Orbital evolution of the Low Mass X-ray Binaries 4U 1822-37, XTE J1710-281 and MXB 1658-298

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Abstract

The orbits of X-ray binaries evolve due to redistribution of the angular momentum due to different types of interactions between the components of the binary system and/or mass loss through wind. Accurate measurement of the rate of change of the orbital period is therefore, useful in order to understand the evolution of compact binary systems. Using the eclipse timing technique, we have derived/updated the estimates of orbital periods and period derivatives in three eclipsing low mass X-ray binaries, 4U 1822-37, XTE J1710-281 and MXB 1658-298. In the first source, 4U 1822-37, we have measured a positive orbital evolution with a timescale of about 5 Myr, which is quite low. Significant orbital period glitches have been observed in the XTE J1710-281, which is similar to that observed in EXO 0748-676. The results from MXB 1658-298 are difficult to describe in simple terms. In view of our results, we discuss several physical mechanisms that could be responsible for the observed orbital evolution in these LMXBs.

Key words: binaries: eclipsing, binaries: individual: 4U 1822-37, XTE J1710-281 and MXB 1658-298

1. Introduction

Low Mass X-ray Binaries (LMXBs) are stellar systems that consist of a compact object, such as a neutron star or a black hole, accreting matter from a companion star by Roche lobe overflow. Being in a binary system, the orbital period of the X-ray binaries, 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 (Lecar et al. 1976), gravitational wave radiation (Verbunt 1983), magnetic braking (Rappaport et al. 1983), 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 occuring in the system.

Here we report the results from eclipse timing of three LMXBs, 4U 1822-37, XTE J1710-281 and MXB 1658-298. The first source, 4U 1822-37, contains a neutron star with a spin period of ∼0.59 s, orbiting its companion every 5.57 hr (Parmar et al. 2000, Jonker et al. 2001). The source is surrounded by an accretion disk corona and the light curve exhibits a narrow and a broad dip in the intensity. Good estimates of the mass of the binary components and the orbital inclination is known with small uncertainties (Munoz-Darias et al. 2005). But only rough estimates of the source intrinsic luminosity and the neutron star's magnetic field have been made.

XTE J1710–281 is a transient LMXB discovered in 1998, and is likely to be associated with the ROSAT source 1RXS J171012.3-280754 (Markwardt et al. 1998). It is a highly variable source and several bursts have been reported to occur. The system has an orbital period of 3.28 hr (Markwardt et al. 2001) and the light curve shows dipping phenomena which could be due to occultations in the outer regions of the accretion disk.

MXB 1658-298 is also a transient X-ray source discovered in 1976 (Lewin et al. 1976). The system has an orbital period of ∼ 7.11 hr, shows erratic intensity variations and about 15 minutes of full eclipse (Cominsky et al. 1989; Wachter et al. 2000). After its discovery in 1976, the source intensity declined and it was not detectable for more than 20 years (Int Zand et al. 1999). The period of renewed activity began in 1999 and lasted for about 2.5 years, during which it was extensively observed by RXTE. Several PRE bursts were detected, alongwith 567 Hz burst oscillations (Wijnands et al. 2001).

In this paper, we have determined the mid-eclipse times of all the three systems, using data collected from various X-ray observatories. These measurements were then used to determine the change in their orbital period and hence estimate the orbital evolution in them.

2. Orbital evolution

Data for the timing analysis of 4U 1822-37, XTE J1710–281 and MXB 1658-298, were obtained from observations made with instruments on-board the Rossi X-ray Timing Explorer (*RXTE*) satellite. In case of 4U 1822-37, data was also taken from instruments on-board *Swift*, *XMM-Newton* and *Chandra* observatories (Jain et al. 2010; Jain et al. 2011; Jain et al. in preparation). The entire analysis was done using FTOOLS from the astronomy software package HEASOFT-ver 6.10. The data were reduced using standard techniques. The background counts were subtracted and the light curves were barycenter corrected. The following subsections describe the results in each source.

