Possible detection of two giant extrasolar planets orbiting the eclipsing polar UZ Fornacis

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ABSTRACT
We present new high-speed, multi-observatory, multi-instrument photometry of the eclipsing polar UZ For in order to measure precise mid-eclipse times with the aim of detecting any orbital period variations. When combined with published eclipse times and archival data spanning ∼27 years, we detect departures from a linear and quadratic trend of ∼60 s. The departures are strongly suggestive of two cyclic variations of 16(3) and 5.25(25) years. The two favoured mechanisms to drive the periodicities are either two giant extrasolar planets as companions to the binary [with minimum masses of 6.3(1.5) and 7.7(1.2) M_Jup] or a magnetic cycle mechanism (e.g. Applegate’s mechanism) of the secondary star. Applegate’s mechanism would require the entire radiant energy output of the secondary and would therefore seem to be the least likely of the two, barring any further refinements in the effect of magnetic fields (e.g. those of Lanza et al.). The two-planet model can provide realistic solutions but it does not quite capture all of the eclipse times measurements. A highly eccentric orbit for the outer planet would fit the data nicely, but we find that such a solution would be unstable. It is also possible that the periodicities are driven by some combination of both mechanisms. Further observations of this system are encouraged.

Key words: accretion, accretion discs – methods: analytical – binaries: close – novae, cataclysmic variables – planetary systems – X-rays: stars.

1 INTRODUCTION
Approximately 20 per cent of the known cataclysmic variables (CVs; see the catalogue of Ritter & Kolb 2003) are polars, where the primary white dwarf has a sufficiently strong magnetic field to lock the system into synchronous rotation with the red dwarf secondary and to prevent completely the formation of an accretion disc.

The material from the secondary overflowing the Roche lobe initially falls towards the white dwarf following a ballistic trajectory until, at some distance from the white dwarf, the magnetic pressure overwhelms the ram pressure of the ballistic stream. From this point on, the accretion flow is confined to follow the magnetic field lines of the white dwarf. The now supersonic accreting material suddenly becomes subsonic at a shock region, which forms at some height above the white dwarf surface. The shock-heated material reaches temperatures of ∼10–50 keV and is therefore ionized. The hot plasma cools by X-ray cooling, in the form of bremsstrahlung radiation. With sufficiently strong magnetic fields we find also cyclotron cooling, in the form of optical/infrared cyclotron radiation (e.g. ST LMi; Imamura, Steiman-Cameron & Wolff 2000; Campbell et al. 2008). See e.g. Warner (1995) for a review of CVs and Cropper (1990) and Patterson (1994) for reviews of magnetic CVs.

UZ For is one of the 15 known eclipsing polars and was discovered with EXOSAT (EXO 033319−2554.2) as a serendipitous X-ray
source (Giommi et al. 1987; Osborne et al. 1988). Extensive follow-up observations at multiwavelengths established an ~126.5-min orbital period, one or two accretion spots depending on accretion state, with magnetic fields of ~53 and ~48 mG and a white dwarf mass of ~0.7 M⊙ (Berriman & Smith 1988; Beuermann, Thomas & Schwwope 1988; Ferrario et al. 1989; Bailey & Cropper 1991). The eclipses of the accretion spots in UZ For are particularly rapid at 1–3 s and can only be resolved with high-speed photometry. Bailey & Cropper (1991) were able to resolve the eclipse of the white dwarf photosphere during a low state, and Perryman et al. (2001) were able to resolve two accretion spots during a higher accretion state. These distinct rapid photometric transitions are ideal for making accurate timing measurements and therefore searching for any long-term period variations in UZ For. Some of the above-mentioned authors have combined their observations with previous eclipse measurements in order to obtain accurate eclipse ephemerides. In general, significant residuals were seen in the observed minus calculated (O – C) values of the orbital period, but no overall trend had been detected (e.g. Perryman et al. 2001). More recently, Dai et al. (2010) claim the existence of a third body orbiting UZ For in order to explain the O – C. However, their singular new eclipse measurement and subsequent derived orbital parameters are grossly incompatible with all of our new observations spanning ~10 years.

