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Dwarf nova oscillations and quasi-periodic oscillations in cataclysmic variables – III. A new kind of dwarf nova oscillation, and further examples of the similarities to X-ray binaries

Brian Warner,⋆ Patrick A. Woudt⋆ and Magaretha L. Pretorius⋆

Department of Astronomy, University of Cape Town, Private Bag, Rondebosch 7700, South Africa

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ABSTRACT

We present measurements of the periods of dwarf nova oscillations (DNOs) and quasi-periodic oscillations (QPOs) in cataclysmic variable stars (CVs), many culled from published literature, but also others newly observed (in VZ Pyx, CR Boo, OY Car, Z Cha, AQ Eri, TU Men, HX Peg, CN Ori, V893 Sco, WX Hyi and EC2117−54). These provide data for 26 systems. We show that in general $P_{\rm QPO} \sim 15\ P_{\rm DNO}$ and that the correlation for CVs extends by three orders of magnitude lower in frequency the similar relationship found for X-ray binaries. In addition, we have found that there is a second type of DNO, previously overlooked, which have periods ∼4 times those of the regular DNOs (as well as those mined from publications, we have observed them in VW Hyi, OY Car, AQ Eri, V803 Cen, CR Boo, VZ Pyx, HX Peg and EC2117−54). Often both types of DNO coexist. Unlike the standard DNOs, the periods of the new type, which we refer to as longer-period DNOs (lpDNOs), are relatively insensitive to accretion luminosity and can even appear in quiescence of dwarf novae. We interpret them as magnetically channelled accretion on to the differentially rotating main body of the white dwarf primary, rather than on to a rapidly slipping equatorial belt as in the case of the standard DNOs. This is supported by published measurements of $v \sin i$ for some of the primaries. Some similarities of the DNOs, lpDNOs and QPOs in CVs to the three types of QPO in X-ray binaries (burst pulsations, high- and low-frequency QPOs) are noted.

Key words: accretion, accretion discs – stars: dwarf novae – novae, cataclysmic variables – stars: oscillations.

1 INTRODUCTION

Dwarf nova oscillations (DNOs) and quasi-periodic oscillations (QPOs) in cataclysmic variables (CVs) have been observed for 30 years – the DNOs were discovered in 1972 (Warner & Robinson 1972), and the QPOs were first recognized in 1977 (Patterson, Robinson & Nather 1977) and were found to be clearly discernible in some earlier light curves.

The accumulated observations of DNOs and QPOs have been listed in Warner (1995a) and discussed there and in the first two papers of this series (Woudt & Warner 2002, Paper I; Warner & Woudt 2002a, Paper II; see also Warner & Woudt 2002b, 2003). The observations of VW Hyi presented and analysed in Paper I, and the discussion given in Paper II, led to the realization that in that star the period ratio $R = P_{\rm QPO}/P_{\rm DNO}$ remains approximately constant at a value ∼15 during the rapid increases in these periods seen near the end of VW Hyi outbursts. We pointed out not only that R is similar to the ratio found for the high- and low-frequency QPOs observed in X-ray binaries (Psaltis, Belloni & van der Klis 1999), but also that the VW Hyi relationship in fact appears to be an extension of the X-ray binary correlation to frequencies two orders of magnitude lower.

Subsequently, Mauche (2002) discovered that DNOs and QPOs observed in the extreme ultraviolet (EUV) and soft X-ray regions during an outburst of the dwarf nova SS Cyg have $R \sim 12$, and the DNO periods (∼8 s) place them between VW Hyi and the X-ray binaries in the two-QPO correlation diagram. This greatly strengthened the evidence for the existence of a general relation between high- and low-frequency QPOs in all of these interacting binaries, irrespective of whether the primary is a black hole, neutron star or white dwarf. The DNOs of the CVs are the analogues of the high-frequency X-ray binary QPOs, and the QPOs of the CVs are the analogues of the low-frequency X-ray QPOs.

In this paper we will be largely interested in presenting new observations of DNOs and QPOs in CVs, and in reinterpreting previously published observations. A complication that arises is that both DNOs and QPOs can show frequency doubling, and these can happen independently of each other (Warner & Woudt, in preparation).

⋆E-mail: warner@physci.uct.ac.za (BW); pwoudt@circinus.ast.uct.ac.za (PAW); retha@mensa.ast.uct.ac.za (MLP)

This may change the measured value of R by a factor of 2 in some cases. QPOs are far less coherent and persistent than DNOs. It is commonly observed that a train of 5–10 moderately coherent QPO cycles is clearly visible, before changing in phase or disappearing altogether.

We first indicate some of the theoretical work that appears relevant to understanding the nature of the rapid oscillations in interacting binaries.

That DNOs are signatures of magnetically controlled accretion on to the equatorial belt of the white dwarf primaries of CVs was proposed by Paczyński (1978), made more quantitative by Warner (1995b) and elaborated in Paper II as the low-inertia magnetic accretor (LIMA) model. The last also develops the idea that QPOs may be caused by prograde travelling waves near the inner edge of the magnetically truncated accretion discs. A simple excitation mechanism, involving magnetic reconnection, leads to the expectation that $R \sim \Omega_{\rm K}/\Delta\Omega \sim (1-\omega_{\rm s})^{-1}$, where $\Omega_{\rm K}$ is the Keplerian frequency in the disc near the corotation radius $r_{\rm co}$, $\Delta\Omega = \Omega_{\rm K} - \Omega_{\rm max}$, where $\Omega_{\rm max}$ is the maximum angular frequency in the transition zone between $r_{\rm co}$ and the inner edge of the disc, and $\omega_{\rm s}$ is the 'fastness parameter' defined by Gosh & Lamb (1979).

A somewhat different physical interpretation is that QPOs are modulations in the rate of mass transfer on to the primary. This concept is used in QPOs of the luminosities of young stars, where the QPOs are envisaged as magnetospheric radial oscillations, caused by field winding and reconnecting, as in the above proposed model for CVs. The radial oscillations produce quasi-periodic modulation of the mass transfer rate, and a typical model has $R \sim 100/(2\pi)$ (Goodson & Winglee 1999).

