1710-281 have shortest duration of the eclipse, making it easier to monitor with X-ray observatories. Though fewer eclipses have been observed in XTE J1710-281, as opposed to more than 400 complete eclipses seen from EXO 0748-676 (Wolff et al. 2009), the mid-eclipse times measured with RXTE-PCA are accurate enough to enable detection of very small orbital period glitches.

Magnetic field cycling of the secondary star is assumed to be the likely cause for the observed orbital period glitches in EXO 0748-676 (Wolff et al. 2009). It is proposed that magnetic activity associated with the secondary star could be responsible for sudden changes in the orbital period. If the secondary star associated with XTE J1710-281 has strong, changing, magnetic activity, it can lead to changes in the structure of secondary star. A changing gravitational quadrupole moment can result into changes in the orbital period of the binary system (Lanza & Rodono 1999; Tauris & van den Heuvel 2006). However, in case of XTE J1710-281, the optical counterpart has been discovered (Ratti et al. 2010) but the type of the companion star is not yet known. Therefore, it is difficult to make a statement on the probable cause for the changing orbital period of XTE J1710-281.

We emphasize that if magnetic cycling of the binary components is indeed a reason behind the observed epochs of orbital period, then long term monitoring of XTE J1710-281, is required to determine the time-scales of magnetic cycling of the secondary star. It may also be useful to foretell the distinct orbital period epochs of XTE J1710-281, if any. Lastly, the forthcoming Indian satellite, ASTROSAT with a very large area X-ray proportional counter (Paul 2009) could be a boon in determining the orbital parameters of the system.

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