Article:

Mhlahlo, N., Buckley, D.A.H., Dhillon, V.S. orcid.org/0000-0003-4236-9642 et al. (8 more authors) (2007) The discovery of a persistent quasi-periodic oscillation in the intermediate polar TX Col. Monthly Notices of the Royal Astronomical Society, 380 (1). pp. 133-141. ISSN 0035-8711

https://doi.org/10.1111/j.1365-2966.2007.12003.x

Mon. Not. R. Astron. Soc. **380,** 133–141 (2007) doi:10.1111/j.1365-2966.2007.12003.x

The discovery of a persistent quasi-periodic oscillation in the intermediate polar TX Col

N. Mhlahlo,[1★] D. A. H. Buckley,[2] V. S. Dhillon,[3] S. B. Potter,[2] B. Warner,[1] P. Woudt,[1] G. Bolt,[4] J. McCormick,[5] R. Rea,[6] Denis J. Sullivan[7] and F. Velhuis[5]

[1]*Astronomy Department, University of Cape Town, Rondebosch 7700, Cape Town, South Africa*
[2]*South African Astronomical Observatory, Observatory 7935, Cape Town, South Africa*
[3]*Physics and Astronomy Department, University of Sheffield, Sheffield S3 7RH*
[4]*Centre for Backyard Astrophysics (Perth), 295 Camberwarra Drive, Craigie, Western Australia 6025, Australia*
[5]*Centre for Backyard Astrophysics (Pakuranga), Farm Cove Observatory, 2/24 Rapallo Place, Farm Cove, Pakuranga, Auckland, New Zealand*
[6]*Centre for Backyard Astrophysics (Nelson), Regent Lane Observatory, Nelson, New Zealand*
[7]*Department of Physics, Victoria University of Wellington, Wellington, New Zealand*

Accepted 2007 May 21. Received 2007 May 19; in original form 2007 April 25

ABSTRACT

We report on the detection of an ∼5900 s quasi-periodic variation in the extensive photometry of TX Col spanning 12 yr. We discuss five different models to explain this period. We favour a mechanism where the quasi-periodic variation results from the beating of the Keplerian frequency of the 'blobs' orbiting in the outer accretion disc with the spin frequency and from modulated accretion of these 'blobs' taking place in a shocked region near the disc/magnetosphere boundary.

Key words: accretion, accretion discs – novae, cataclysmic variables.

1 INTRODUCTION

TX Col was first discovered as an X-ray source (1H0542-407) in the HEAO-1 all-sky survey. X-ray (EXOSAT) and optical observations (Tuohy et al. 1986; Buckley & Tuohy 1989a) established this system as a new intermediate polar (IP), a subclass of magnetic cataclysmic variable stars (mCVs) where the white dwarf is in asynchronous rotation with the orbital motion of the system. A white dwarf rotation period of ∼1911 s and an orbital period of ∼5.7 h were determined from a combination of radial velocity, X-ray and optical intensity modulations. TX Col showed very hard X-ray spectra ($kT \geqslant 10$ keV) with the hard X-rays modulated strongly at the beat period (2106 s). The hard X-rays are thought to result due to a strong shock forming above the white dwarf surface where the accreted material is heated to high temperatures (∼10^8 K; Norton et al. 1997) and are reflected and reprocessed in regions fixed in the binary frame (the bright spot or the secondary), producing the beat period.

Observed changes in the amplitude and the power spectra of the optical light curves of TX Col over a long period of time (1989–2002), signifying variations in its accretion behaviour, have sparked a debate concerning the exact accretion mode in TX Col: whether or not accretion occurs via a disc, directly from the accretion stream or some combination of both (known as disc-overflow accretion; Norton et al. 1997).

The detection by Tuohy et al. (1986) and Buckley & Tuohy (1989a) of the beat period in the photometry and X-rays was indicative of strong disc-overflow, stream-fed accretion or even reprocessing from regions that are fixed in the rotating frame of the binary.

Later optical photometry in 1989 (Buckley & Sullivan 1992) showed a persistent periodicity at ∼1054 s, exactly half the previously observed beat period of ∼2106 s. This 1054-s harmonic was not seen in the previously published photometry and was attributed to reprocessing of X-rays from both magnetic poles in regions fixed in the orbital phase. This could also be due to direct or overflowing stream of material flipping between the two magnetic poles of the white dwarf.

Further optical photometry of TX Col was obtained at the South African Astronomical Observatory (SAAO), Cerro Tololo Inter-American Observatory (CTIO) and the Mt John University Observatory (MJUO) in 1994 (Buckley 1996), which no longer showed either the beat period or its harmonic, but instead revealed a strong period near 6000 s and other quasi-periodic light variations at similar low frequencies. Our 2002 observations reported here, together with those obtained by the Centre for Backyard Astrophysics (CBA), show that TX Col power spectra were dominated by high-amplitude quasi-periodic light variations in 2002. A prominent quasi-periodic oscillation (QPO) period at ∼5900 s (∼170 μHz) was detected, the same period as detected in the data of 1990 and 1994.

The purpose of this study is to investigate the origin/cause of this oscillation. We start by presenting the photometry of TX Col in Section 2, and in Section 3 we analyse the entire data set, that is, our 2002 data and the archival data from 1989 to 1994. The analysis of the QPO period is done in Section 4, and in Section 6 we discuss and interpret the results.

★E-mail: nceba@maia.saao.ac.za

Table 1. Observation table of the 2002 photometry of TX Col obtained over a period of a month at the SAAO and by the CBA stations in New Zealand and Australia. HJD (start) marks the start time of the observing run in Heliocentric Julian Days (HJD).