Returning to interacting binaries, in a study of field winding, inflation and reconnection in the region connecting the inner disc to the primary, Uzdensky (2002) concludes that quasi-periodic oscillations should occur. Such QPOs could cause mass transfer modulation and/or travelling waves. Titarchuk & Wood (2002) interpret the whole range of the two-QPO correlation as evidence for magnetoacoustic oscillations in the transition zone, driven by the adjustment to sub-Keplerian flow.

The next two sections of this paper are devoted to accumulating values of $P_{\rm DNO}$ and $P_{\rm QPO}$ and the resulting estimates of R: in Section 2 we examine published papers in order to extract values of R; in Section 3 we describe new photometric observations of CVs that lead to further determinations of R. In Section 4 we draw attention to a new type of DNO that is occasionally seen, which could be confused with the standard DNOs; and in Section 5 we compare the DNOs and QPOs in CVs with the two-QPO correlation and other properties of X-ray binaries. Section 6 contains a final discussion and assessment.

2 PUBLISHED OBSERVATIONS OF DNOs AND QPOs

The values of R, their possible variation for any given star, and their range from star to star, have not previously been given much attention, but in the light of the newly discovered possible connection between CV and X-ray QPOs these ratios are of great interest. In this section we examine the published studies of CVs with this in mind. Ideally, we would prefer light curves where both DNOs and QPOs are present simultaneously. However, largely through the lower interest in QPOs in the past, DNO periods are often the only ones quoted. We can expand the list of useful results by including observations of 'double' DNOs, making use of the conclusion (Papers I and II) that in at least some CVs (VW Hyi, WZ Sge) the QPO frequency is the difference (i.e. beat) frequency of the two DNOs. The true DNO is the shorter of the two periods; the longer period is the result of reprocessing of the DNO by the travelling wave that is thought to produce the QPO (Paper II). By using the beat frequency we in effect generate a 'pseudo'-QPO; this may not be visible directly in the light curve because the travelling wave may happen not to intercept our line of sight, but its presence is indirectly observed by the shielding and reprocessing effects it has on the disc, which generate the double DNO.

2.1 RU Peg

The CV in which QPOs were first noticed was the dwarf nova RU Peg. Patterson et al. (1977) found ∼50 s oscillations clearly discernible in the light curve, which, because of their low coherence, were transformed into a barely significant broad and noisy band of power in the Fourier transform (FT). The QPOs were present during all five nights of the 1975 November outburst. In addition, on four of the nights more stable oscillations, characteristic of DNOs, were seen in the FTs at periods near 11.6 s but with unusually small amplitudes ∼0.6 mmag (millimagnitudes).

The value of R for RU Peg, using the above numbers, is ∼4.5. This is so far removed from the value ∼15 that we see in VW Hyi and the X-ray binaries that it would seem that the QPO 'type star' itself is highly anomalous. However, the following reasoning leads to a different conclusion. The QPOs at ∼50 s are clearly present; taking these as the starting point we could look for DNOs at a period $\sim 50/15 \sim 3.3$ s. The integration time used by Patterson et al. (1977) was 4 s, so the 'predicted' DNOs are above their Nyquist frequency. However, if a ∼3.3 s signal were actually present in the RU Peg light curve, it could show up at the beat frequency between ∼3.3 s and 4 s. This is of the order of the period of the DNOs actually observed in RU Peg. The relatively long integration time resulted in a reduction of amplitude by a factor of $\sin x/x$, where $x = \pi\, \delta t/P_{\rm DNO}$ and δt is the integration time. Thus the true DNO amplitude in RU Peg would be a factor of 4.7 larger, or 2.8 mmag, which is more in line with what is commonly observed in dwarf novae near maximum of outburst.

The value of the ratio R for RU Peg, deduced from the posited DNO period (at 2.97 s – the alias of 11.6 s) and the QPO period, is 16.8.

A few years ago DNOs at ∼3 s would have seemed unlikely or impossible. But the observation of ∼3 s DNOs in the EUV and X-ray regions of SS Cyg during outburst (van Teeseling 1997; Mauche 1998) should remove that prejudice. In SS Cyg the DNOs had undergone a sudden frequency doubling, and it is possible that the same happened in RU Peg. We note that DNOs are associated with the Keplerian period close to the primary, and that it requires large masses to produce these short periods. The mass of the white dwarf in SS Cyg is indeed quite large – 1.20 $M_\odot$ according to Robinson, Zhang & Stover (1986) – and the mass of the primary in RU Peg is 1.38 $M_\odot$ (Friend et al. 1990).

It is possible that the 11.6 s oscillation is an example of the longer-period dwarf nova oscillations (lpDNOs) discussed in Section 4 of this paper. However, the implication would be that any true DNO would appear at ∼3 s, which does not change the implied value of R.

2.2 V3885 Sgr

Hesser, Lasker & Osmer (1974) observed 29.08 s and 30.15 s DNOs in the nova-like V3885 Sgr. No QPOs were commented on, so we use the estimate $P_{\rm QPO} = 819$ s from the beat period, to deduce $R = 28.2$.

2.3 WZ Sge

The 27.87 s and 28.95 s DNOs and the 742 s QPO seen in the light curve of WZ Sge (they are intermittently present outside of outburst: these are described in Paper II), lead to $R = 26.6$.

2.4 SS Cyg

The *EUVE* observations of SS Cyg in outburst by Mauche (2002) give a DNO period of 7.7 s and a QPO period of 83 s; his soft X-ray (*Chandra*) observations give DNOs at 9.1 s and a QPO at 111 s. From his analysis, Mauche finds $R = 10.4$ and $R = 11.4$ respectively.

