

Cyclical period changes in Z Chamaeleontis

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ABSTRACT

We report the identification of cyclical changes in the orbital period of the eclipsing dwarf nova Z Cha. We used times of mid-eclipse collected from the literature and our new eclipse timings to construct an observed-minus-calculated diagram covering 30 yr of observations (1972–2002). The data present cyclical variations that can be fitted by a linear plus sinusoidal function with period 28 ± 2 yr and amplitude 1.0 ± 0.2 min. The statistical significance of this period by an F -test is larger than 99.9 per cent. The derived fractional period change, $\Delta P/P = 4.4 \times 10^{-7}$, is comparable to that of other short-period cataclysmic variables (CVs), but is one order of magnitude smaller than those of the long-period CVs. Separate fits to the first and second halves of the data lead to ephemerides with quite different cycle periods and amplitudes, indicating that the variation is not sinusoidal or, most probably, is not strictly periodic. The observed cyclical period change is possibly caused by a solar-type magnetic activity cycle in the secondary star. An incremental variation in the Roche lobe of the secondary star of $\Delta R_{L2}/R_{L2} \simeq 1.7 \times 10^{-4}$ is required in order to explain both the observed period change and the modulation of the quiescent brightness previously reported by Ak, Ozkan & Mattei.

Key words: accretion, accretion discs – binaries: eclipsing – stars: dwarf novae – stars: evolution – stars: individual: Z Cha.

1 INTRODUCTION

Z Cha is a short-period ($P_{\text{orb}} = 1.78$ h) eclipsing cataclysmic variable (CV). In these binaries, a late-type star (the secondary) overfills its Roche lobe and transfers matter to a companion white dwarf (the primary). In most CVs the donor star has lower mass than the accreting star. As conservative mass transfer in such situations would lead to an increase in the orbital separation (and therefore the cessation of mass transfer via Roche lobe overflow), the existence of CVs as mass transfer binaries implies that they must continuously lose angular momentum in order to sustain the mass transfer process. As a consequence, the binary should evolve slowly towards shorter orbital periods (on time scales of 10^8 – 10^9 yr). Possible mechanisms suggested for driving the continuous angular momentum loss are magnetic braking via the wind of the secondary star (for $P_{\text{orb}} > 3$ h) and gravitational radiation (for $P_{\text{orb}} < 3$ h) (King 1988). At very short periods, when the secondary star becomes fully degenerate ($M_2 \lesssim 0.08 M_{\odot}$), mass loss leads to an expansion of this star and

reverses the secular trend, resulting thereafter in an increasing orbital period. However, the predicted mass transfer rate after this period minimum is low ($\dot{M}_2 \simeq 10^{-12} M_{\odot} \text{ yr}^{-1}$) and few CVs are expected to be observed in such evolutionary stage (Warner 1995).

The secular evolution of the binary can in principle be detected by measuring the changes in the orbital period of eclipsing CVs. Eclipses provide a fiducial mark in time and can usually be used to determine the orbital period (and its derivative) with high precision. However, attempts to measure the long-term orbital period decrease in CVs have been disappointing: none of the studied stars show a positive detection of an orbital period decrease (e.g. Beuermann & Pakull 1984). Instead, most of the well observed eclipsing CVs¹ show cyclical period changes (e.g. Bond & Freeth 1988; Warner 1988; Robinson, Shetrone & Africano 1991; Baptista, Jablonski & Steiner 1992; Echevarria & Alvarez 1993; Wolf et al. 1993; Baptista et al. 1995; Baptista, Catalán & Costa 2000). The most promising explanation of this effect seems to be the existence of a solar-type (quasi- and/or multi-periodic) magnetic activity cycle in the secondary star modulating the radius of its Roche lobe and, via

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¹ I.e. those with well-sampled observed-minus-calculated ($O - C$) eclipse timings diagram covering more than a decade of observations.

gravitational coupling, the orbital period on time scales of the order of a decade (Applegate 1992; Richman, Applegate & Patterson 1994). The relatively large amplitude of these cyclical period changes probably contributes to mask the low amplitude, secular period decrease.