2.1. 4U 1822-37

Figure 1 shows the 1.5−12 keV long term *RXTE*-ASM light curve. The X-ray intensity of the source has reduced by ~ 40 % over the last 13 years and there are long term fluctuations at time scales of about an year. For the eclipse timing, all the light curves were folded with the known orbital period of 5.5706 hr (Parmar et al. 2000) and a Gaussian model was fit to the eclipse phase. A sample of the eclipse phase is shown in Figure 2, wherein the solid line is the best fit Gaussian curve. The arrival time of the eclipse which occured closest to the mid time of the observation was taken for the analysis. From data spread over 13 years, we obtained 16 new mid eclipse times (see Jain et al. 2010). These were combined with the known values (Hellier et al. 1994, Parmar et al. 2000). A quadratic model was fitted to the mid eclipse time measurements to obtain an updated ephemeris. We have determined an orbital period (P_{orb}) of 0.232108872(15) d and a period derivative ($\dot{P_{orb}}$) of $1.32(3) \times 10^{-10}$ d d^{-1} (at T_0 = MJD 45614). This imply an orbital evolution timescale of $4.82(12) \times 10^6$ yr. The resiudal curve is shown in Figure 3.

We also tried to obtain an independent measurement of orbital evolution using the technique of pulse folding and χ^2 maximisation (Naik et al. 2004, Jain et al. 2007). But in this source, the light travel time across the orbit is of the same order as the spin period of the pulsar, therefore, determination of orbital parameters by this technique has limited accuracy.

We have also performed a pulsation analysis to determine the spin period of the neutron star and the pulse period evolution. The light curves were corrected for the orbital motion using the long term orbital solution obtained from the eclipse timing technique described above. Figure 4 shows the spin period history of the neutron star. The pulse period was found to be continuously decreasing with time at an average rate ($\dot{P_{spin}}$) of -2.481(4) $\times 10^{-12}$ s s^{-1}, indicating a spin-up timescale of 7578(13) yr.

2.2. XTE J1710-281

We have analyzed all the *RXTE*-PCA archival data, which covered a full X-ray eclipse. From data spread over ∼12 years (1999-2011), we have found 65 complete eclipses (Jain et al. 2011). Figure 5 shows a sample of the eclipse profile of XTE J1710-281. All the 65 X-ray eclipse light curves were fitted with a five-parameter ramp function, and mid-eclipse times were determined. We fitted a constant and a linear model to the eclipse measurements between MJD 52132 - 54410. This gave an orbital period of 0.1367109674 (3) d (epoch MJD 51250.924540 (4)) and 1σ limits of 0.2×10^{-12} d d^{-1} and -1.6×10^{-12} d d^{-1}, on the orbital period derivative ($\dot{P}_{orb}$). Before and after the above mentioned MJD range, we found shifts in the mid-eclipse times. We refer to the periods before and after these shifts as three epochs in the orbital period.

Figure 6 shows the "observed minus calculated" (O - C) diagram for all the eclipse measurements of XTE J1710-281, obtained after subtracting the linear component obtained from epoch 2. It is obvious from the figure that a polynomial function consisting of linear (P_{orb}), quadratic ($\dot{P_{orb}}$), cubic ($\ddot{P_{orb}}$) etc terms cannot be fitted to the observed dataset. A piecewise linear function could be more appropriate. But, there are few observations in epoch 1, hence one cannot determine the orbital period during epoch-1, with very high accuracy. It appears that the second orbital period glitch occured around MJD 54847 (orbital cycle of 26308). We therefore put lower limits on orbital period changes of ΔP = 1.4 ms (1.7×10^{-8} d) between epoch-1 and epoch-2; and a ΔP = 0.56 ms (0.7×10^{-8} d) between epoch-2 and epoch-3. The detection significance of the two orbital period glitches are 11σ and 16σ respectively.