2.5 V436 Cen

The outburst light curve in which DNOs were detected with an average period of 19.6 s (Warner 1975) has been further analysed and we find strong QPOs with $P_{\rm QPO} \sim 475$ s. This gives $R \sim 24$. Also, in one section of the light curve obtained on 1975 June 11 there is a double DNO with periods 19.45 s and 20.20 s (and a QPO at ∼500 s was visible at this time). Using the double DNO we get $R = 26$.

2.6 V2051 Oph

DNOs at 56.12 s, 28.06 s and 29.77 s during the late decline phase of a dwarf nova outburst were found in V2051 Oph by Steeghs et al. (2001), and they observed the beat at 486 s. This gives $R = 17.3$.

2.7 UX UMa

Warner & Nather (1972) and Nather & Robinson (1974) found DNOs in the nova-like UX UMa, with periods near 29 s. As pointed out in Paper II, the O–C diagram shown by Nather & Robinson contains ∼650 s QPOs in it. These give $R \sim 22$.

2.8 IX Vel

The bright nova-like IX Vel frequently has DNOs over the range 24.6–29.1 s (Warner, O'Donoghue & Allen 1985). Williams & Hiltner (1984) made an autocorrelation analysis of extensive high-speed photometry and found evidence for the presence of a persistent ∼500 s time-scale. The latter is probably caused by QPOs, which give $R \sim 18$.

2.9 TY PsA

Light curves of TY PsA during outburst have shown strong DNOs near 27 s (Warner, O'Donoghue & Wargau 1989). During one run late on the descending branch of the outburst, QPOs at 245 s were also present. Formally this gives $R \sim 9$, but it is possible that frequency doubling of the QPO had taken place.

2.10 GK Per

GK Per is a particularly interesting object as it is an old nova that now shows dwarf nova outbursts. Furthermore, it has a clear 351 s primary spin period, $P_{\rm spin}$, detected in X-rays (Watson, King & Osborne 1985), which shows up as ∼380–440 s QPOs (which, for the sake of consistency, we here call DNOs) after optical processing from some part of the accretion disc (Patterson 1981; Nogami, Kato & Baba 2002). It also has longer-period QPOs, around 5000 s, seen in X-rays (Watson et al. 1985) and in the optical – both in the continuum (Nogami et al. 2002) and in emission lines (Morales-Rueda, Still & Roche 1996, 1999 hereafter MSR).

Two very important conclusions are arrived at by MSR: first, that the optical modulation can be interpreted as variable radiation of the entire disc, from the 'QPO radius' outwards, caused by the obscuration of the X-ray illuminating source by a blob at the QPO radius in the inner disc; and secondly, that the QPOs arise from beating between more typical DNOs and the magnetic accretion curtain spinning with the white dwarf (as proposed by Watson et al. 1985). Both of these proposed structures are very similar to the LIMA model presented for DNOs and QPOs in Paper II, but with the difference that in GK Per the field of the white dwarf is high enough to prevent slippage of the accreting equatorial belt relative to the interior. That is, GK Per is a standard intermediate polar (IP), with the high inertia of the entire primary receiving the accretion torque. Nogami et al. (2002) conclude that the unstable optical DNOs are probably the 351 s (constant-period) rotating beam being reprocessed off the (varying-period) QPO source, which in the LIMA model is a slow travelling wave moving progradely near the inner edge of the truncated disc.

We feel it is appropriate, therefore, to include GK Per in the inventory of CVs possessing both DNOs and QPOs, and deduce that $R \sim 5000/380 = 13.2$.

As pointed out in Paper II, in general it will be difficult to detect QPOs in the common IPs (with spin periods ∼1000 s), because 1000 s × $R \sim 4$ h is comparable to their orbital periods ($P_{\rm orb}$),[1] and a QPO signal would then need very long observational runs to distinguish it from orbital modulation. In GK Per, which has $P_{\rm orb} =$ 2 d, no such confusion arises.

2.11 RX And

Szkody (1976) found 35.7 s DNOs about 1 mag down from the peak of an outburst. In the light curve there is some weak evidence for QPOs with a period ∼17 min (see fig. 2 of Szkody 1976), which gives $R \sim 28$.

2.12 SW UMa

Robinson et al. (1987) found DNOs with periods near 22.3 s on several nights during the middle and late phases of the superoutburst of SW UMa in 1986 March. In addition they found QPOs with periods near 300 s. In the 1992 March superoutburst, a few days after maximum, Kato, Hirata & Mineshige (1992) found large-amplitude QPOs with a period of 366 s, but their photometric repetition time was too long (28 s) to be able to detect DNOs. We have $R = 13.5$ from the Robinson et al. observations.

2.13 U Gem

Soft X-ray modulations have been observed during outbursts of U Gem. Those at a typical DNO period, namely 21.1 s, and amplitude of 12 per cent, were found by Cordova et al. (1980, 1984) in one out of three outbursts observed, and a QPO, also of 12 per cent amplitude, at 585 s in a different outburst (Cordova & Mason 1984).

[1] More generally, as pointed out by Barrett, O'Donoghue & Warner (1988), the most frequent kind of IP has $P_{\rm orb} \approx 14\ P_{\rm spin}$, which we see results in $P_{\rm QPO} \approx P_{\rm orb}$. There is no obvious physical reason for this coincidence.

Table 1. Observing log.

