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

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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 (from a combination of radial velocity, X-ray and optical intensity to high temperatures (above the white dwarf surface where the accreted material is heated to high temperatures (~10⁸ K; Norton et al. 1997) and are reflected and reprocessed in regions fixed in the rotating frame of the white dwarf.

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.

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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).

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...
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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.

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
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 likely due to noise 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 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.

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 of TX Col were determined from the 1989–2002 combined photometry. Values of $\omega - \Omega = 474.803499 \pm 0.000089$ µHz (2106.1344 ± 0.00040 s), $\omega = 523.584953 \pm 0.000099$ µHz (1909.90974 ± 0.00036 s) and $2(\omega - \Omega) = 949.447975 \pm 0.000018$ µHz (1053.24356 ± 0.00002 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 $\Omega = 474.788 \pm 0.014$ µHz, respectively. More accurate values of the beat, the harmonic of the beat and the spin frequencies of TX Col were 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.

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 = 2452291.311340, 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               |

Fig. 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.
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 ± 0.000 047 µHz (5895.176 ± 0.001 63 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 and 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 and 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) 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
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 $\Omega$, and the magnetosphere spinning with $\omega$, 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.
This model explained the QPOs observed in the IP GK Per, where
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
\[ P_{\text{KEP}} = \frac{2\pi R_{\text{out}}}{v_{\text{KEP}}} \sim 2000–12\,000 \text{ s}, \]
for any reasonable values of \( v_{\text{KEP}} \) between \( \sim400 \) and \( 600 \) km s\(^{-1}\) (\( V_{\text{KEP}} \sin i \sim 172 \text{ km s}^{-1} \) and \( i < 25^\circ \)) of the outer disc radius,
\[ R_{\text{out}} = \frac{GM_1}{v_{\text{KEP}}^2} \sim 2 - 8\times10^{10} \text{ cm}. \]
The white dwarf mass range between \( M_1 \sim 0.5 \) and \( 1 \) M\(_\odot\) (Ramsay 2000; Suleimanov, Revnivtsev & Ritter 2005) is considered here:
\[ \frac{1}{P_{\text{KEP}}} - \frac{1}{P_{\text{SH}}} = \frac{1}{P_{\text{QPO}}} \]
gives QPO periods that we observe in the data (\( \sim6000\) s) for values of \( P_{\text{KEP}} \) 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 \( \sim200–600\) s, for any white dwarf mass between \( M_1 \sim 0.5–1 \) M\(_\odot\) and inner disc radius,
\[ R_{\text{in}} = \frac{GM_1}{v_{\text{KEP}}^2} \sim 2 - 4\times10^9 \text{ cm}. \]
These periods are inconsistent with the QPO time-scales of \( \sim6000\) 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
\[ \frac{1}{P_{\text{spin}}} - \frac{1}{P_{\text{KEP}}} = \frac{1}{P_{\text{QPO}}}. \]
gives $P_{\text{QPO}} \sim 6000$ s which we observe in our data for values of $P_{\text{Kep}}$ in the lower range near 3000 s (equation 1) and for reasonable values of $R_{\text{out}} \sim 3 \times 10^{10}$ km s$^{-1}$ (Buckley & Tuohy 1989a) and $v_{\text{Kep}} \sim 600$ 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 $\sim 0.2$, 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 ($\sim 0.2$; 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 2297.46–245 2297.6, 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, $r_{\text{co}}$, predicted by the Spruit & Taam (1993) model can roughly be estimated to be $t_{01} = 1/\nu_{01} \Omega_{1} \sim 356$ s (Spruit & Taam 1993), where $\nu_{01} = \alpha_{0} (R_{1})^{2} \sim 0.1$ and assuming the $\alpha$ viscosity parameter is $\sim 0.1$ (Shakura & Sunyaev 1973). These time-scales are inconsistent with the observed QPO time-scales. However, at $R_{\text{out}}$ where we suggest there are orbiting ‘blobs’, $t_{01} \sim 5000$ s. The latter time-scales are consistent with the QPO time-scales. This could suggest that there is evolution of ‘blobs’ from $R_{\text{out}}$ 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 $P_{\text{spin}}/P_{\text{orb}}$ 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 has 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.

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