Z Cha seemed to be a remarkable exception in this scenario. The eclipse timings analysis of Robinson et al. (1995) shows a conspicuous orbital period increase on a time-scale of $P/|\dot{P}| = 2 \times 10^7$ yr, not only at a much faster rate than predicted ($\approx 10^9$ yr) but also with the opposite sign to the expected period decrease.

In this Letter we report new eclipse timings of Z Cha which indicate a clear reversal of the period increase observed by Robinson et al. (1995). The revised $(O - C)$ diagram shows a cyclical period change similar to that observed in many other well studied eclipsing CVs. The observations and data analysis are presented in Section 2 and the results are discussed and summarized in Section 3.

2 OBSERVATIONS AND DATA ANALYSIS

Time-series of high-speed differential CCD photometry of Z Cha were obtained on 1995 October and 2000 April at the Laboratório Nacional de Astrofísica, Brazil, and on 2002 February at the South African Astronomical Observatory. The observations were performed under good sky conditions and covered a total of 11 eclipses while the target was in quiescence. The time resolution ranged from 10 to 30 s. The 2000 April run was made in white light (W). A summary of these observations is given in Table 1. Data reduction included bias subtraction, flat-field correction, cosmic ray removal, aperture photometry extraction and absolute flux calibration. A more complete analysis of these data will be presented in a separate paper. Here we will concentrate on the measurement of the mid-eclipse times.

Mid-eclipse times were measured from the mid-ingress and mid-egress times of the white dwarf eclipse using the derivative technique described by Wood, Irwin & Pringle (1985). For a given observational season, all light curves were phase-folded according to a test ephemeris and sorted in phase to produce a combined light curve with increased phase resolution. The combined light curve is smoothed with a median filter and its numerical derivative is calculated. A median-filtered version of the derivative curve is then analysed by an algorithm which identifies the points of extrema (the mid-ingress/egress phases of the white dwarf). The mid-eclipse phase, ϕ_0 , is the mean of the two measured phases. Finally, we adopt a cycle number representative of the ensemble of light curves and compute the corresponding observed mid-eclipse time (HJD) for this cycle including the measured value of ϕ_0 . This yields a single, but robust, mid-eclipse timing estimate from a sample of eclipse light curves. These measurements have a typical accuracy of about 4 s.

For Z Cha the difference between universal time (UT) and terrestrial dynamical time (TDT) scales amounts to 19 s over the data set. The difference between the barycentric and the heliocentric corrections is smaller than 1 s, as Z Cha is close to the ecliptic pole. The mid-eclipse timings have been calculated on the solar system bari-

Table 1. Log of the observations.

Date	Filter	Telescope	Cycles
1995 October 23	V	1.6 m/LNA	130 874, 130 875
2000 April 14	W	0.6 m/LNA	152 817–152 820
2002 February 12	R	1.9 m/SAAO	161 795, 161 797, 161 799
2002 February 13	R	1.9 m/SAAO	161 810, 161 812

Table 2. New eclipse timings.

Cycle	HJD (2 450 000+)	BJDD (2 450 000+)	$(O - C)^a$ (cycles)
130 874	0014.702 94	0014.703 58 (4)	+0.0115
152 818	1649.514 43	1649.515 15 (4)	−0.0043
161 803	2318.890 47	2318.891 19 (4)	−0.0072

^aObserved minus calculated times with respect to the linear ephemeris of Table 3.

centre dynamical time (BJDD), according to the code by Stumpff (1980). The TDT and ephemeris (ET) time-scales were assumed to form a contiguous scale for our purposes. The new eclipse timings are listed in Table 2. The corresponding uncertainties in the last digit are indicated in parentheses.

The data points were weighted by the inverse of the squares of the uncertainties in the mid-eclipse times. We arbitrarily adopted equal errors of 5×10^{-5} d for the optical timings in the literature (Cook & Warner 1984; Cook 1985; Wood et al. 1986; van Amerongen, Kuulkers & van Paradijs 1990), and a smaller error of 2×10^{-5} d for the timing of Robinson et al. (1995), half the error in our measurements, and combined the 74 timings to compute revised ephemerides for Z Cha. Table 3 presents the parameters of the best-fitting linear, quadratic and linear plus sinusoidal ephemerides with their 1σ formal errors quoted. We also list the rms values of the residuals and the $\chi^2_{\nu_2}$ value for each case, where ν_2 is the number of degrees of freedom.