Object	Type	Run no.	Date of obs. (start of night)	HJD of first obs. (+245 0000.0)	Length (h)	t_{in} (s)	Tele- scope	V (mag)
CR Boo	AM CVn	S6852	2003 Mar 08	2707.42816	5.48	6	30 inch	14.6
		S6862	2003 Mar 10	2709.42381	5.53	6, 7, 8	30 inch	14.9
OY Car	DN	S6488	2002 Feb 16	2323.50036	2.88	7	74 inch	16.1[a,b]
		S6722	2003 Feb 01	2672.36465	2.80	4, 5	40 inch	12.7[a]
		S6724	2003 Feb 01	2672.54450	1.94	5	40 inch	12.8[a]
V803 Cen	AM CVn	S6731	2003 Feb 02	2673.55791	1.57	2	40 inch	13.6
		S6735	2003 Feb 03	2674.46651	2.12	4	40 inch	13.8
		S6740	2003 Feb 04	2675.56672	1.79	6	40 inch	13.8
Z Cha	DN	S6061	2000 Feb 06	1581.35872	3.93	5	40 inch	13.6[a]
AQ Eri	DN	S6159	2000 Dec 27	1906.31477	3.01	8	74 inch	17.5
		S6510	2002 Aug 28	2515.64338	0.66	2, 4	74 inch	13.4[b]
		S6516	2002 Aug 30	2517.56521	2.14	3, 5	74 inch	13.5
		S6520	2002 Aug 31	2518.59417	1.89	3, 5	74 inch	13.5
VW Hyi	DN	S6133	2000 Aug 28	1785.54592	2.84	1, 2	74 inch	12.0[c]
WX Hyi	DN	S6248	2001 Sep 22	2175.51773	0.55	6	40 inch	14.5
		S6463	2002 Jul 10	2466.48576	3.30	6	30 inch	14.8
TU Men	DN	S6695	2002 Dec 26	2635.27795	4.40	1.5, 5, 6	74 inch	14.9
CN Ori	DN	S6702	2002 Dec 29	2638.29558	1.71	5	74 inch	12.3[d]
HX Peg	DN	S6475	2002 Jul 13	2469.55275	1.06	8	30 inch	15.8
		S6584	2002 Oct 14	2562.24520	1.55	5	40 inch	13.1
		S6646	2002 Nov 25	2604.26516	1.95	6, 8	40 inch	13.1
		S6650	2002 Nov 26	2605.26913	3.04	6	40 inch	13.1
		S6656	2002 Nov 29	2608.26764	1.62	5, 6	40 inch	13.2:
VZ Pyx	DN	S6066	2000 Mar 07	1611.29893	1.65	3, 4	74 inch	12.2:
		S6569	2002 Jun 03	2556.59832	0.80	6	40 inch	12.2:
V893 Sco	DN	S6095	2000 Jun 01	1697.32730	7.12	5	74 inch	14.1[a]
EC 21178−5417	NL	S6544	2002 Sep 07	2525.28604	6.11	5, 6, 10	40 inch	13.7[a]
		S6548	2002 Oct 01	2549.30417	5.27	5, 6	40 inch	13.6[a]
		S6549	2002 Oct 03	2551.27063	2.34	6	40 inch	13.6[a]
		S6551	2002 Oct 04	2552.27894	3.72	5	40 inch	13.7[a]
		S6553	2002 Oct 05	2553.35755	0.80	5	40 inch	13.8[a]
		S6555	2002 Oct 06	2554.23099	1.39	6	40 inch	13.6[a]
		S6557	2002 Oct 07	2555.22744	1.59	6, 10	40 inch	13.6[a]
		S6564	2002 Oct 08	2556.22808	1.95	6	40 inch	13.6[a]
		S6570	2002 Oct 09	2557.28798	2.53	5	40 inch	13.7[a]
		S6574	2002 Oct 10	2558.33980	1.53	6	40 inch	13.6[a]
		S6580	2002 Oct 12	2560.30188	1.47	5	40 inch	13.8[a]
		S6599	2002 Oct 31	2579.25335	0.88	4, 5	40 inch	13.7[a]
		S6634	2002 Nov 17	2596.25676	0.80	2, 6	40 inch	13.7[a]
		S6639	2002 Nov 18	2597.25077	0.62	10	40 inch	13.8[a]
		S6641	2002 Nov 24	2603.27788	1.62	6	40 inch	13.7[a]
		S6660	2002 Nov 30	2609.26322	1.03	6	40 inch	13.7[a]
		S6666	2002 Dec 01	2610.26547	1.06	6	40 inch	13.6[a]
		S6670	2002 Dec 17	2626.28606	0.83	6	40 inch	13.8[a]

Notes: DN = dwarf nova; NL = nova-like; t_{in} is the integration time; ':' denotes an uncertain value; [a]mean magnitude out of eclipse; [b]B magnitude; [c]I magnitude; [d]magnitude estimate from VSNET.

These give $R = 27.8$, but may refer to very different stages in the evolution of the outbursts. DNOs with periods ∼25 s have also been observed with *EXOSAT* (Mason et al. 1988) and with *EUVE* during outburst (Long et al. 1996).

2.14 V533 Her and BT Mon

Rodríguez-Gil & Martinez-Pais (2002) have found 23.33 min quasi-periodic flaring in the emission lines of the old nova V533 Her. They propose that V533 Her could therefore be a candidate intermediate polar, as has been suggested also for another old nova, BT Mon, which shows ∼30 min quasi-periodic flaring (Smith, Dhillon & Marsh 1998). However, for several years V533 Her had a 63.63 s coherent luminosity variation (Patterson 1979) that put it clearly in the DQ Herculis class of rapid-rotation intermediate polars.[2] It is more probable, therefore, that the QPO flares in V533 Her and BT

[2] The disappearance was at one time thought to be uncharacteristic of a rotational modulation and could imply non-radial oscillation of the primary (Robinson & Nather 1983), but time moves on and (a) no monoperiodic white dwarf pulsator has ever been found, (b) no pulsating white dwarf has ceased pulsating, (c) the only CV with an oscillating primary is GW Lib (Warner & van Zyl 1998) in which the mass accretion rate is so low that the primary is cool enough to sit in the DA instability strip, and (d) the high mass accretion rate in an old nova such as V533 Her produces an accretion disc luminosity that prevents detection of flux direct from the primary (but, as in

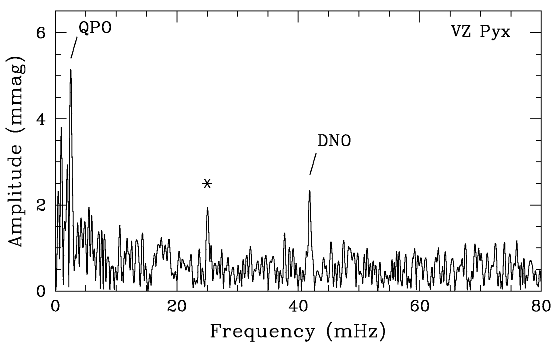

Figure 1. The Fourier transform of run S6569 of VZ Pyx. The QPO and DNO periods are marked. The asterisk marks a spurious signal: the telescope's periodic drive error at 40 s.