Nevertheless, recent results of long-term studies of some CV-related objects are beginning to show trends. Parsons et al. (2010) presented high-speed ULTRACAM photometry of eight post-common-envelope (post-CE) binaries. They detect significant departures from linearity in some of these systems and suggest magnetic braking or a third body as possible mechanisms to drive the O – C values. High-precision eclipse measurements of the post-CE binary NN Ser (Beuermann et al. 2010) show strong evidence for two additional bodies superposed on the binary’s linear ephemeris. Significant and complicated departures from a linear ephemeris have also been seen in the eclipsing polar HU Aqr (Schwarz et al. 2009). They find that neither a sinusoidal nor a quadratic ephemeris are sufficient to describe their O – C departures; thus, more eclipse observations over the next few years will be needed in order to refine the ephemerides. Qian et al. (2010) discovered that the O – C curve of the eclipsing polar DP Leo shows a cyclic variation with a period of 23.8 years. They claim that this is a result of a giant extrasolar planet orbiting DP Leo, recently refined by Beuermann et al. (2011).

Here we present new High-speed Photo-POlarimeter (HIPPO), Berkeley Visible Imaging Tube (BVIT), SALTICAM and University of Cape Town photo-polarimeter (UCTPOL) photometry of UZ For, spanning 10 years, and use these observations to determine accurate mid-eclipse times of the main accretion spot in UZ For. We combine these with previous mid-eclipse times, which we either measure from archival data or extract from the literature, and analyse for any period variations in UZ For. Note that adding these newer data to timing from the literature gives a baseline of 27 years.

2 OBSERVATIONS

All of the eclipse times extracted from the literature were published as Heliocentric Julian Dates. We have assumed that the Coordinated Universal Time (UTC) system was used in all cases as this was not explicitly stated in any of the publications. We recomputed all times for the light traveltime to the barycentre of the Solar system, converted to the barycentric dynamical time (TDB) system and the times are listed (Table 1) as Barycentric Julian Date (BJD; see Eastman, Siverd & Scott Gaudi 2010, for achieving accurate absolute times and time standards). By doing this we have removed any timing systematics, particularly due to the unpredictable accumulation of leap seconds with UTC, and effects due to the influence of primarily Jupiter and Saturn when heliocentric corrections only are applied. We either calculate or recalculate appropriate errors depending on the signal-to-noise ratio (S/N) and time resolution at the time of the spot ingress and egress. Table 1 also lists the eclipse depth of the accretion spot and the observatory/instrument used.

All of our new observations were also converted to BJD. We note that our new ground-based instruments were synchronized to GPS to better than a millisecond. Given the high-speed nature of these instruments, their timing accuracies have been verified through simultaneous multi-instrument observations. The remaining space observatories have documented reports on the performance of their on-board clocks.

2.1 Eclipse times from the literature

The earliest UZ For eclipse measurements were made using EXOSAT and published by Osborne et al. (1988). The data are of poor time resolution but are at a sufficiently early epoch to provide constraints for model fitting. Beuermann et al. (1988) and Ferrario et al. (1989) observed multiple eclipses spectrophotometrically. These are also of very low time resolution; however, the combination of multiple eclipses provides usable data. Allen et al. (1989) presented the first high-speed photometry that could resolve the accretion spot. A typographical error in the eclipse time was corrected by Ramsay (1994). This was soon followed with more high-quality optical low-state photometry by Bailey & Cropper (1991) and high-state photometry by Imamura & Steiman-Cameron (1998) and Extreme Ultraviolet Explorer (EUV) light curves by Warren, Sirk & Vallerga (1995). An additional high-quality STJ eclipse was also published by de Bruijne et al. (2002) and three more, with the same instrument, by Perryman et al. (2001). From the latter data we were able to obtain the raw observations and remeasure and confirm the eclipse times.

2.2 ROSAT (1991)

Observations were retrieved from the HEASARC archive and events were extracted using an aperture centred on the source and also a background region. The resulting light curves were subtracted after appropriate scaling from the differing areas. The observations spanned ~1 d and multiple eclipses were covered. The reduced data were binned and folded on the orbital period in order to produce a single eclipse light curve from which the eclipse was measured.

2.3 HST FOS (1992)

UZ For was observed by Hubble Space Telescope (HST) with FOS on 1992 June 11 in two consecutive, rapid mode observations consisting of 925 spectra each with 1.64 s exposure times. This data set was originally published in Stockman & Schmidt (1996), but their mid-eclipse times were not quoted. Therefore, the HST data products from this observation were downloaded from the HST archive at the Space Telescope Science Institute (MAST). The flux and wavelength-calibrated individual spectra were extracted and the flux summed up between 1255 and 1518 Å (far-UV) to create a light curve. The far-UV part of the spectrum was chosen as
Table 1. Mid-eclipse times of the main accretion spot of UZ For. BJD\textsubscript{TDB} is the BJD in the TDB system. Times have also been barycentrically corrected.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>BJD\textsubscript{TDB}+2400000</th>
<th>\Delta BJD\textsubscript{TDB}</th>
<th>Width (s)</th>
<th>Observatory/instrument</th>
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<td>468(2)</td>
<td>1.9 m/hippo</td>
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</table>