Observing date	Place	HJD (start) 245 0000+	Exposure time (s)	Length (h)
2002 January 2	CBA: Pakuranga	2276.8955	35	6.7
2002 January 5	CBA: Perth	2280.0609	54	4.1
2002 January 6	CBA: Pakuranga	2280.8871	35	3.9
2002 January 10	CBA: Perth	2285.0623	54	5.6
2002 January 10	CBA: Perth	2286.0304	54	3.2
2002 January 15	SAAO	2290.4031	20	5.0
2002 January 16	CBA: Pakuranga	2290.8856	35	6.3
2002 January 16	SAAO	2291.3113	20	3.3
2002 January 18	SAAO	2293.2848	20	8.0
2002 January 19	CBA: Perth	2294.0340	54	6.4
2002 January 19	SAAO	2294.2872	20	8.0
2002 January 20	CBA: Pakuranga	2294.8728	35	7.1
2002 January 20	CBA: Perth	2295.0630	54	5.7
2002 January 20	SAAO	2295.2811	20	8.2
2002 January 21	SAAO	2296.3296	20	6.7
2002 January 22	CBA: Pakuranga	2296.8773	35	7.1
2002 January 22	SAAO	2297.3502	20	6.0
2002 January 23	CBA: Nelson	2297.8740	35	5.9
2002 January 23	CBA: Pakuranga	297.9040	35	1.7
2002 January 23	SAAO	2298.2809	20	5.0
2002 January 25	SAAO	2299.2905	20	4.3
2002 January 26	SAAO	2301.4193	20	4.4
2002 January 27	CBA: Perth	2302.0760	54	4.9
2002 January 27	SAAO	2302.2681	20	8.1
2002 January 28	New Zealand	2302.8933	35	3.7
2002 January 29	CBA: Pakuranga	2303.8625	35	6.9
2002 January 29	CBA: Nelson	2303.8877	35	5.5
2002 January 29	SAAO	2304.2765	20	7.6
2002 January 30	CBA: Nelson	2304.8810	35	7.4
2002 January 31	CBA: Perth	2306.0758	54	4.6
2002 January 31	SAAO	2306.2631	20	4.8
2002 February 1	CBA: Perth	2307.0115	54	5.7
2002 February 1	SAAO	2307.2613	20	7.8
2002 February 2	SAAO	2308.2611	20	7.8
2002 February 3	CBA: Nelson	2308.9022	40	5.3
2002 February 3	SAAO	2309.2672	20	6.7
2002 February 4	SAAO	2310.2608	20	7.8
2002 February 6	CBA: Nelson	2311.8649	40	6.3

2 PHOTOMETRIC OBSERVATIONS

The optical photometry of TX Col was obtained at SAAO in 2002 January using the 1.0-m telescope at Sutherland with the University of Cape Town (UCT) CCD photometer in frame-transfer mode using *B* and *I* filters. Additional photometry was obtained by the CBA group nearly at the same period. The archival data obtained from SAAO, MJUO and CTIO, from 1989 to 1994, were retrieved and analysed alongside the CBA and our 2002 photometry. No filters were used for the CBA and the archival data.

The photometry was grouped and analysed in three sections: the SAAO and the CBA data sets combined (hereafter the 2002 combined photometry), the 1989, the 1990, the 1991 and the 1994 data sets combined (hereafter the archival photometry) and the 2002 combined data together with the archival photometry combined (hereafter the 1989–2002 combined photometry).

Table 2. Observation table for photometry obtained from near the end of 1989 to near the end of 1990, in 1991 and 1994 at SAAO and at MJUO.

Observing Date	Place	HJD (start) 244 0000+	Exposure time (s)	Length (h)
1989 November 26	SAAO	7857.2898	10	7.2
1989 November 28	MJUO	7858.9643	10	4.3
1989 November 29	MJUO	7859.9037	10	4.9
1990 January 18	SAAO	7910.3101	10	1.2
1990 January 19	SAAO	7911.3036	10	1.8
1990 September 16	SAAO	8150.5609	5	2.2
1990 September 21	SAAO	8156.4647	10	4.3
1990 November 9	SAAO	8205.3513	10	6.0
1990 November 12	SAAO	8208.3624	10	5.7
1990 November 20	SAAO	8216.4194	20	4.2
1990 December 18	SAAO	8244.3007	10	7.0
1990 December 19	SAAO	8245.3192	10	6.6
1990 December 20	SAAO	8246.2972	10	7.0
1990 December 21	SAAO	8247.2986	10	6.7
1990 December 22	SAAO	8248.2979	10	7.1
1990 December 23	SAAO	8249.2983	10	7.2
1990 December 24	SAAO	8250.3812	10	1.0
1990 December 24	SAAO	8250.4514	10	3.5
1991 April 10	SAAO	8357.2506	10	3.4
1991 April 12	SAAO	8359.2727	10	3.0
1991 April 13	SAAO	8360.2279	10	2.5
1991 April 18	SAAO	8365.2443	10	2.4
1991 October 31	SAAO	8561.3939	10	3.3
1991 November 1	SAAO	8562.3618	10	5.9
1991 November 2	SAAO	8563.3508	10	6.4
1991 November 3	SAAO	8564.3396	10	6.2
1991 November 4	SAAO	8565.3481	10	6.4
1991 November 5	SAAO	8566.3897	10	3.2
1991 November 8	SAAO	8569.4055	10	4.5
1991 November 9	SAAO	8570.3421	10	4.0
1991 November 11	SAAO	8572.3390	10	4.0
1991 December 9	SAAO	8599.9170	10	5.6
1991 December 10	SAAO	8600.9501	10	4.7
1994 January 10	MJUO	9363.0505	5	2.2
1994 January 11	MJUO	9363.9155	5	5.7
1994 January 11	SAAO	9364.3142	5	5.2
1994 January 12	MJUO	9364.9178	5	4.2
1994 January 13	SAAO	9366.3508	5	5.2
1994 January 14	SAAO	9367.3141	5	3.8
1994 January 14	SAAO	9367.4797	5	1.3
1994 January 15	SAAO	9368.3107	5	6.1
1994 January 15	CTIO	9367.5792	10	2.1
1994 January 16	MJUO	9368.9178	5	3.9
1994 January 16	CTIO	9368.5783	10	2.4
1994 January 16	SAAO	9369.2957	5	5.4
1994 January 17	CTIO	9369.5518	10	2.2
1994 January 17	SAAO	9370.3225	5	5.0
1994 January 18	CTIO	9370.5740	10	1.4

2.1 The 2002 combined data reduction

For the SAAO observations, the integration times were 20 s. Sky flat-fields were taken at twilight throughout the observation week. The observation period was nearly three weeks and 6349 *B*-band images in total were taken. The data were reduced using the DOPHOT program (Mateo & Schechter 1989). The CBA photometry was acquired during the period from 2002 January 2 to 2002 February 6 spanning the entire SAAO campaign. CBA observers in Australia (Perth) and New Zealand (Pakuranga and Nelson) participated in