Mon are connected with the same physical phenomenon that causes the brightness QPOs. For V533 Her, $R = 23.33/1.060 = 22.0$.

3 NEW OBSERVATIONS

We have used the University of Cape Town CCD Photometer (O'Donoghue 1995) on the 30-, 40- and 74-inch telescopes of the South African Astronomical Observatory at Sutherland to observe the CVs listed in this section. A log of these observations is given in Table 1. Many runs that do not contain oscillations have been omitted from this list.

3.1 VZ Pyx

VZ Pyx is the optical equivalent of the X-ray source 1H 0857−242, identified by Remillard et al. (1994) as a CV with dwarf nova outbursts. These authors found photometric modulations with periods near 49 min during the decay phases of three outbursts and suggested that this could be the signature of an IP. They found no periodic modulation in the X-ray observations [but a possible X-ray period is quoted by Patterson (1994), the evidence for which has not been published] and reported no optical modulations at typical DNO periods. Barwig, Wimmer & Bues (1993) found no periodic modulations at quiescence. VZ Pyx is listed as a probable IP in the review by Patterson (1994). On the other hand, Kato & Nogami (1997) point out that its outburst and superoutburst behaviours are like those of normal non-magnetic SU UMa stars and not those of outbursting IPs, and Szkody & Silber (1996) find that *IUE* spectra obtained in quiescence show the low-excitation emission lines typical of a dwarf nova with a disc and that 'there is no compelling argument for magnetic accretion from the UV data'.

We have observed VZ Pyx near maximum of outburst, as reported in Table 1, and find both QPOs and DNOs present in run S6569. The FT of S6569 is shown in Fig. 1, where a QPO with period 390.5 s and amplitude 5 mmag, and a DNO with mean period 23.86 s (the period increased slightly during the run) and mean amplitude 2.5 mmag are evident. The ratio $R = 16.4$.

The QPO is at a much shorter period than the ~3000 s modulation seen previously near the ends of outbursts. The latter is very long for a QPO in a short-period ($P_{\rm orb} = 1.78$ h) system, and is possibly associated with inhomogeneities rotating at the outer edge of the disc. In the LIMA model of DNOs (Paper II) it is not possible for DNOs of variable period seen directly from the primary to exist in an IP (if the magnetic field is strong enough to produce an IP it will prevent free circulation of an equatorial belt) and to date none have been observed in any certified IP.[3] We conclude that VZ Pyx is not an IP. More photometric studies of VZ Pyx late in outburst are required to see if the ~3000 s modulation is a regular feature and whether there is any evidence that it is coherent – and also to follow the period increase in the DNOs.

3.2 EC 21178−5417

EC 2117−54 is a $V \sim 13.7$, UV-rich star discovered in the ongoing Edinburgh–Cape Survey (Stobie et al. 1997). We have found it to be an eclipsing nova-like CV with $P_{\rm orb} = 3.708$ h; details of its position, finding chart, orbital light curve and spectra will be reported elsewhere – here we describe the results of high-speed photometry. Our photometric runs on EC 2117−54 are listed in Table 1.

EC 2117−54 turns out to be a rich source of DNOs and QPOs, and as a bright CV with a similarly bright reference star nearby it provides a system that is easily studied even in quite poor observing conditions. Its eclipses will be particularly useful for investigating phase shifts and physical locations of the oscillating sources within the system. In this paper we will discuss only the presence and periods of the DNOs and QPOs, and in particular in this section we consider only the normal DNOs and QPOs that lead to estimates of the ratio R. As with other nova-likes (e.g. UX UMa: Warner & Nather 1972; Knigge et al. 1998) the DNOs are not always visible in the FTs – our success rate (at least once in a run) for detecting them in EC 2117−54 is 83 per cent.

Table 2 contains the list of detected oscillations (the meaning of lpDNOs is given in Section 4). In some cases the variations within a run are described in more detail in Section 4.2.2. The DNO periods cluster around 23 s but the differences are much greater than the errors (derived from least-squares fits of sinusoids to the DNOs), which provides the first indication that these are indeed DNOs and not produced by stable rotation of the primary (as e.g. in DQ Her). The periodicities are not always present at full strength throughout the individual runs.

In section I of run S6544 there is a double DNO with periods 22.10 s and 23.27 s – see Fig. 2. These beat together at a period of 440 s; there is a broad low-amplitude signal in the FT near 470 s (which we would not have thought significant without the DNO evidence, but it should be remembered that the unstable nature of QPOs spreads and lowers their amplitude in an FT). By analogy with VW Hyi and other CVs with double DNOs, the shorter of the two periods is the true DNO; the longer period is a sideband formed by reprocessing of the revolving DNO beam off the QPO travelling wave (Paper II). We therefore have $R = 440/22.1 = 19.9$.

In section III of run S6551 there is a double DNO at 10.82 s and 11.40 s. These are the harmonics of fundamentals of which only one is seen in the FTs of another portion of the run. The periods 2 × 10.82 s and 22.69 s beat to give a pseudo-QPO period of 468 s, but in this case a genuine QPO is seen in the FT of that part of the run, centred on 500 s and with amplitude 6.3 mmag. This run gives $R = 21.6$.

DQ Her and some nova-like variables, does allow the reprocessed radiation from the magnetically channelled accretion to be detected).