2.3. MXB 1658-298

The mid-eclipse time measurements of MXB 1658-298 were first given by Cominsky et al. (1989), using data obtained during the SAS-3 and HEAO-1, during the 1976 outburst. The source then underwent a long quiescent period of about 20 years until 1999, when it was detected in ourburst again. The outburst lasted for about 2.5 years and extensive observations were made with RXTE and Beppo-SAX. Wachter et al. (2000) reported eclipse measurements by using the *RXTE* data from initial few days of renewed activity. We have analyzed all the newer *RXTE*-PCA archival data, which covered a full X-ray eclipse. From data spread over more than 1 year (April 1999 - October 2000), we have found 24 complete eclipses (a detailed report will be presented in Jain et al. in preparation).

The mid eclipse times of MXB 1658-298 were determined by modeling each ingress and egress transition with a five-parameter "step and ramp" model, as done in case of XTE J1710-281. Sample of the eclipse profile is shown in Figure 7. We fitted a quadratic model to all the mid eclipse time measurements made between 1976 - 2000. The best fitting model gave an orbital period of 0.296504509 (8) d and a period derivative of 8.4 (9) $\times$ 10^{-12} d d^{-1} (at MJD 43058.72665 (11)). This imply an orbital evolution timescale of 97(10) Myr. The residual curve is plotted in Figure 8. The left panel shows the residuals of the present eclipse timing measurements, along with the previously known results. It is clear from the figure, that if secular orbital evolution is assumed, then there is difficulty in connecting the eclipse measurements with the earlier known results. The panel on right shows the expanded view for observations made between 1999 - 2000. One possibility is that there is a sinusoidal variation in the mid eclipse record of this source. This is shown with solid curve in the right panel. There is also possibility of an orbital period glitch, occuring around the orbital cycle of 29,000.

3. Discussion

This work presents measurement of orbital evolution in three systems, 4U 1822-37, XTE J1710-281 and MXB 1658-298. All of these are eclipsing low mass X-ray binaries; but the timescale of orbital evolution and the possible cause for the same are different in each source.

In 4U 1822-37, the measured rate of change of orbital period is much greater than that expected due to gravitational wave radiation. The timescales of orbital evolution due to tidal interaction between the components of the binary system range from a few Myr in HMXBs to about 10^{10} yr in LMXBs. Possibility of a conservative mass transfer in the system needs to be taken cautiously. It requires a large mass transfer rate corresponding to luminosity near the Eddington rate. This could be possible because the source is surrounded by a corona. It also requires a low magnetic field neutron star, similar to millisecond pulsars like SAX J1808.4-3658 (Jain et al. 2007). There is evidence of wind outflow, but no clear estimate of rate of wind outflow (Bayless et al. 2010). Secular changes, like magnetic cycling in the secondary star is also a possible mechanism, but in case of 4U 1822-37, the evolutionary history of the companion star is unknown (Munoz-Darias et al. 2005). We conclude that the orbital evolution in this system is complex including the effects of a large mass transfer rate and X-ray irradiated wind outflow.

The variation in the orbital ephemerides of XTE J1710-281, is significantly different from that seen in most of the other LMXB systems. During the period from MJD 52132 to MJD 54410, the limits on the orbital period derivative, is more than an order of magnitude smaller than those measured in the other LMXBs (4U 1820-30, SAX J1808.4-3658, Her X-1, X 2127+119 and 4U 1822-37. Outside the above MJD range, the observed trend in the residual (O-C) behaviour, is also different from that seen in the aforementioned LMXBs. Rate of orbital evolution is quite high. The observed O-C variation strongly resemble the one seen in EXO 0748-676, where, magnetic field cycling of the secondary star is proposed to be the likely mechanism for the observed trend in orbital evolution (Wolff et al. 2009). But in case of XTE J1710-281, the type of 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 timescales 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.

In MXB 1658-298, the mechanism behind the observed orbital evolution is uncertain. It is difficult to describe the eclipse measurements in simple terms. The most commonly used models for fitting the orbital ephemeris, such as a quadratic polynomial function can not be used in this case. If we consider a secular orbit evolution, there is difficulty in connecting to the old measurements. If there is an orbital period glitch, then we need not connect with old measurements, because there could be more glitches in the past. There could be a sinusoidal variation in the eclipse measurements, similar to the variation seen in the triple systems like 4U 1820-30 (Chou et al. 2001).