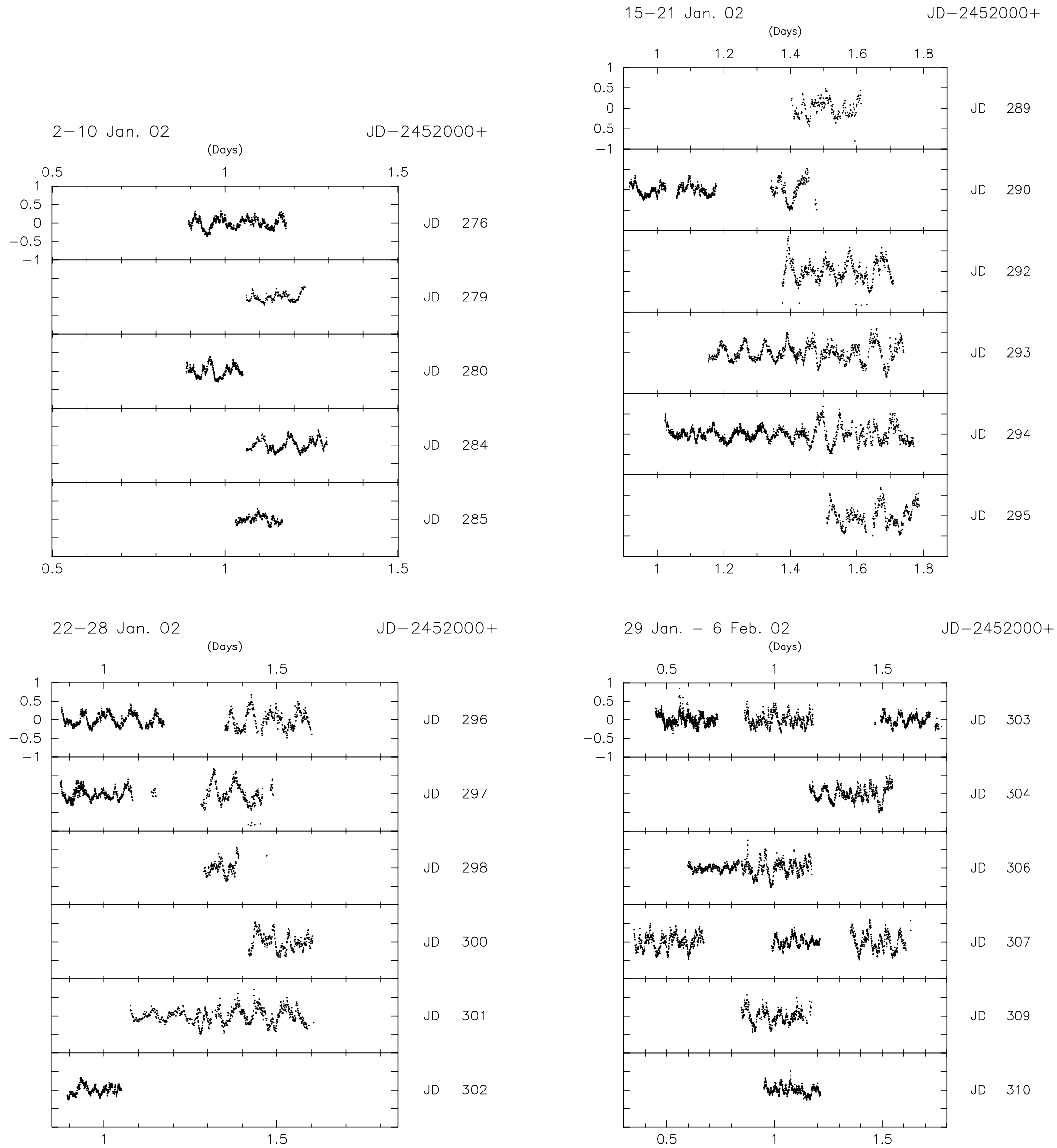

Figure 1. TX Col light curves obtained from January 2 to February 6 2002 at SAAO and by CBA groups in New Zealand and Australia. The ordinates are intensity measurements with the mean subtracted and normalized. The value 1 on the *x*-axis corresponds to the JD value shown to the right-hand side of the plots. Time is plotted on the abscissa, that is, the values on the horizontal axis add or subtract to the JDs, depending on whether the data points lie before or after the value 1 on the *x*-axis.

the 2002 campaign. A 0.35-m Schmidt–Cassegrain telescope with a Santa Barbara Instruments Group (SBIG) ST6 CCD camera (CBA: Nelson), Meade LX200 10-inch f/10 with an SBIG ST7e CCD camera (CBA: Pakuranga) and 10-inch f6.3 LX200 SBIG ST7 CCD camera (CBA: Perth) were used. Table 1 shows the observation logs.

The CBA and the SAAO photometry were combined before the analyses. Before analysis of the two data sets, all the data were converted from magnitude scale into relative intensity scale and the mean for each set subtracted and used to normalize. This was done because the data were obtained from different instruments in different scales. A sample of the normalized light curves of the 2002 combined photometry is shown in Fig. 1. The SAAO data show excursions (large variations in amplitude) which are not seen in the CBA data. They are possibly due to the effect of the filter.

2.2 The archival data and the 1989–2002 combined photometry

The white-light archival photometry obtained in 1989 November, 1990 January, 1990 September, 1990 November and 1990 December, 1991 April, 1991 November and 1991 December and in 1994 January at the SAAO, the MJUO and the CTIO was also analysed. The SAAO 0.75- and 1.0-m telescopes were used with the UCT photometer employing a photomultiplier. For the MJUO observations, a two-channel photomultiplier photometer attached to the McClellan 1.0-m telescopes was used. Table 2 shows the observations.

3 PERIOD ANALYSIS

Discrete Fourier transforms (DFTs) were produced (Kurtz 1985) to reveal the periodicities in the data. The results are displayed in

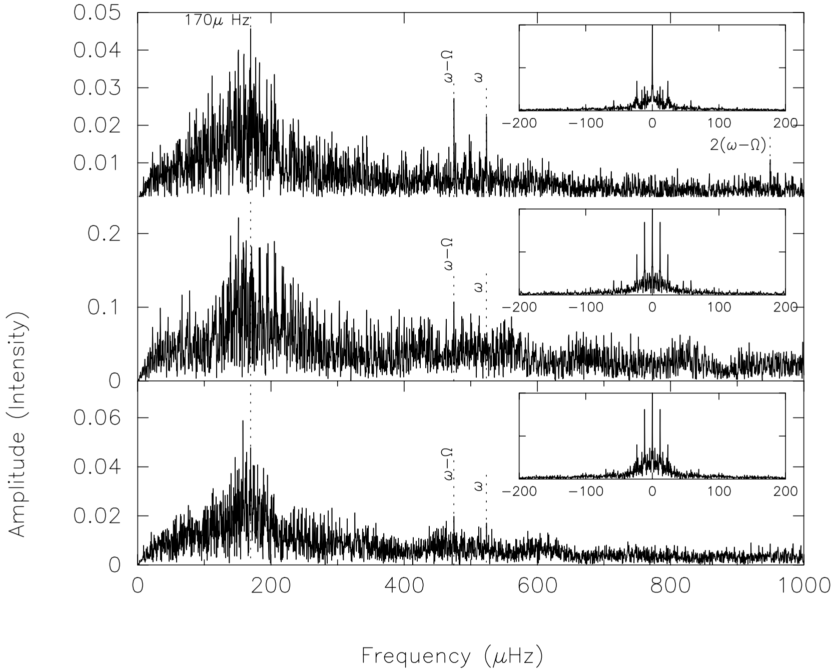

Figure 2. Amplitude spectra of the CBA data (bottom panel), the SAAO data (middle panel) and the 2002 combined data (top panel). The inserts shown are the window spectra for each data set.