[3] Reprocessed DNOs, in which the variable period of the travelling wave is involved, may be variable, as in GK Per.

Table 2. DNOs, lpDNOs and QPOs in EC 2117−54.

Run no.	Sect.	Length (s)	DNO period (s) [amplitude (mmag)]		lpDNO period (s) [amplitude (mmag)]		QPO period (s) [amplitude (mmag)]
S6544	I	2765	23.27 (0.03) [2.4]	22.10 (0.04) [1.5]	94.21 (0.26) [4.3]		480 [3.7]
	II	1728	23.21 (0.07) [2.2]		–		–
	III	1728	–		–		–
	IV	1166	–		96.01 (1.11) [3.9]		–
	V	3240	25.46 (0.07): [1.9]		79.90 (0.43) [4.2]	184.0 (1.6) [4.2]	
	VI	1417	23.14 (0.06) [3.3]		–		496 [7.2]
S6548	I	1797	22.43 (0.06) [3.0]		–		–
	II	2938	–		–		–
	III	2246	–		–		–
	IV	1728	–		–		–
	V	2048	–		–		–
S6549		8433	–		–		–
S6551	I	1210	22.54 (0.05) [2.9]		91.57 (0.10) [3.5]		–
	II	1987	22.69 (0.05) [2.3]		–		500 [6.3]
	IIIa	1331	10.82 (0.03) [4.0]	11.40 (0.03) [3.9]	92.25 (0.57) [5.5]		500 [6.3]
	IIIb	1365	22.80 (0.07) [2.8]		95.62 (0.80) [4.0]		–
	IIIc	1382	22.72 (0.04) [3.6]		–		–
	IV	1296	–		–		–
	V	1037	–			195.1 (2.8) [6.4]	–
S6553	I	1443	–		–		–
	II	1434	23.23 (0.10) [2.0]		–		–
S6555		2454	12.74[a] (0.04) [2.1]		–		–
S6557	I	1953	–		–		–
	II	1555	–		–		–
	III	1987	22.68 (0.04): [2.3]		–		–
S6564	I	821	–			169.5 (2.5) [7.6]	–
	II	2246	–		–		–
	III	1210	–		–		–
S6570	I	3197	22.67 (0.04) [1.9]		–		332 [7.0]
	II	1382	–		–		–
S6574	I	1987	–		–		–
	II	2246	–		–		–
S6580	I	1728	23.02 (0.05) [3.0]		–		373 [6.5]
	II	2367	–		–		–
S6599	I	1469	23.67 (0.11) [2.7]		–		–
	II	1728	23.41 (0.10) [2.0]	11.01 (0.02) [2.5]	–		–
S6634		2868	23.28 (0.05) [2.3]	13.2[b]	–		–
S6639		2229	23.18 (0.09) [3.3]		–		–
S6641	I	2920	23.18 (0.05) [2.1]		95.82 (0.69) [2.7]		–
	II	2773	–		101.03 (0.55): [2.9]		–

Table 3. – *continued*

Run no.	Sect.	Length (s)	DNO period (s) [amplitude (mmag)]		lpDNO period (s) [amplitude (mmag)]	QPO period (s) [amplitude (mmag)]
S6660	I	778	–		–	–
	II	1166	23.19 (0.11) [2.6]	21.42 (0.12) [2.0]	–	214: [7.9]
S6666	I	1909	–		–	–
	II	1909	23.29 (0.05) [2.8]		–	–
S6670		1840	–		–	–

Notes. Uncertainties in the periods are quoted after the periods in parentheses; ':' denotes an uncertain value. [a]This is the observed period, which is probably the beat period with the integration time. The true period would be 11.31 s. [b]This is the observed period, which is probably the beat period with the integration time. The true period would be 11.0 s.

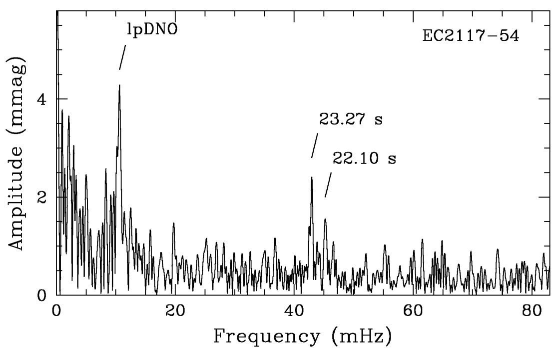

Figure 2. The Fourier transform of the first 45 min of run S6544 of EC 2117−54. The lpDNO and DNO periods are marked. The light curve has been pre-whitened at the low-frequency modulation visible in Fig. 14.

In section II of run S6599 there are two DNOs in the FT – at 23.41 s and 11.01 s. The latter is a first harmonic, though again there is no signal at the fundamental. The fundamental beats with 23.41 s at a period of 368 s. There is no signal at this, putative, QPO period in the FT, but we note that 368/22.04 gives $R = 16.7$.

Run S6660 has a double DNO that has a beat at 281 s; the observed QPO is near 214 s. The observed $R = 13.1$. Runs S6570 and S6580 give observed values of $R = 14.6$ and $R = 16.2$ respectively.

Runs S6555 and S6634 contained apparent harmonics that are probably beats with the integration lengths. The true periods are given in footnotes to Table 2.

3.3 CN Ori

CN Ori was observed on 2002 December 29 during outburst. A double DNO was visible in the first ∼1 h of the light curve with peaks at 12.10 s and 11.23 s. The beat period between these two periodicities is 156.6 s; there is no sign in the FT of a peak at this period. This run gives $R = 13.9$.

3.4 WX Hyi

We observed WX Hyi following an outburst in 2001 September, when it had almost returned to quiescence. In this run (S6248) strong QPOs at 185 s are visible (see Fig. 3). These QPOs remained coherent for ∼10 cycles. At the same time, DNOs are apparent in the FT at 19.4 s (amplitude 3.8 mmag). This gives $R = 9.5$. QPOs at 191 s were also observed during another run of WX Hyi in 2002 July (run S6463), but will be reported in detail elsewhere.