\textsuperscript{a}de Bruijne et al. (2002); \textsuperscript{b}Perryman et al. (2001); \textsuperscript{c}Imamura & Steiman-Cameron (1998); \textsuperscript{d}Warren et al. (1995); \textsuperscript{e}Ramsay (1994); \textsuperscript{f}Bailey & Cropper (1991); \textsuperscript{g}Allen et al. (1989); \textsuperscript{h}Ferrario et al. (1989); \textsuperscript{i}Beuermann et al. (1988); \textsuperscript{j}Osborne et al. (1988).

This seems to have the least contribution from the accretion stream. The end-times for each spectra were obtained from the observation header keywords and the group-delay time subtracted in order to obtain times of start of each exposure. Two consecutive eclipses were observed and folded and binned into a single eclipse from which measurements were made.

### 2.4 EUVE (1993 and 1995)

UZ For was observed with EUVE on 1993 November 18 and on 1995 January 15 for 102 and 76 ks, respectively. These data were retrieved from the STScI archive and reduced following the recipe from [http://archive.stsci.edu/euve/](http://archive.stsci.edu/euve/). Light curves were produced using the xray.xtiming package in IRAF with a 1 s time resolution. For each observation, multiple eclipses were covered which were folded and binned into two single eclipses from which measurements were made.

### 2.5 UCTPOL (2002 and 2005)

One unfiltered and two BG39-filtered eclipses were obtained in 2002 with the UCTPOL at 10 s time resolution. Two eclipse times were extracted: one from the unfiltered and the second from the folded BG39-filtered eclipses. Three unfiltered eclipses were obtained in 2005 at 10 and 1 s time resolution. Two eclipse times were extracted. On both occasions, simultaneous linear and circular polarimetric observations were also made and reduced as in Cropper (1985).
2.6 XMM Optical Monitor (2002)

Observations were made in fast mode using the XMM–Newton Optical Monitor (OM; Mason et al. 2001) between 2002 August 7 and 8, two orbits after UCTPOL observations. The UVW1 filter was used [centre wavelength 2910 Å, full width at half-maximum (FWHM) 500 Å] and the data were reduced using omfchain running under sas v9.0. Although three consecutive eclipses were observed, two had incomplete coverage. Nevertheless, upon folding and binning, a high S/N eclipse profile was obtained and eclipse measurements taken.

2.7 Swift (2005)

Observations were made in event mode using the Swift UV Optical Telescope (Roming et al. 2005) between 2005 February 2 and 6. There were a number of pointings, some lasting a few 100 s and others a few 1000 s. The U filter [centre wavelength 3450 Å, FWHM 875 Å] and the V filter were used. Light curves were extracted using apertures centred on the source (radius 3 arcsec) and also a source-free background region with much larger aperture radius. The light curve was generated by suitably scaling the size of the apertures. Two eclipses were observed in full, one of which was simultaneous with the UCTPOL observations.

2.8 SALTICAM (2007)

UZ For was observed with SALTICAM (O’Donoghue et al. 2006) on SALT on 2007 November 12. SALTICAM was in slot-mode configuration, allowing a time resolution of 1 s with no deadtime. The data were reduced using the SALT slottools data reduction package (Crawford et al. 2010). One eclipse of high time resolution and S/N was observed from which measurements were made.

2.9 BVIT (2009)

BVIT (Siegmund et al. 2008) is a visible photon counting detector designed as a guest facility on the SALT to provide very high time resolution (<25 ns) and high S/N, full imaging photometry. UZ For was observed during a BVIT commissioning run on 2009 January 25 simultaneous with the HIPPO on the 1.9-m telescope of the South African Astronomical Observatory. The data were extracted making use of the idl data reduction software developed by the instrument team and binned into 0.5 s bins. One eclipse of high time resolution and S/N was observed from which measurements were made.

2.10 HIPPO (2009 January and 2010 September, October and November)

Unfiltered photopolarimetric observations were made with the HIPPO (Potter et al. 2010) on four separate occasions and reduced as in Potter et al. (2010). The single eclipse in 2009 January was observed simultaneously with the BVIT observations. Multiple eclipses were observed on the other occasions which were folded and binned from which measurements were made.