Fig. 1 presents the $(O - C)$ diagram with respect to the linear ephemeris in Table 3. van Teeseling (1997) reports that a positive offset of 90 s (plus an additional offset of 0.0025 cycles) was needed in order to centre the x-ray eclipse of Z Cha around phase zero with respect to the ephemeris of Robinson et al. (1995). We used this information to assign a representative eclipse cycle to his measurement and to compute the $(O - C)$ value with respect to the linear ephemeris in Table 3. His X-ray timing is plotted as a cross in Fig. 1 and is fully consistent with our results.

The significance of adding additional terms to the linear ephemeris was estimated by using the F -test, following the prescription of Pringle (1975). Not surprisingly, the quadratic ephemeris is no longer statistically significant. From the σ_1 and σ_5 values in Table 3 we obtain $F(3, 69) = 130.7$, which corresponds to a 99.99 per cent confidence level for the linear plus sinusoidal ephemeris

Table 3. Ephemerides of Z Cha.

Linear ephemeris	
BJDD = $T_0 + P_0 E$	
$T_0 = 2\,440\,264.68\,070 (\pm 4)$ d	$P_0 = 0.074\,499\,304\,8 (\pm 5)$ d
$\chi^2_{\nu_2} = 49.2, \nu_2 = 72$	$\sigma_1 = 3.27 \times 10^{-3}$ cycles
Quadratic ephemeris	
BJDD = $T_0 + P_0 E + c E^2$	
$T_0 = 2\,440\,264.680\,88 (\pm 8)$ d	$P_0 = 0.074\,499\,300 (\pm 2)$ d
$c = (+2.8 \pm 1.1) \times 10^{-14}$ d	$\sigma_2 = 3.13 \times 10^{-3}$ cycles
$\chi^2_{\nu_2} = 48.0, \nu_2 = 71$	
Sinusoidal ephemeris	
BJDD = $T_0 + P_0 E + A \cos[2\pi(E - B)/C]$	
$T_0 = 2\,440\,264.6817 (\pm 1)$ d	$B = (120 \pm 4) \times 10^3$ cycles
$P_0 = 0.074\,499\,297 (\pm 2)$ d	$C = (136 \pm 7) \times 10^3$ cycles
$A = (7.2 \pm 1.0) \times 10^{-4}$ d	$\sigma_5 = 1.09 \times 10^{-3}$ cycles
$\chi^2_{\nu_2} = 3.99, \nu_2 = 69$	