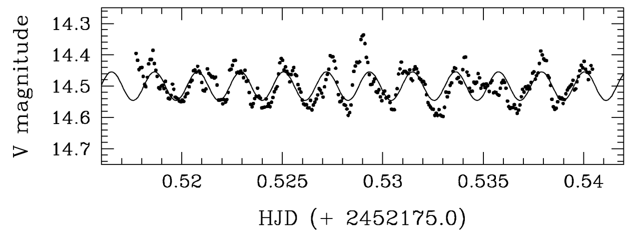

Figure 3. The light curve of WX Hyi (run S6248), showing the 185 s QPO clearly. Superimposed is the result from the non-linear sinusoidal least-squares fit.

3.5 OY Car

Optical DNOs with periods from 19.4 s to 28.0 s have been seen in OY Car at the end of superoutburst (Schoembs 1986), and 18 s DNOs have been observed with the *HST*, also at the end of superoutburst (Marsh & Horne 1998). No simultaneous DNOs and QPOs have hitherto been detected.

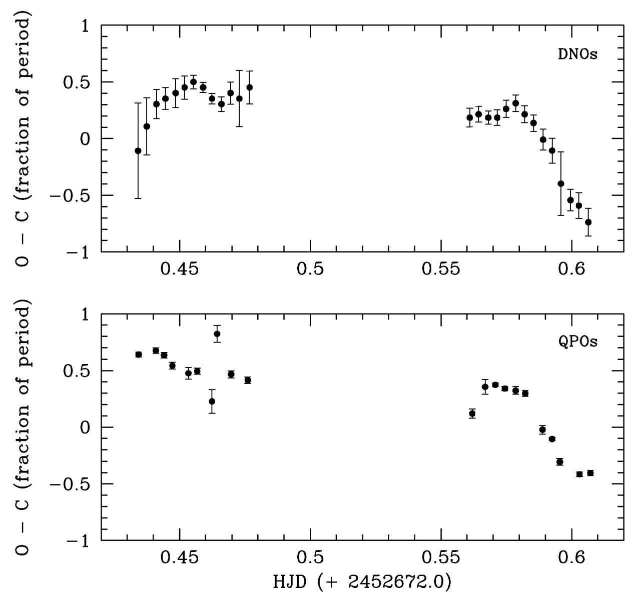

Figure 4. The O–C diagram of DNOs (upper panel) and QPOs (lower panel) in OY Car. Data from run S6722 are shown on the left, data from run S6724 are displayed on the right. The DNOs are displayed relative to a period of 17.62 s (run S6722) and 17.79 s (run S6724); the QPOs are displayed relative to a period of 281 s (run S6722) and 338 s (run S6724).

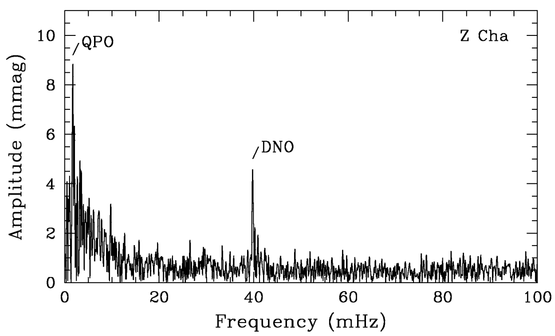

Figure 5. The Fourier transform of the first ∼1.5 h of run S6061 of Z Cha. The QPO and DNO periodicities are marked.

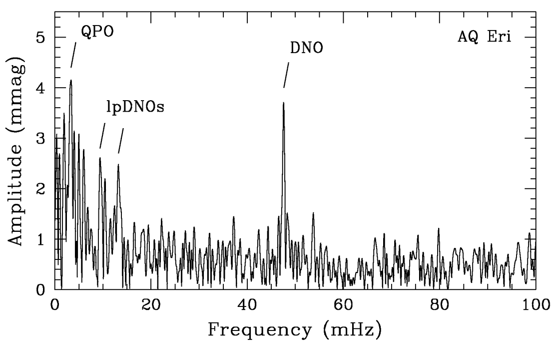

Figure 6. The Fourier transform of run S6510 of AQ Eri. The QPO, DNO and lpDNO frequencies are marked.

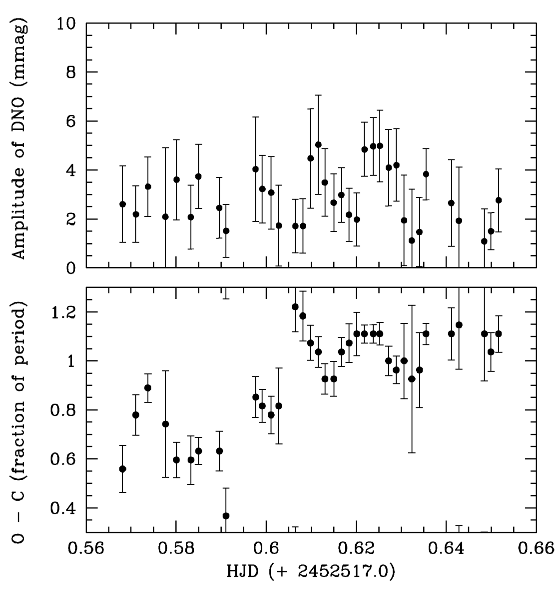

Figure 7. The O–C diagram (lower panel) of the 23.5 s DNO in AQ Eri (run S6516). The upper panel shows the amplitude variations of the DNO.