Fig. 2 for the 2002 combined photometry. The spin and the beat frequencies are detected at $\omega = 523.636 \pm 0.019$ μHz and $\omega - \Omega = 474.788 \pm 0.014$ μHz, respectively. More accurate values of the beat, the harmonic of the beat and the spin frequencies of TX Col were determined from the 1989–2002 combined photometry. Values of $\omega - \Omega = 474.803\,499 \pm 0.000\,089$ μHz ($2106.134\,44 \pm 0.000\,40$ s), $\omega = 523.584\,953 \pm 0.000\,099$ μHz ($1909.909\,74 \pm 0.000\,36$ s) and $2(\omega - \Omega) = 949.447\,975 \pm 0.000\,018$ μHz ($1053.243\,56 \pm 0.000\,02$ s) were measured. It should be noted that the errors quoted above are formal estimates from DFTs after fitting by least squares a sinusoid to the data, and therefore are optimistic. However, spectral windows show no cycle count ambiguity for the total DFT, suggesting that the periods are stable (this can be seen in Fig. 4).

The 1989–2002 combined photometry, however, does not show any modulation at the orbital frequency, and the orbital frequency was determined by taking the difference between the spin and the beat frequencies and was found to be $\Omega = 48.781\,454 \pm 0.000\,013$ μHz ($5.694\,3317 \pm 0.000\,0015$ h). The orbital period and the spin period were used to derive the orbital and the spin radial velocity ephemerides, respectively (Mhlahlo et al., in preparation).

4 QUASI-PERIODIC OSCILLATIONS

The 2002 combined photometry (Fig. 2, upper panel) shows high-amplitude QPOs with a dominant QPO frequency appearing at ∼170 μHz.

To check if this QPO peak was due to noise, the data were subjected to a Fisher Randomization test (Fisher 1935). This involves the construction of an artificial data set of the same mean and the same standard deviation as the original, and the random swapping of the y-data values while the x-data values are kept the same. The y values are randomly moved so that they are associated with different x points. Periodograms of the swapped data are then computed (10 000 times in this case) and the height of the resulting noise peaks in the 10 000 periodograms compared with that of the peaks in the original periodogram. Any peak in the original periodogram with a height less than that in the swapped data is most likely a noise peak and is rejected. The lower the number of periodograms with higher peaks, the better. This means that the probability that the peak under examination is a noise peak is $n/10\,000$, where n is the number of periodograms with higher peaks. Strictly speaking, this is not a confidence level. This method is non-parametric in a sense that it does not rely on a model specified in terms of a set of unknown parameters. It just gives an indication of the believability of the peak. After this exercise, it was found that the QPO was likely not due to noise.

Table 3. Measured amplitudes and phases at QPO peak maximum obtained from least-squares fitting of the 169.56 μHz QPO to the 2002 combined photometry from 15 to 23 January 2002. The first data point, HJD = 245 2291.311 340, of 16 January (SAAO) was used as a phase reference point. NZ and Aust. denote data obtained in New Zealand and Australia, respectively, by the CBA group. 'Norm. intensity' refers to normalized intensity.

Date (2002)	Place	Amplitude (norm. intensity)	Phase of maximum (cycles)
January 15	SAAO	0.04 ± 0.02	0.1 ± 0.09
January 16	CBA (NZ)	0.03 ± 0.01	0.97 ± 0.04
January 16	SAAO	0.30 ± 0.01	0.39 ± 0.01
January 18	SAAO	0.13 ± 0.02	0.13 ± 0.02
January 18	CBA (Aust.)	0.20 ± 0.01	0.28 ± 0.01
January 19	SAAO	0.22 ± 0.01	0.317 ± 0.01
January 20	CBA (NZ)	0.10 ± 0.01	0.35 ± 0.01
January 20	CBA (Aust.)	0.10 ± 0.01	0.37 ± 0.01
January 20	SAAO	0.14 ± 0.01	0.1 ± 0.02
January 21	SAAO	0.07 ± 0.02	0.21 ± 0.04
January 22	CBA (NZ)	0.15 ± 0.01	0.48 ± 0.01
January 22	SAAO	0.21 ± 0.01	0.60 ± 0.01
January 23	CBA (NZ)	0.11 ± 0.01	1.00 ± 0.01
January 23	SAAO	0.22 ± 0.02	0.62 ± 0.01