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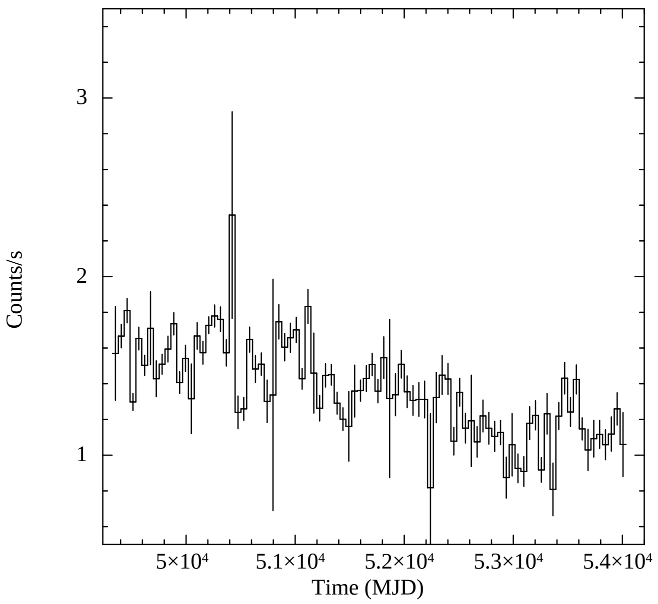

Figure 1: 1.5−12 keV *RXTE*-ASM light curve of 4U 1822-37, binned with 50 d.

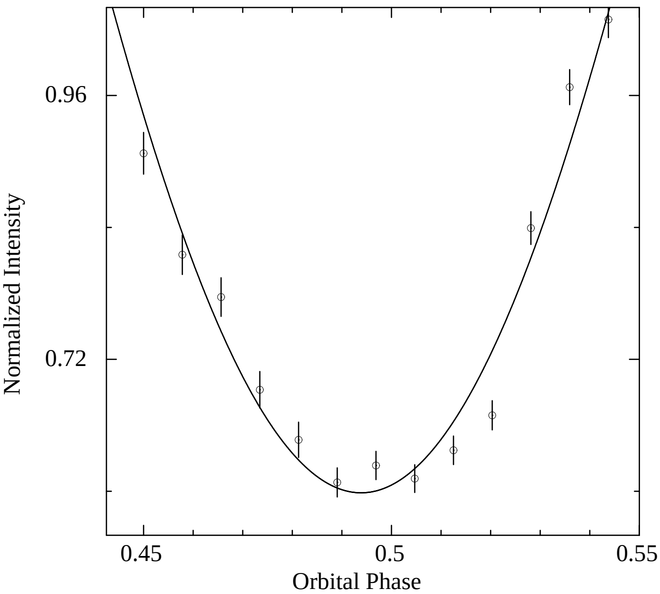

Figure 2: A sample of the eclipse phase of 4U 1822-37. The solid line shows the best fit Gaussian model.

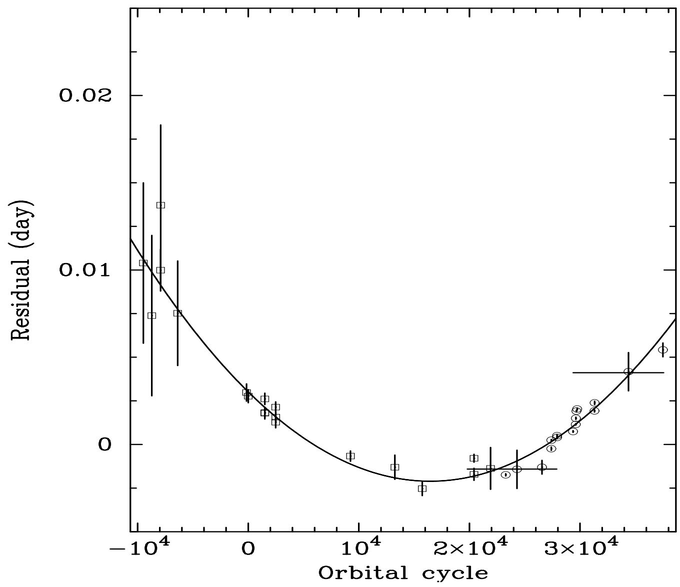

Figure 3: The mid eclipse time residuals of 4U 1822-37, relative to the best fit linear ephemeris (orbital period of 0.232108547 d).