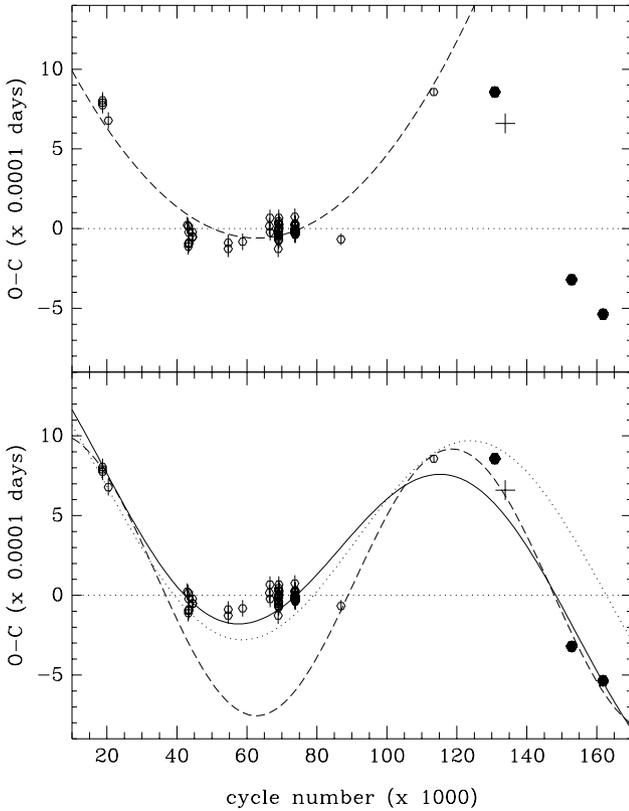


Figure 1. The $(O - C)$ diagram of Z Cha with respect to the linear ephemeris of Table 3. The optical timings from the literature are shown as open circles, the x-ray timing from van Teeseling (1997) is shown as a cross, and the new timings are indicated as solid circles. The dashed line in the upper panel depicts the quadratic ephemeris of Robinson et al. (1995) while the solid line in the lower panel shows the best-fitting linear plus sinusoidal ephemeris of Table 3. Best-fitting linear plus sinusoidal ephemerides for the data on the first half of the time-interval ($E < 80 \times 10^3$ cycle, dotted curve) and for the last half of the time-interval ($E > 80 \times 10^3$ cycle, dashed curve) are also shown in the lower panel.

with respect to the linear fit. The best-fitting linear plus sinusoidal ephemeris is shown as a solid line in the lower panel of Fig. 1.

However, the eclipse timings show systematic and significant deviations from the best-fitting linear plus sinusoidal ephemeris. The fact that $\chi^2_{\nu} > 1$ emphasizes that the linear plus sinusoidal ephemeris is not a complete description of the data, perhaps signalling that the period variation is not sinusoidal or not strictly periodic. We explored these possibilities by making separate fits to the first half of the data set ($E < 80 \times 10^3$ cycle) and to the second half of the data set ($E > 80 \times 10^3$ cycle). The results are shown in the lower panel of Fig. 1, respectively, as dotted and dashed curves. The older timings point towards a longer cycle period with a lower amplitude ($A = 1.13$ min, $P_{\text{cyc}} = 29$ yr), whereas the more recent timings are best described by a shorter cycle period of larger amplitude ($A = 1.23$ min, $P_{\text{cyc}} = 23$ yr). These results indicate that the period changes are not sinusoidal or not periodic.

3 DISCUSSION

Our results reveal that the orbital period of Z Cha is no longer increasing as previously found by Robinson et al. (1995). Instead,

the $(O - C)$ diagram shows conspicuous cyclical, quasi-periodic changes of amplitude 1 min on a time-scale of about 28 yr.

Cyclical orbital period changes are seen in many eclipsing CVs (Warner 1995 and references therein). The cycle periods range from 4 yr in EX Dra (Baptista et al. 2000) to about 30 yr in UX Uma (Rubenstein, Patterson & Africano 1991), whereas the amplitudes are in the range 0.1–2.5 min. Therefore, Z Cha fits nicely in the overall picture drawn from the observations of orbital period changes in CVs.

If one is to seek for a common explanation for the cyclical period changes in CVs, then models involving apsidal motion or a third body in the system shall be discarded as these require that the orbital period change be strictly periodic, whereas the observations show that this is not the case (Richman et al. 1994 and references therein). We may also discard explanations involving angular momentum exchange in the binary, as cyclical exchange of rotational and orbital angular momentum (Smak 1972; Biermann & Hall 1973) requires discs with masses far greater than those deduced by direct observations, and the time-scales required to allow the spin-orbit coupling of a secondary of variable radius are much shorter than the tidal synchronization scales for these systems ($\sim 10^4$ yr, see Applegate & Patterson 1987).

The best current explanation for the observed cyclical period modulation is that it is the result of a solar-type magnetic activity cycle in the secondary star (Applegate & Patterson 1987; Warner 1988; Bianchini 1990). Richman et al. (1994) proposed a model in which the Roche lobe radius of the secondary star R_{L2} varies in response to changes in the distribution of angular momentum inside this star (caused by the magnetic activity cycle), leading to a change in the orbital separation and, therefore, in the orbital period. As a consequence of the change in the Roche lobe radius, the mass transfer rate \dot{M}_2 also changes. In this model, the orbital period is the shortest when the secondary star is the most oblate (i.e. its outer layers rotate faster), and is the longest when the outer layers of the secondary star are rotating the slowest.

The fractional period change $\Delta P/P$ is related to the amplitude $\Delta(O - C)$ and to the period P_{mod} of the modulation by (Applegate 1992),

$$\frac{\Delta P}{P} = 2\pi \frac{\Delta(O - C)}{P_{\text{mod}}} = 2\pi \frac{A}{C}. \quad (1)$$

Using the values of A and C in Table 3, we find $\Delta P/P = 4.4 \times 10^{-7}$. This fractional period change is comparable to those of other short-period CVs, but is one order of magnitude smaller than those of the CVs above the period gap ($\Delta P/P \simeq 2 \times 10^{-6}$) (Warner 1995).