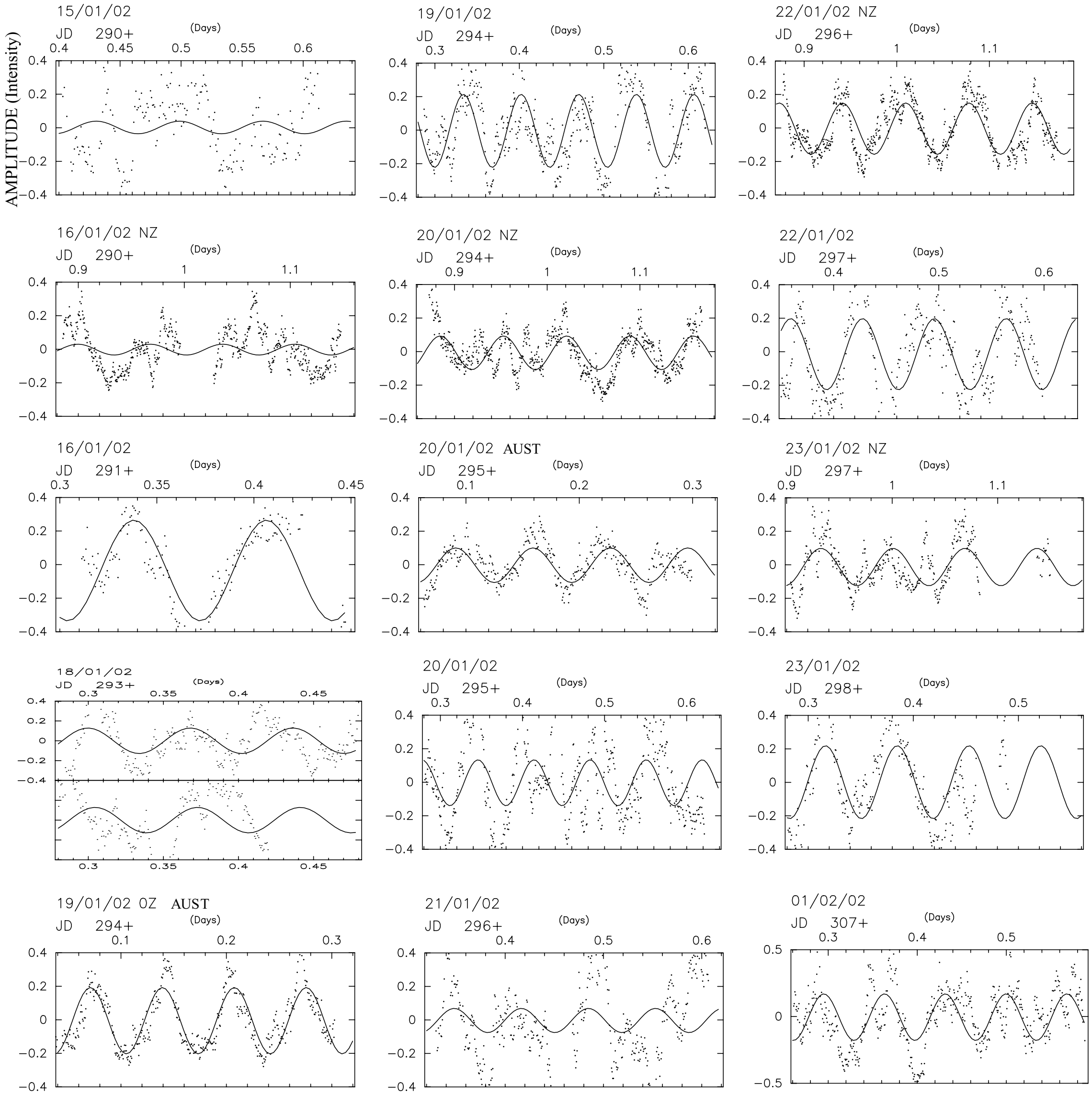

Figure 3. Sample light curves of the 2002 combined photometry on consecutive nights. NZ and AUST stand for CBA stations in New Zealand and in Australia, respectively, and the rest of the panels are runs obtained at SAAO. The QPO periodicity was fitted to the data as represented by a solid line. A strong variation at the QPO period can be seen during a number of runs, more especially on January 19 and January 22. The JDs run from 245 2290 to 245 2307.

The data were fitted at the QPO frequency on consecutive nights and the results are displayed in Table 3 and Fig. 3. As can be seen in Table 3, the phase of peak maximum of the 170 μHz QPO frequency shifts from one night to the next, relative to the first data point of the night of 2002 January 16 which was chosen as the zero point (since those data seem to have the highest amplitude), confirming that this period is quasi-periodic. However, the DFTs of the archival data show that the QPO period is also present in the 1990 photometry (Fig. 4), and perhaps in the 1994 data, and this suggests that this period is stable on a long time-scale and is a QPO that persistently reappears due to some physical/geometrical changes and/or characteristic of TX Col. The QPO period is also present in the 1989–2002 combined photometry and has the highest amplitude in this data set (Fig. 4). The QPO frequency was measured from the DFT of the 1989–2002 combined data, and a value of 169.630 206 ± 0.000 047 μHz (5895.17 648 ± 0.00 163 s) was obtained.

The light curve of 20 January 2002 (SAAO) (see Fig. 3, middle column of panels, fourth panel from the top) shows an interesting behaviour; excursions or a change in frequency between Julian Day (JD) = 245 2295.44 − 245 2295.54 where in one QPO cycle approximately three shorter oscillations, on the time-scale of the spin or the beat period, are observed. The light curve of 2002 February 1 (between JD = 245 2307.46 − 245 2295.6) shows a nearly similar effect. The data within the above-mentioned JD ranges are strongly modulated near the spin frequency (see first and fourth panels in Fig. 5) and the DFTs show a peak near the spin frequency (second and last panels in Fig. 5).

5 SPIN VARIATIONS

The data of January 20 and February 1 falling within the Heliocentric Julian Day (HJD) ranges mentioned above were phase-folded on the radial velocity spin ephemeris HJD(maximum) = 245 2290.286 025 + 0.022 105 436(4)E which is derived in Mhlahlo et al. (in preparation) using a spin period determined from the 1989–2002 photometry (Section 3). We phased our spectroscopy such that maximum