3 RESULTS

3.1 The eclipses

A sample of our new and archival eclipse data is shown in Fig. 1 phased on our new ephemeris (see below and Table 2). The eclipse profiles are of varying quality and at multiple wavelengths. All of the eclipses can be understood in the framework of the standard polar model and from the general literature on UZ For (see Section 1). UZ For undergoes periods of either one- (e.g. Bailey & Cropper 1991) or two-pole (e.g. Perryman et al. 2001) accretion states, which has been most clearly captured by our SALTICAM (2007) and BVIT (2009) observations, respectively. During both accretion states the rapid fall and rise in flux at phases \( \sim -0.031 \) and \( \sim 0.031 \) correspond to the ingress and egress of the main accretion region. During the two-pole accretion state a second accretion region is additionally present, seen as the fall and rise in flux at phases \( \sim -0.027 \) and \( \sim 0.027 \). The remaining gradual fall and rise during phases \( \sim -0.031 \) to \( -0.025 \) and \( \sim 0.025 \) to 0.031 is attributed to the ingress and egress, respectively, of the white dwarf photosphere and takes about 40 s each.

3.2 The O–C

In Table 1 we list all of our new mid-eclipse times as well as those we have measured from archival data or extracted from the literature. The orbital period calculation of Perryman et al. (2001) was used to calculate the cycle number for each eclipse. The period is sufficiently accurate to unambiguously assign cycle counts to the entire \( \sim 27 \) years of eclipses. The eclipse observed in our 2005 UCTPOL, photometry was used to define the epoch (cycle 0). This period and epoch were next used as the starting point to perform a least-square quadratic fit with appropriate weighting set by the eclipse error measurements. The resulting fit gives a reduced \( \chi^2 \) > 95 with peak-to-peak residuals of \( \sim 60–80 \) s. Note that we have not included the eclipses of Diao et al. (2010) in our analysis as their O–C values are over \( 300 \) s compared to our quadratic ephemeris. We believe their measurement and/or time standard conversion to be in error.

It is immediately apparent that there are significant departures from the quadratic ephemeris with a trend that appears to be periodic (see top plot of Fig. 2 for residuals, albeit from a different quadratic fit, see below).

We next investigated the solutions resulting from models consisting of a quadratic plus an elliptical fit to the eclipse times. A best reduced \( \chi^2 \) of 6.2 was achieved. An F-test shows that it is the better model (compared to the quadratic ephemeris) with a confidence of \( >99.999 \) per cent even though the elliptical term adds five more parameters to the model.

However, significant residuals still remain \( \sim (10 \) s) for some of the eclipse times (not shown). We next attempted a simultaneous quadratic plus two ellipticals fit to the eclipse times. The second elliptical term adds further five parameters to the model, giving 13 in total. Therefore, given the large number of parameters, a grid of starting parameters for minimization was required in order to explore the resulting degeneracy in the solutions. Approximately \( 10^7 \) minimizations were calculated. During minimization all 13 parameters were free to vary. Predictably, the results have better reduced \( \chi^2 \) but with degeneracy in many of the parameters. Formally, the F-test confirms that adding a second elliptical term is the better model with a high level of confidence (\( >99.999 \) per cent) for the solutions with reduced \( \chi^2 = 1.0 \). Other solutions with reduced \( \chi^2 = 4.0 \) and 3.0 are also significantly better with a 98 and 99.9995 per cent confidence, respectively. We explore the degeneracy in the multidimensional \( \chi^2 \) space in Section 4.2.
Figure 1. A sample of our new eclipse observations phased on our new ephemeris (Section 4.2). Vertical grey bars indicate ingress and egress of the main accretion spot. Solid vertical bars indicate times of white dwarf ingress and egress assuming a duration of 40 s.

4 DISCUSSION

4.1 The O − C

Our results suggest that the deviations in the eclipse O − C are best described by the combination of a quadratic term plus two elliptical terms. This is highly suggestive of both secular and cyclic period variations.

Period changes in binary systems are generally understood to be due to gravitational radiation, magnetic braking, solar-type magnetic cycles in the secondary star (Applegate’s mechanism) and/or the presence of a third body in an orbit around the binary.

Applegate’s mechanism and/or the presence of a third body would be more consistent with cyclic variability. The latter would produce strictly periodic cycles, while non-strictly periodic cycles would be expected from the former mechanism. Therefore, we next look at each of these mechanisms in turn.