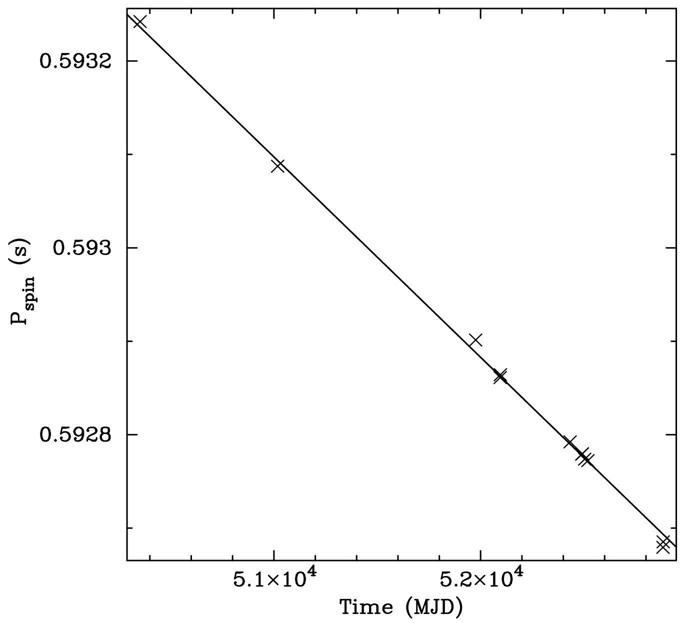

Figure 4: The spin period history of 4U 1822-37.

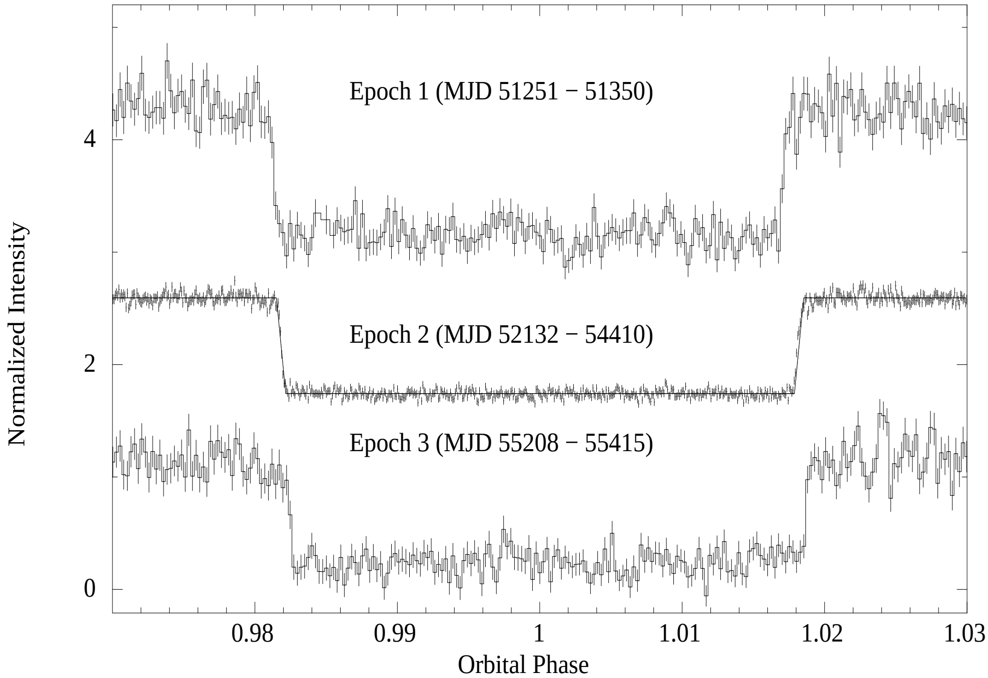

Figure 5: A sample of 2−20 keV folded light curve of XTE J1710-281. The light curves were folded with a period of 0.1367109674 d at an epoch of MJD 51250.924540. The normalised intensities during epoch-1 and epoch-2 have been rescaled. The solid line in the middle light curve (epoch 2) shows the best fit five-parameter model to the X-ray eclipse.