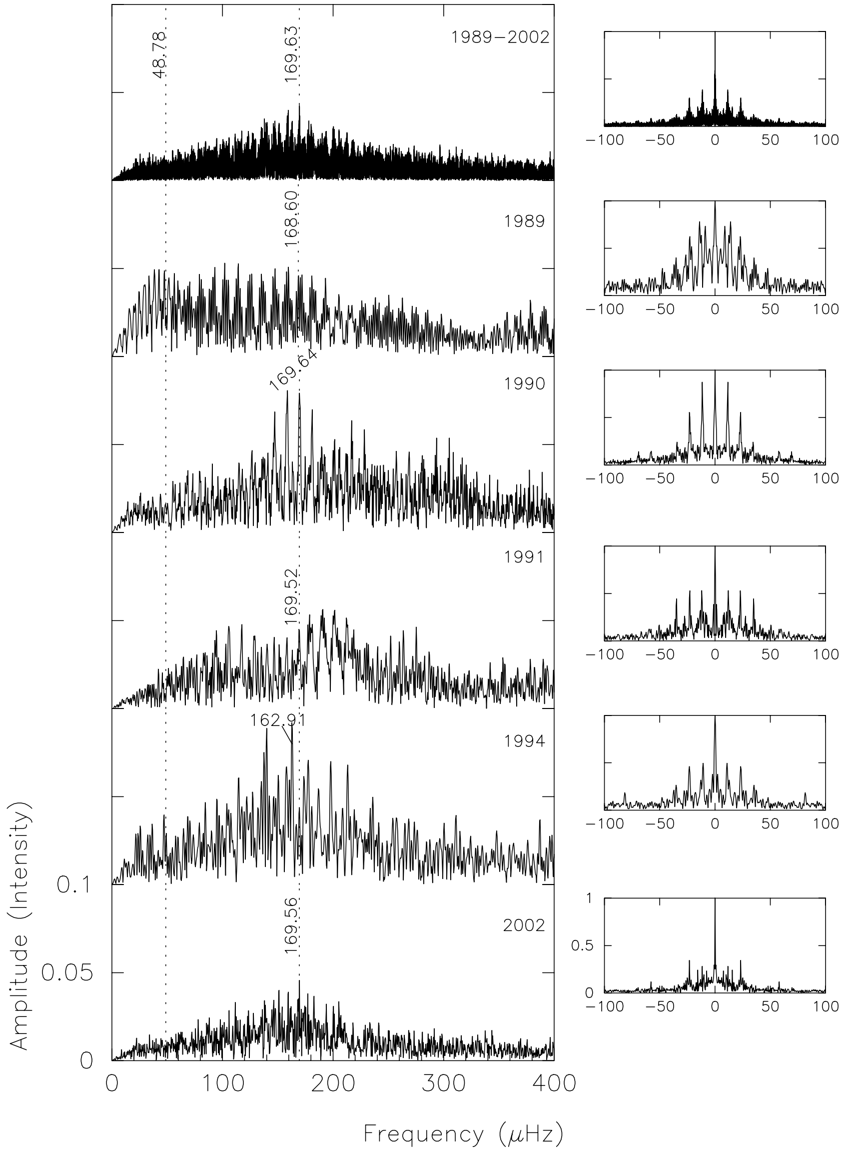

Figure 4. DFT amplitude spectra showing light variations in the frequency range: 0–400 μHz in (from top to bottom) the total combined photometry, the 1989, the 1990, the 1991, the 1994 and the 2002 combined photometry. The frequencies listed are the closest to the QPO peak detected in 2002. The dotted line on the left-hand side marks the location of the orbital period if it was present. All the plots are on the same scale. The window spectra are shown on the right-hand side also plotted on the same scale.

redshift appears at $\phi = 0.0$. The data show maximum intensity near phase $\phi = 0.2$ (middle panel in Fig. 5). The data of the 2002 February 1 (not shown) also showed maximum intensity near phase $\phi = 0.2$. Fig. 6 shows the 2002 combined photometry phase-folded on the radial velocity spin ephemeris (see above). Maximum intensity is seen at phase $\phi \sim 0.14$.

6 DISCUSSION AND INTERPRETATION

Optical beat modulations are thought to result from reprocessing of X-rays in regions that are fixed in the orbital frame of reference such as the front face of the secondary and/or the bright spot (Hassall et al. 1981; Patterson 1981; Wickramasinghe, Stobie & Bassell 1982). The reprocessing model has been used by Buckley & Tuohy (1989b) to explain the optical beat frequency observed in TX Col.

The disc-overflow model, where beat modulations result from the interaction between the stream of material from the secondary rotating with the binary frame at Ω, and the magnetosphere spinning with ω, after the stream has hit and overflowed the outer edge of the disc, has been used successfully as an alternative model to explain X-ray beat pulses. It is generally accepted that disc-overflow accretion will result in the simultaneous existence of the beat and the spin pulses in the data, having comparable amplitudes (Norton et al. 1997; Hellier 1998). These pulses have been observed in the X-rays of TX Col, which establishes disc-overflow as one of the modes of accretion. Our optical data of 2002 have shown a dominant modulation at the beat period and another modulation at the spin period. The spin and the sideband (beat period) are not always detected in TX Col, which is interesting. This is possibly a result of disc-overflow and will be discussed in detail in Mhlahlo et al. (in preparation).

In addition to the beat and the spin modulations, TX Col amplitude spectra are dominated by high-amplitude QPOs.

We investigate five different models to explain the QPO periodicity.

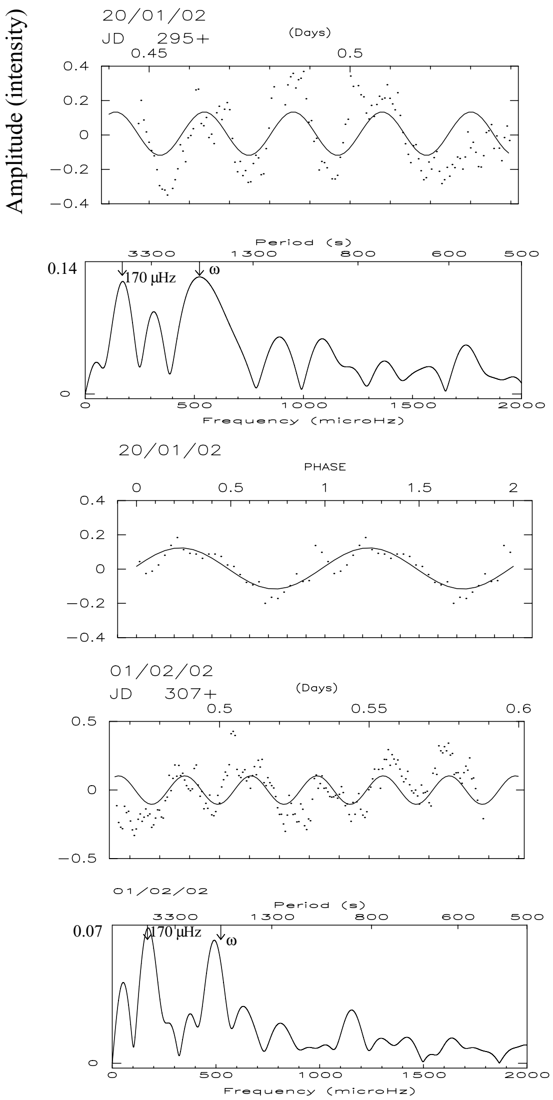

Figure 5. The top panel shows the light curve of 2002 January 20 fitted at the spin frequency. The second panel from the top shows a DFT where the spin and the QPO frequencies were detected, and the middle panel shows the data phase-folded on the spin frequency. The fourth panel is the light curve of the 2002 February 01 also fitted at the spin frequency, and the fifth panel is a corresponding DFT. The solid line represents a fit to the data.

(i) A successful model for QPOs and dwarf nova oscillations (DNOs) was proposed by Warner & Woudt (2002) where QPOs are caused by slow-moving prograde waves at the inner edge of the disc. Warner, Woudt & Pretorius (2003) showed that many observations in CVs and X-ray binaries obey the relation $P_{\rm QPO}/P_{\rm spin} \sim 15$. This model explained the QPOs observed in the IP GK Per, where $P_{\rm QPO}/P_{\rm spin} \sim 14$ (Hellier & Livio 1994). However, TX Col does not obey this relation since $P_{\rm QPO}/P_{\rm spin} \sim 3$ and so this model cannot be applied as it is to this system.