4.2 Tertiary and quaternary components

We now explore the degeneracy in the multidimensional $\chi^2$ space of the model fits containing one quadratic plus two elliptical terms in the context that the variations are due to the effect of third and
Table 2. Mid-eclipse ephemerides of the main accretion spot of UZ For and corresponding planet model parameters. Ephemeris parameters correspond to the representative solution (Fig. 3) and are rounded off to the 1σ errors. The planet parameter errors were calculated using the range in parameter space of possible solutions and not the smaller 1σ errors of any one fit. Minimum planet masses are listed assuming coplanarity. $M_{3,4,\text{fnc}}$ is the mass function. The combined mass of the primary and secondary stars is assumed to be $0.84\,M_\odot$.

<table>
<thead>
<tr>
<th>Quadratic term</th>
<th>$T_0 = 2453405.30086(3)$ d</th>
<th>Planet parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{bin}} = 0.087865425(2)$ d</td>
<td>$M_{3,\text{fnc}} = 2.9(1.1)10^{-7},M_\odot$</td>
</tr>
<tr>
<td></td>
<td>$A = -7(2)10^{-14}$</td>
<td>$M_{3,\text{Jup}} = 6.3(1.5)$</td>
</tr>
</tbody>
</table>

1st elliptical term

| $\nu_1 = (E + T_3)f_3$ | $P_3 = 16(3)$ years |
| $T_3 = 60383(416)$ (binary cycle) | $a_3 = 5.9(1.4)\,\text{au}$ |
| $f_3 = 0.000098(3)$ (cycles per binary cycle) | $a_{1,2} = 0.042(1)\,\text{au}$ |
| $\varpi_3 = 0.85(5)$ |
| $K_{\text{bin},(3)} = 0.00025(2)$ d |
| $e = 0.04(5)$ |

2nd elliptical term

| $\nu_4 = (E + T_4)f_4$ | $P_4 = 5.25(25)$ years |
| $T_4 = 4833(215)$ (binary cycle) | $a_4 = 2.8(5)\,\text{au}$ |
| $f_4 = 0.000288(2)$ (cycles per binary cycle) | $a_{1,2} = 0.025(1)\,\text{au}$ |
| $\varpi_4 = 1.20(6)$ |
| $K_{\text{bin},(4)} = 0.000141(6)$ d |
| $e = 0.05(5)$ |

Figure 2. The O − C after successive subtraction of the three terms comprising our new eclipse ephemeris. Top: O − C after subtraction of the quadratic term with the first elliptical term overplotted (dashed curve). Middle: O − C after subtraction of the first elliptical term with the second elliptical term overplotted (dashed curve). Bottom: the final O − C residuals after subtraction of the second elliptical term. Diamonds are our new data or data that we have reduced from archives. Crosses are eclipse times from the literature and converted (by us) to BJD$_{\text{TDB}}$.

fourth bodies in the system. Then the changes in the O − C arise because of the light-time effect caused by the gravitational influence of the additional bodies.

As a first step, we plot the distribution of the period of the two elliptical orbits for those solutions which had reduced $\chi^2 < 2.5$ (Fig. 3). The starting grid, for minimization, had period values between 2 and 50 years, and Fig. 3 shows that the minimized solutions have clustered in the period ranges $\sim 13$–$19$ and $\sim 5$–$5.5$ years.

All of the solutions with reduced $\chi^2 \leq 1.0$ ($\chi^2 \leq 28$, shown as the black crosses in Fig. 3) show periods centred on approximately
5.3 and 15 years, giving a period ratio of $R_p \sim 2.8$. The corresponding predicted eccentricities of these solutions are $\gtrsim 0.1$ for both ellipses. We performed $N$-body simulations on a sample of these solutions. The Euler method was used with sufficiently small time-steps to ensure accurate calculations. We tested the accuracy of our code by first applying it to single elliptical orbits comparable to the innermost high-eccentricity orbit. Our code preserves the eccentricity and the semimajor axis to better than 10 per cent, and the periastron angle to $<0.1\,\text{rad}$ over a time period corresponding to $>10^5\,\text{orbit}$s of the outermost body. We then defined orbital solutions that have essentially the same two-planet orbital elements to the starting conditions after $>10^5\,\text{orbit}$s of the longer period as stable. As expected, we found that they all are very unstable orbits and are therefore unrealistic solutions.

We next looked at the solutions with reduced $\chi^2$ in the range 1.0 $< \chi^2 < 2.5$, which are shown as the dark grey triangles in Fig. 3. They occupy a larger area of the plot which overlaps with the previous solutions. However, most of these solutions still require the longer period elliptical to have a large eccentricity (>0.1 and typically 0.4). $N$-body simulations within this parameter range also revealed unstable orbits.