The predicted changes in Roche lobe radius and mass transfer rate are related to the fractional period change by (Richman et al. 1994),

$$\frac{\Delta R_{L2}}{R_{L2}} = 39 \left(\frac{1+q}{q} \right)^{2/3} \left(\frac{\Delta \Omega}{10^{-3} \Omega} \right)^{-1} \frac{\Delta P}{P}, \quad (2)$$

and by,

$$\frac{\Delta \dot{M}_2}{\dot{M}_2} = 1.22 \times 10^5 \left(\frac{1+q}{q} \right)^{2/3} \left(\frac{\Delta \Omega}{10^{-3} \Omega} \right)^{-1} \frac{\Delta P}{P}, \quad (3)$$

where $\Delta \Omega/\Omega$ is the fractional change in the rotation rate of the outer shell of the secondary star involved in the cyclical exchange of angular momentum, $q (= M_2/M_1)$ is the binary mass ratio, and the minus signs were dropped.

In the framework of the disc instability model (Smak 1984; Warner 1995 and references therein), the mass transferred from the secondary star will accumulate in the outer disc regions during the quiescent phase. Hence, changes in \dot{M}_2 will mainly affect the luminosity L_{bs} of the bright spot where the infalling material hits the outer edge of the disc. The luminosity of the bright spot is $L_{\text{bs}} \propto \dot{M}_2$. The bright spot in Z Cha contributes about 30 per cent of the total optical light (on an average over the orbital cycle) (Wood et al. 1986). Therefore, one expects that the changes in mass transfer rate lead to a modulation in the quiescent brightness of the system of $\Delta m = (\Delta L_{\text{bs}}/L) \simeq 0.3(\Delta \dot{M}_2/\dot{M}_2) \simeq (0.06 - 0.12)$ mag for $\Delta\Omega/\Omega = (1-2) \times 10^{-3}$ (Richman et al. 1994) and $q = 0.15$ (Wood et al. 1986).

Ak, Ozkan & Mattei (2001) reported the detection of cyclical modulations of the quiescent magnitudes and outburst intervals of a set of dwarf novae, which they interpreted as the manifestation of a magnetic activity cycle in their secondary stars. They found that the quiescent brightness of Z Cha is modulated with an amplitude of $\Delta m = 0.16$ mag on a time-scale of 14.6 yr. Unfortunately, they do not list the epoch of maximum brightness.

The observed amplitude of the brightness modulation is larger than that predicted from the orbital period change with the assumption of $\Delta\Omega/\Omega = (1-2) \times 10^{-3}$. The model of Richman et al. (1994) can account for both the measured period changes and the observed brightness modulation if $\Delta\Omega/\Omega \simeq 2.7 \times 10^{-3}$. This yields $\Delta R_{L2}/R_{L2} \simeq 1.7 \times 10^{-4}$.

The predicted change in the Roche lobe radius of the secondary star in Z Cha is comparable to the observed change in the radius of the Sun as a consequence of its magnetic activity cycle (Gilliland 1981). The period of the quiescent brightness modulation is very close to half of the period of the observed P_{mod} and may correspond to the first harmonic of a non-sinusoidal or non-strictly periodic period change.

The analysis of Ak et al. (2001) covers only 18 yr of observations. It would be interesting to see whether the 28 yr orbital period change also appear as a modulation in the quiescent magnitude in a data set covering a larger time-interval. A simple and interesting test of the Richman et al. (1994) model is to check its prediction that the maximum of the brightness modulation coincides with the minimum of the orbital period modulation, which occurred at $E \simeq 5.2 \times 10^4$ cycle (or about JD 2 444 150) for Z Cha.

Finally, we remark that, if the magnetic activity cycle explanation is right, our confirmation that Z Cha also shows cyclical period changes underscores the conclusion of Ak et al. (2001) that even fully convective secondary stars possess magnetic activity cycles (and, therefore, magnetic fields).

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