(ii) Retter et al. (2004) reported evidence for large superhumps in TX Col, at 7.1 h (positive superhump) and at 5.2 h (negative superhump), in addition to the orbital period. These periods are understood as resulting from beating of the orbital period and the apsidal or the modal precession of the disc. Their observations of TX Col taken between 2002 December and 2003 February, about a year after our campaign, showed large-amplitude QPOs. A possibility, therefore, is that the interaction between the superhump frequency and

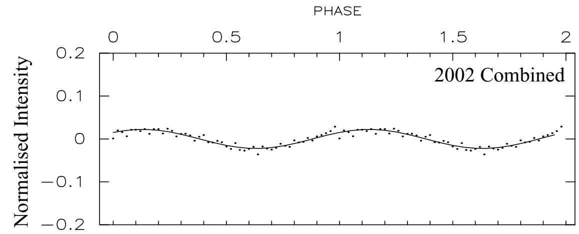

Figure 6. The simultaneous photometry (2002 combined data set) of TX Col folded on the spin ephemeris, HJD (maximum) = 245 2290.286 025 + 0.022 105 436(4)E, and binned using 50 bins. Maximum line intensity is observed at phase $\phi \sim 0.14$. The horizontal scale is in spin phase.

the Keplerian frequency of the material at the outer disc produces a new frequency – the QPO. Using the orbital parameters of TX Col, we find that the Keplerian period of the material at the outer disc edge is

$$P_{\rm KEP} = \frac{2\pi R_{\rm out}}{v_{\rm KEP}} \sim 2000\text{–}12\,000\ {\rm s}, \qquad (1)$$

for any reasonable values of $v_{\rm KEP}$ between ∼400 and 600 km s^{-1} ($V_{\rm KEP} \sin i \sim 172$ km s^{-1} – $i < 25°$) and of the outer disc radius,

$$R_{\rm out} = \frac{GM_1}{v^2_{\rm KEP}} \sim 2 - 8 \times 10^{10}\ {\rm cm}.$$

The white dwarf mass range between $M_1 \sim 0.5$ and 1 M$_\odot$ (Ramsay 2000; Suleimanov, Revnivtsev & Ritter 2005) is considered here:

$$\frac{1}{P_{\rm KEP}} - \frac{1}{P_{\rm SH}} = \frac{1}{P_{\rm QPO}}$$

gives QPO periods that we observe in the data (∼6000 s) for values of $P_{\rm KEP}$ near 5000 s. This would imply a smaller disc, though.
The presence of the 7.1 h period is deemed unlikely, whereas that of the 5.2 h is possible but not conclusive (Tansel AK, private communication). Our extensive data do not show evidence for these superhump periods.

(iii) The theoretical analysis of King (1993) and Wynn & King (1995) suggested that the flow of matter in IPs can take the form of diamagnetic 'blobs' that orbit about the white dwarf. Hellier (2002a) argued that, following the theory of King (1993) and Wynn & King (1995), TX Col can be explained as having a combination of a stream and orbiting blobs. A similar suggestion was put forward for GK Per where it was thought that QPOs result due to vertically extended 'blobs' orbiting within the inner accretion disc edge and providing modulated reprocessing of, or illumination by, the white dwarf (Morales-Rueda, Still & Roche 1996).
We find that the Keplerian period of the material at the inner disc edge is ∼200–600 s, for any white dwarf mass between $M_1 \sim 0.5$–1 M$_\odot$ and inner disc radius,

$$R_{\rm in} = \frac{GM_1}{v^2_{\rm KEP}} \sim 2\text{–}4 \times 10^9\ {\rm cm}.$$

These periods are inconsistent with the QPO time-scales of ∼6000 s observed in our data. Therefore, theories where the QPO is a beat between the spin frequency and the frequency of material orbiting the white dwarf at the inner edge of the disc or where the QPO results from reprocessing off blobs or bulge orbiting at the inner edge of the disc (Watson, King & Osborne 1985) are not supported by our observations for TX Col.

(iv) However, the beat of the spin period with the Keplerian period at the outer disc, that is

$$\frac{1}{P_{\rm spin}} - \frac{1}{P_{\rm KEP}} = \frac{1}{P_{\rm QPO}},$$

gives $P_{\rm QPO} \sim 6000$ s which we observe in our data for values of $P_{\rm KEP}$ in the lower range near 3000 s (equation 1) and for reasonable values of $R_{\rm out} \sim 3 \times 10^{10}$ km s^{-1} (Buckley & Tuohy 1989a) and $v_{\rm KEP} \sim 600$ km s^{-1}. Though this model seems to give the expected result, it alone does not explain why the QPO variation has a higher amplitude (compared to the beat and the spin periods).

(v) Therefore, we suggest that in addition to there being 'blobs' at the outer edge of the disc from which white dwarf emission is reprocessed to give rise to QPO frequency, there is modulated accretion occurring at the magnetosphere/disc boundary that gives rise to the same QPO frequency.

Spruit & Taam (1993) showed that conditions at the inner edge of the disc can cause variations of the magnetosphere boundary and that material can accumulate outside the magnetosphere. Spruit & Taam (1993) pointed out that their model could be applied to IPs to explain the QPO phenomena seen in these systems. This model was used recently by Mhlahlo et al. (2007b) to describe the outburst of EX Hya.

Our results have shown that maximum intensity of the continuum light occurs at spin phase ∼0.2, when the greatest projected surface area of the accretion curtain is nearly facing the observer (Mhlahlo et al., in preparation). Since the continuum light curves are dominated by the QPOs, it follows that most of the QPO emission also comes from this region, near the white dwarf. The spin modulation appearing in the QPO continuum light curves also shows maximum intensity near this phase (∼0.2; Section 4), suggesting that continuum spin modulations also emanate from this region. The variable intensity and excursions in the QPO light curves (Fig. 3) suggest that it is an accretion process that gives rise to the QPO emission. We proposed that it is near the above-mentioned region where the QPO modulations result, due to accretion.

Between JD = 245 2295.44−245 2295.54 and JD = 245 2307.46−245 2295.6, there are possibly no 'blobs' that are picked up by the accretion curtains and accreted via the Spruit and Taam mechanism by the white dwarf. This results in the observed spin modulated emission in the QPO continuum light curves.

We suggest that the material that forms a 'base excursion' (Mhlahlo et al., in preparation, see also Hellier et al. 1989; Mhlahlo et al. 2007b) due to overflow stream falling near the magnetosphere/disc boundary, and the 'blobs' that drift from the outer disc towards this same shocked region, pile up near this region and are dumped on to the surface of the white dwarf via a mechanism similar to that of Spruit and Taam before the field lines snap to produce a prograde travelling wave (or 'wall') of Warner & Woudt (2002).