We therefore identified those solutions which had orbital eccentricities $<0.1$ for both planets and which had stable orbits according to our $N$-body simulations. These are represented as the light grey diamonds in Fig. 3 which also overlap with the higher eccentric solutions presented above. However, the best of these solutions gives $\chi^2 = 58$ [28 degrees of freedom (d.o.f.), giving $\chi^2 = 2.06$], which is a significantly poorer fit compared to our best-fitting highly eccentric orbital solutions and also gives a formally poor fit to our data.

We note that our models assume the two planets to be coplanar. There may yet be a set of realistic, more eccentric solutions, if the planets have inclined orbits with respect to each other. We have not investigated this additional parameter space as our data set is of neither sufficient quality nor quantity to warrant it.

Given these caveats, in order to calculate the implied two-planet parameters, we selected the best-fitting low eccentric and stable solutions. Additionally, we applied period errors that encompass the whole range of solutions in Fig. 3. We note that the two-planet parameters calculated below are not specific to this one best-fitting solution but are representative of all the solutions with reduced $\chi^2 < 2.5$ shown in Fig. 3. The calculations are independent of the eccentricities. This particular solution is marked as the large black cross in Fig. 3; the two elliptical parameters are listed in Table 2 and overplotted on the O $-$ C in Fig. 2.

The amplitudes of the oscillations can be used to calculate the projected distances $a \sin i$ from the centre of mass of the binary to the centre of mass of each of the triple systems [0.042(1) and 0.025(1) au for the long and short, respectively]. Setting the binary mass to be $0.7\,M_{\odot}$ + 0.14$M_{\odot}$ gives the corresponding mass functions [$f(m_{1,4}) = 2.9 \times 10^{-3}\,M_{\odot}, 5.3 \times 10^{-3}\,M_{\odot}$]. With the binary inclination at $i = 80^\circ$ the respective minimum masses for the third and fourth bodies (assuming they are in the plane of the binary) are 0.006(1) and 0.007(1)$M_{\odot}$ and would therefore qualify as extrasolar giant planets [6.3(1.5) and 7.7(1.2)$M_{\text{Jup}}$] for orbital inclinations $i_3 > 25^\circ$ and $i_4 > 32^\circ$, respectively. The quoted errors include the range in periods shown in Fig. 3 and not the formal 1$\sigma$ errors of one of the solutions. In addition, the quoted errors include the propagated uncertainties in the inclination and binary mass. These parameters are summarized in Table 2.

The equation for the times ($T$) of mid-eclipse of the main accretion spot are then given by

$$T(\text{BJD}_{\text{TDB}}) = T_0 + P_{\text{bin}}E + AE^2$$

$$+ K_{\text{bin},(3)} \sin(\nu_1 - \sigma_1) \left[ \frac{1 - e_1^2}{1 + e_1 \cos(\nu_1)} \right]$$

$$+ K_{\text{bin},(4)} \sin(\nu_1 - \sigma_4) \left[ \frac{1 - e_4^2}{1 + e_4 \cos(\nu_4)} \right],$$

where $T_0$, $P_{\text{bin}}$, $A$ and $E$ are the time of epoch, the binary orbital period (days), the quadratic parameter (related to the rate of period decrease by $P_{\text{bin}} = 2A/P_{\text{bin}}$) and the binary cycle number which comprise the quadratic term of the ephemeris. In the context that the two elliptical terms are due to third and fourth bodies in the system, the parameters of the elliptical terms are $K_{\text{bin},(3,4)}$, the amplitudes of the eclipse time variations as a result of the light-traveltime effect of the two bodies; $\nu_1(3,4)$, the true anomalies of the two bodies, which progresses through $2\pi$ over the orbital periods [$P_{(3,4)}$] and are functions of $E$; the times of the periastron passages [$T_{(3,4)}$] and the orbital frequencies (in cycles per binary orbital cycle) of the two bodies ($f_{(3,4)}$). $e_{1,4}$ are the eccentricities and $\sigma_{(3,4)}$ are the longitudes of periastron passage measured from the ascending node in the plane of the sky. Similar elliptical variations have been seen in NN Ser and DP Leo (Beuermann et al. 2010, 2011).

Fig. 2 shows the fit and the O $-$ C residuals after successive subtraction of the three terms comprising our new eclipse ephemeris with parameters listed in Table 2. The top and middle plots show that the two elliptical terms describe the time of eclipse variations very well. The lower plot shows the final O $-$ C residuals after subtraction of the full ephemeris. Some residuals still remain, which could be reduced further if larger eccentricities were permitted, particularly for the outer planet. Such orbital solutions may exist, especially given the possible indication that the planets could be locked in a 3:1 ratio. However, better sampled observations are required to further constrain the solutions.