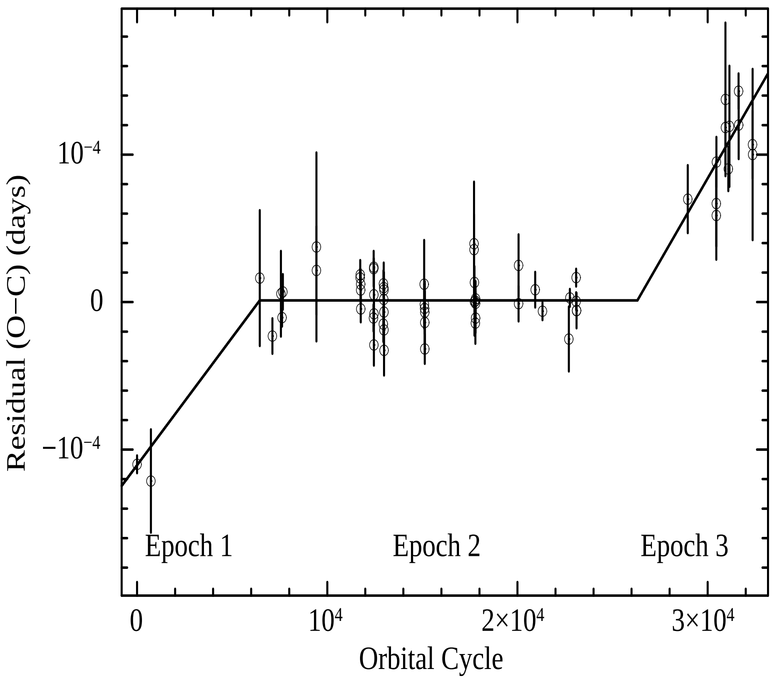

Figure 6: The observed minus calculated times (residuals, O-C) for eclipses observed in XTE J1710-281 during 1999-2010, obtained from *RXTE*-PCA observations.