The critical density required to push the magnetosphere inward for the accretion of the accumulated 'blobs' to take place is possibly reached quicker in TX Col than in EX Hya, resulting in the frequent accretion of the 'blobs' and in the production of the QPOs that we observe in the data. This could explain why we do not see outbursts in TX Col.

The viscous time-scale at the co-rotation radius, $r_{\rm co}$, predicted by the Spruit & Taam (1993) model can roughly be estimated to be $t_0 = 1/\bar{\nu_0}\Omega_{\rm s} \sim 356$ s (Spruit & Taam 1993), where $\bar{\nu_0} = \alpha(\frac{H}{r_{\rm co}})^2 \sim 0.1$ and assuming the α viscosity parameter is ∼0.1 (Shakura & Shunyaev 1973). These time-scales are inconsistent with the observed QPO time-scales. However, at $R_{\rm out}$ where we suggest there are orbiting 'blobs', $t_0 \sim 5000$ s. The latter time-scales are consistent with the QPO time-scales. This could suggest that there is evolution of 'blobs' from $R_{\rm out}$ towards the magnetosphere.

This could also suggest that TX Col has an extended accretion curtains where material is accreted from a ring near the Roche lobe, a similar situation as in EX Hya (King & Wynn 1999; Belle et al. 2002; Norton, Wynn & Somerscales 2004; Mhlahlo et al. 2007a). In this geometry, the QPO period would result due to the 'blobs' orbiting in the ring of material being swept up by the magnetic field lines. This would occur when an orbiting 'blob' is on the side facing the magnetic field lines. This is unlikely, though, given the $P_{\rm spin}/P_{\rm orb}$ ratio of TX Col. Also, such a behaviour can be confirmed by the detection of a spin period modulated at radial velocities near those of the outer ring material due to co-rotation of outer ring material with the accretion curtain (Mhlahlo et al. 2007a).

7 SUMMARY

The photometry of TX Col has been dominated by QPOs but no interpretation for their origin had been provided before. A 5900-s QPO period is detected in the 1990, the 1994 and the 2002 photometry, and we interpret it as follows: the QPO period results due to the beating of the Keplerian period of the orbiting 'blobs' with the spin period and from the storage and the release of 'blobs' near the magnetosphere, where the stored material is rapidly accreted by the white dwarf.

ACKNOWLEDGMENTS

NM would like to acknowledge financial support from the Sainsbury/Linsbury Fellowship Trust and the University of Cape Town. NM would also like to thank D. O'Donoghue for the use of his program, EAGLE.

REFERENCES

Belle K., Howell S. B., Sirk M., Huber M. E., 2002, ApJ, 577, 359
Buckley D. A. H., Tuohy I. R., 1989a, ApJ, 344, 376
Buckley D. A. H., Tuohy I. R., 1989b, in Christopher W. Mauche, ed., Proc. 11th North American Workshop on Cataclysmic Variables and Low Mass X-Ray Binaries. Cambridge Univ. Press, Cambridge, p. 231
Buckley D. A. H., Sullivan D. J., 1992, in Nikolaus Vogt, ed., ASP Conf. Ser. Vol. 29, Viña Del Mar Workshop on Cataclysmic Variable Stars. Astron. Soc. Pac., San Francisco, p. 387
Buckley D. A. H., 1996, in Evans A., Wood J. H., eds, Proc. IAU Colloq. 158, Ap&SS Library Vol. 208, Cataclysmic Variables and Related Objects. Kluwer, Dordrecht, p. 185
Fisher R. A., 1935, The Design of Experiments. Hafner, New York
Hassall B. J. M., 1981, MNRAS, 197, 275
Hellier C., 1998, New Astron. Rev., 22, 973
Hellier C., 2002, in Gänsicke B. T., Beuermann K., Reinsch K., eds, ASP Conf. Ser. Vol. 261, The Physics of Cataclysmic Variables and Related Objects. Astronomical Society of the Pacific, San Francisco, p. 92
Hellier C., Livio M., 1994, ApJ, 424, 57
Hellier C., Mason K., Smale A. P., Corbet R. H. D., O'Donogue D., Barrett P. E., Warner B., 1989, MNRAS, 238, 1107
King A., 1993, MNRAS, 261, 144
King A., Wynn D. W., 1999, MNRAS, 310, 203
Kurtz D. W., 1985, MNRAS, 213, 773
Mateo M., Schechter. P. L., in Grosbol P. J., Murtagh F., Warmaels R., eds, ESO Conf. Workshop Proc. No. 31, 1st ESO/ST-ECF Data Analysis Workshop. ESO, Garching, p. 69
Mhlahlo N., Buckley D. A. H., Dhillon V., Potter S. B., Warner B., Woudt P., 2007a, MNRAS, 378, 211
Mhlahlo N., Buckley D. A. H., Dhillon V., Potter S. B., Warner B., Woudt P., 2007b, MNRAS, in press (doi:10.1111/j.1365-2966.2007.12077.x) (astro-ph/0706.0887)
Morales-Rueda L., Still M. D., Roche P., 1996, MNRAS, 283, L58

Norton A., Hellier C., Beardmore A. P., Wheatley P. J., Osborne J. P., Taylor P., 1997, MNRAS, 289, 362
Norton A., Wynn A., Somerscales C., 2004, ApJ, 614, 349
Patterson J., Price C. M., 1981, ApJ, 243, L83
Ramsay G., 2000, MNRAS, 314, 403
Retter A., Liu A., Bos M., 2005, in Sion E. M., Vennes S., Shipman H. L., eds, Ap&SS Library Vol. 332, White Dwarfs: Cosmological and Galactic Probes. Springer, Dordrecht, p. 251
Shakura N. I., Shunyaev R. A., 1973, A&A, 24, 337
Spruit H. C., Taam R. E., 1993, ApJ, 402, 593
Suleimanov V., Revnivtsev M., Ritter H., 2005, A&A, 435, 191
Tuohy I. R., Buckley D. A. H., Remillard R. A., Bradt H. V., Schwartz D. A., 1986, ApJ, 311, 275
Warner B., Woudt P., 2002, MNRAS, 335, 84
Warner B., Woudt P., Pretorius M. L., 2003, MNRAS, 344, 1193
Watson M. G., King A. R., Osborne J., 1985, MNRAS, 212, 917
Wickramasinghe D. T., Stobie R. S., Bassell M. S., 1982, MNRAS, 200, 605
Wynn G. A., King A., 1995, MNRAS, 275, 9

This paper has been typeset from a TEX/LATEX file prepared by the author.