4.3 The secular variability

The secular variability amounts to a decrease in the orbital period of $P_{\text{bin}} = -1.56(5) \times 10^{-12}\,\text{s}^{-1}$. Of the 1416 solutions that comprise...
the ‘chosen’ parameter space (light grey area in Fig. 3) only one solution showed a \( P_{\text{obs}} \) consistent with 0. It has a reduced \( \chi^2 = 2.6 \). The rest predict a minimum in the period decrease rate of \( P_{\text{obs}} = -1.0 \times 10^{-12} \text{ s}^{-1} \). Formally, an F-test shows that adding the quadratic parameter to the ephemeris is the better model with a 99.99 per cent level of confidence (\( \chi^2 = 109 \) and 86 for 30 and 29 d.o.f. for the two models, respectively).

Similar levels of period decrease have been detected in other similar short period binaries, e.g. DF Leo (Schwope et al. 2002), NN Ser (Brinkworth et al. 2006) and HU Aqr (Schwarz et al. 2009), for which gravitational radiation and magnetic braking have been shown to be either insufficient or problematic in the framework of the standard CV evolutionary model. Future observations are needed to show if these variations are indeed secular or periodic.

### 4.4 Applegate’s mechanism

Applegate (1992) proposed that solar-like magnetic cycles would drive shape changes in the secondary, thus redistributing the angular momentum within the star, changing its oblateness. This then leads to a change in its quadrupole moment and consequently a change in orbital period at the expense of some energy. This has been the preferred mechanism to explain such cyclic variations in CVs and other long-period close binaries (Algol, RS CVn and W UMa stars).

Following the prescription of Applegate (1992), the energy required to generate a period change is

\[
\Delta E = \Omega_0 \Delta J + \frac{\Delta J^2}{2 \Omega_0}.
\]

The initial differential rotation \( \Omega_0 \Delta J \) is set to zero in order to calculate the minimum energy required. The effective moment of inertia \( I_{\text{eff}} = I_S + I_1 \) is calculated by assuming the star is separated into a shell \( I_S \) and a core \( I_1 \). We experimented with a range of shell masses. \( \Delta J \) is the change in angular momentum and is given by

\[
\Delta J = -\frac{G M^2}{R} \left( \frac{a}{R} \right)^2 \Delta P.
\]

We used the secondary star mass from Bailey & Cropper (1991), namely \( M = 0.14 M_\odot \), and the corresponding radius \( R = 0.177 R_\odot \) following Patterson (1984). \( a = 5.5 \times 10^8 \text{ m} \) is the binary separation using \( a = 3.53 \times 10^{10} (M_1/M_\odot)^{1/3} (1 + q)^{1/3} P_1^{2/3} (h) \) (Warner 1995, equation 21b). \( \Delta P \) can be obtained from equation (38) of Applegate (1992) relating the amplitude of orbital period modulation and the amplitude of the \( O - C \) oscillation:

\[
\frac{\Delta P}{P} = \frac{2 \pi (O - C)}{P_{\text{mod}}}.
\]

where \( P \) and \( P_{\text{mod}} \) are the orbital and modulation period, respectively (using \( P_3 \) as listed in Table 2). The solid curve in Fig. 4 shows the minimum energy required to drive the maximum observed period change in UZ For, as a function of assumed secondary shell mass. The two horizontal lines represent the total radiant energy of the secondary assuming \( 2880 < T_{\text{eff}} < 3020 \text{ K} \) and hence the amount of energy available.

The situation is not so clear cut if one instead integrates over shells and allows for the quadrupole moment of the core (using the calculations of Brinkworth et al. 2006). This raises the minimum energy by about an order of magnitude, perhaps by a factor of 2. Therefore, with further refinements, magnetic fields may yet be shown to be able to drive the period changes seen here.

### 4.5 Spot motion

The eclipse times are derived from the observed ingress and egress times of the accretion spot and not the centre of the white dwarf itself. Therefore, the observed \( O - C \) values could be a result of motion of the spot on the white dwarf. In addition, the ingress and egress of the white dwarf photosphere have been observed to take about 40 s (seen unambiguously in the low-state observations of Bailey & Cropper (1991) and confirmed in our low-state SALTICAM 2007 observations) and therefore could accommodate a ~40–60 s of spot motion.