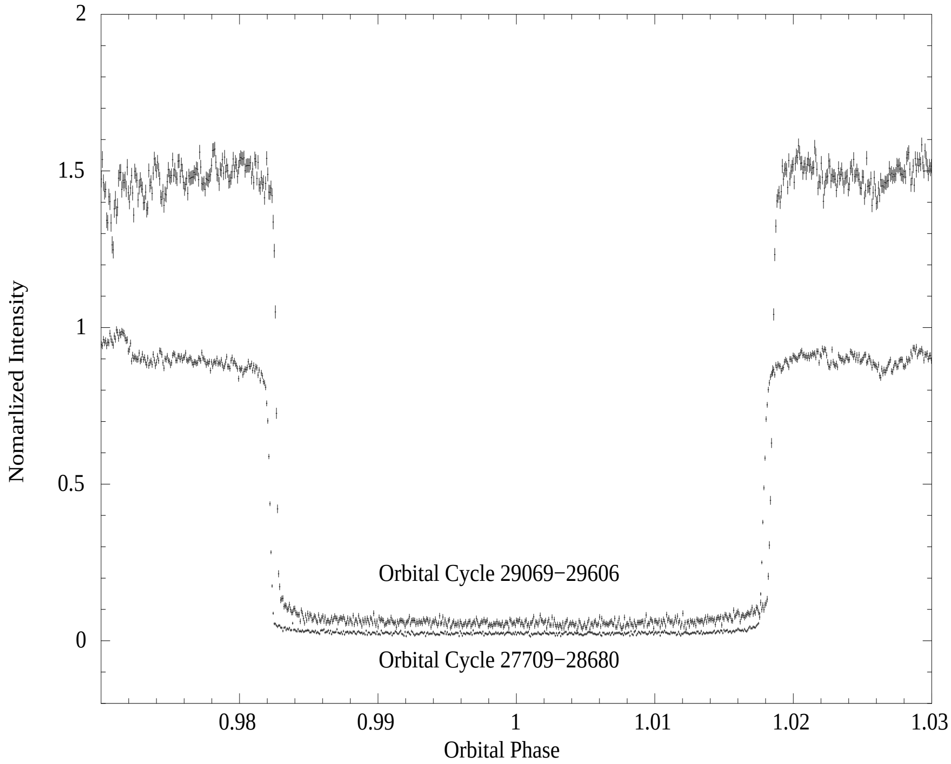

Figure 7: Average eclipse profile (ingress and egress) before and after a possible orbital glitch in MXB 1658-298.

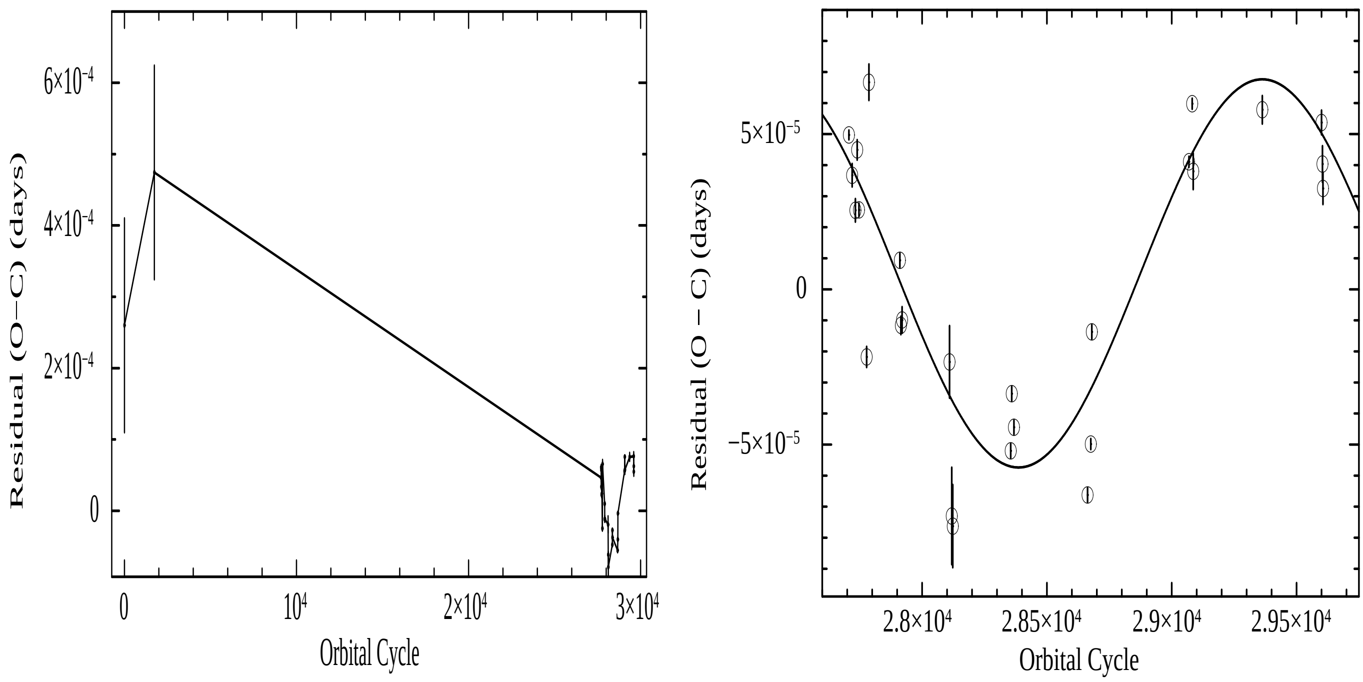

Figure 8: The mid-eclipse time residuals of MXB 1658-298, from observations made during 1976-2000. The O-C variation is plotted relative to the best-fitting linear ephemeris (orbital period of 0.2965045780 (9) d). The figure on right shows the expanded view of observations made between 1999 - 2000.