To assess this possibility, we investigated the actual morphologies of the eclipse profiles in order to measure the relative phases of the white dwarf photosphere ingress and egress to that of the main accretion spot. Accordingly, we display a sample of our eclipse observations in Fig. 1 phase folded and binned on our new ephemeris. The two upper eclipse profiles are the HIPPO 2010 and the BVIT 2009 observations, respectively. These correspond to the two newest data points in Fig. 2 which show an \( O - C \) shift of ~30 s with respect to each other on the quadratic-subtracted \( O - C \) plot (Fig. 2, upper plot). Therefore, if the spot did indeed change locations, on the surface of the white dwarf, between these two observations, then we should observe a corresponding relative phase shift between spot ingress/egress to that of the white dwarf photosphere ingress/egress. However, one can see that the beginning of the white dwarf photosphere ingress (solid vertical line at phase ~0.026) is consistently ~40 s (0.005 phase) ahead of the spot egress (vertical grey bars) between these two observations. Thus, one would have expected the relative time difference between the white dwarf photosphere and spot to be shorter by ~30 s between the two observations and not approximately equal as observed. Therefore, we conclude that the spot has not moved on the surface of the white dwarf during these observations, at least within our measurable errors of about 1–5 s. The same relative phase difference (spot, white dwarf photosphere) is also apparent in the other eclipse profiles in which the spot and white dwarf photosphere are resolved (see the next five plots in Fig. 1 corresponding to the SALTICAM 2007, UCTPOL
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2005, Swift 2002, UCTPOL 2002 and SCAM 1999 observations). Furthermore, the same unchanging relative time differences are seen in the ingresses, although the white dwarf photosphere ingress emission may be complicated by an additional contribution from the accretion stream. The stream is not visible during the white dwarf photosphere egress, which can be understood from simple eclipse geometrical arguments, and confirmed through HST UV spectroscopy (Stockman & Schmidt 1996).

We note, however, that the longitude of the accretion spot should be expected to change during different accretion states. For example, Schwoppe et al. (2001) calculated a change in spot longitude of \( \sim 10^\circ \) between high and intermediate accretion states in the eclipsing polar HU Aqr. This would translate to about a shift of \( \sim 2-3 \) s in the \( O-C \) values (Schwarz et al. 2009) which therefore cannot account for the observed \( O-C \) values. This implies that if there was a similar spot motion in UZ For during different accretion states, it cannot account for the large shift seen in the measured \( O-C \) values.

Additionally, there was not any measurable movement of the spot in latitude during our observations. This is apparent from Table 1 where the eclipse width measurements agree within errors: a change in spot latitude would have resulted in a corresponding change in eclipse length.

5 SUMMARY AND CONCLUSION

We have detected departures in the eclipse times of UZ For from a simple quadratic ephemeris of up to \( \sim 60 \) s. The departures are suggestive of two periodicities of \( \sim 16 \) and \( \sim 5.25 \) years. The two favoured mechanisms to drive the periodicities are either two giant extrasolar planets as companions to the binary or a magnetic cycle mechanism (e.g. Applegate’s mechanism) of the secondary star. However, Applegate’s mechanism would require the entire radiant energy output of the secondary and therefore would seem to be the least likely of the two, barring any further refinements in the effect of magnetic fields (e.g. Lanza et al. 1998). A two-planet model is also problematic given the quality of the data in that a high eccentric orbit, for at least one of the planets, seems to be required to fully capture all of the eclipse times.

If it can be confirmed that the residuals are due to a third and a fourth body, then the planets formed either in a pre-CE circumbinary protoplanetary disc (first generation) or in a disc that resulted from the CE phase (second generation; Perets 2010). The separation of the progenitor binary is of the order of a few au, comparable to that of the planets, which implies that only second generation planets could have formed at the orbits suggested here. However, Beuermann et al. (2010) suggested that for the planets around NN Ser a slowly expanding CE could provide the dynamical force to drag inwards planets formed further out, which would have otherwise been lost to the system due to the decrease in mass of the central binary (Alexander, Chau & Henriksen 1976). In either case, we note that the semimajor axis of even the shortest period object poses no problem for orbit stability (Holman & Wiegert 1999).

It is intriguing that Qian et al. (2011) propose a very similar two elliptical model fit for the polar HU Aqr, also using eclipse timing results. In particular, they also find that the larger ellipse requires a high eccentricity (0.51) to correctly capture all of the data. Therefore, their two-planet model for HU Aqr seems to have a similar problem with orbit instabilities that we have found for UZ For.

As yet there is insufficient data on UZ For to identify conclusively the mechanism responsible for the periodic changes in its eclipse times, and indeed more than one mechanism could be present. Further good S/N, high time resolved observations of UZ For and other similarly eclipsing systems are encouraged.

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