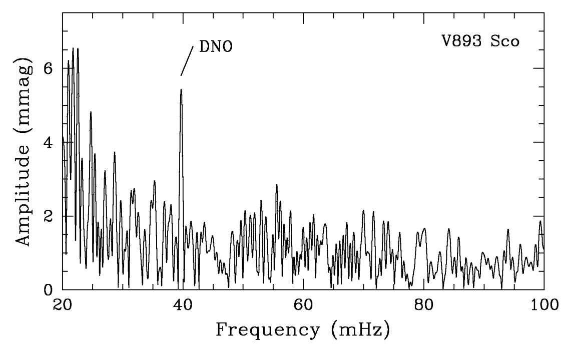

Figure 8. The Fourier transform of a section of run S6095 of V893 Sco. The DNO frequency is marked.

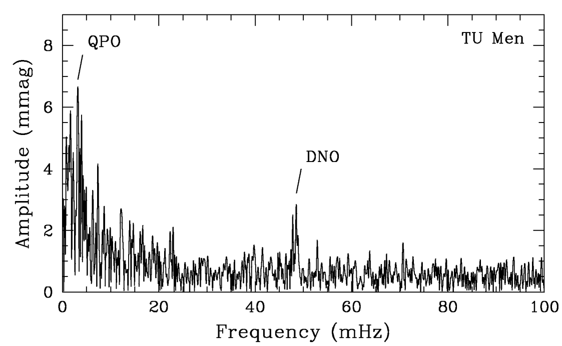

Figure 9. The Fourier transform of the first hour of run S6695 of TU Men. Both the QPO and DNO frequencies are marked.

We have extensive coverage of the 2003 February superoutburst of OY Car, but list in Table 1 only the runs that are relevant to the current discussion, which are near maximum light and obtained on the same night with an interruption between them.

Run S6722 shows a DNO at 17.62 s and QPOs at 281 s; later that night run S6724 shows a DNO at 17.79 s and a QPO initially at 338 s, which later changed to 297 s. The phase diagrams shown in Fig. 4 show a correlation between the behaviour of the DNOs and QPOs. Values of $R = 15.9$ and 19.0 are given by these data.

3.6 Z Cha

Z Cha was observed during the 2000 February outburst (run S6061, see Table 1) and a distinct DNO at 25.15 s was seen in the FT. The FT of the pre-whitened light curve (of the first 1.5 h of run S6061) is shown in Fig. 5. In this section a distinct QPO signal at 585 s is present. This gives $R \approx 23.3$.

3.7 AQ Eri

AQ Eri is an SU UMa type dwarf nova with an orbital period of 1.46 h and a magnitude range $V = 12.5$–17.5. It was reported at $V = 12.9$ on 2002 August 27; we observed it on its decline from maximum. The observations are listed in Table 1. DNOs and QPOs were detected for the first time in this star. In addition we have one earlier light curve obtained in quiescence.

The FT of the first light curve (run S6510), with the lowest frequencies (partly caused by a superhump) filtered out, is shown in Fig. 6. There is a very prominent single DNO at 21.0 s and a broad QPO feature centred on ∼296 s. These give $R \approx 15.0$. There are other spikes in the FT, which will be discussed in Section 4.7.

Two nights later (run S6516) the filtered FT again shows a QPO centred on ∼270 s and the DNO has lengthened to 23.5 s and now shows considerable structure. The latter is caused by lower coherence, as illustrated in the O–C diagram (Fig. 7). For this night $R = 12.8$.

One night later there is no evidence for a QPO or a DNO. The latter probably had become too incoherent to be detected in an FT.

3.8 V893 Sco

V893 Sco is an eclipsing dwarf nova with an orbital period of 1.82 h. We have observed it extensively and find that it frequently has large-amplitude QPOs with periods ∼350 s, as first detected (at 343 s) in one light curve by Bruch, Steiner & Gneiding (2000). Only part of one of our runs (S6095) has a DNO in it. This is listed in Table 1 and was obtained during an outburst. The FT is shown in Fig. 8; the large amount of 'red noise' is largely due to QPO and flickering activity. We removed the eclipses in the light curve before this analysis. The QPO period is 375 s and the DNO period is 25.2 s, which gives $R = 14.9$.

3.9 TU Men

TU Men is an SU UMa type dwarf nova with an orbital period above the period gap of 2.813 h. We observed TU Men on decline from outburst (approximately mid-way down) on 2002 December 26 (run S6695, see Table 1), and detected simultaneous DNOs and QPOs in the first hour of the light curve. The FT of the first hour of run S6695 is shown in Fig. 9. The DNO period is 20.6 s and the QPO period is 313 s, which gives $R = 15.2$.

4 OTHER DNOS/QPOS: A NEW TYPE OF DNO

In a few CVs more than one set of DNOs or QPOs has been observed. This raises the possibility that if only one modulation is seen it may be difficult to know to which group it belongs (see e.g. Section 4.10). We therefore examine what is known about oscillations other than those that have the relationship $P_{\rm QPO} \sim 15 P_{\rm DNO}$. We start by discussing observations of VW Hyi.

4.1 VW Hyi

During seven of nine nights (December 22–30) of the superoutburst of VW Hyi in 1975 December, Haefner, Schoembs & Vogt (1977, 1979, see also Schoembs 1977) saw a persistent sinusoidal modulation with amplitudes from 0.5 to 11 mmag, and an apparently erratically changing period in the range 86.0–92.8 s (averaging ∼88.1 s) but unchanging in mean period as VW Hyi decreased in brightness from 10.6 to 13.7 mag. This contrasts with the rapidly increasing periods of the normal DNOs and QPOs over this magnitude range (Paper I). Schoembs & Vogt (1980) detected a 74 s QPO near the end of the 1978 October VW Hyi superoutburst.

4.1.1 New observations and possible interpretation

We have observed similar 'longer-period' dwarf nova oscillations (lpDNOs) in VW Hyi, but only on rare occasions. Of the 51 runs on VW Hyi listed in table 1 of Paper I, lpDNOs are definitely present in only five (S0018, 75.6 s; S0129, 93.1 s; the first half of S1594, 71.2 s; S2243, 75.9 s; and S6184, 83.0 s), and a run accidentally omitted from Paper I (S6133, see Table 1, made near the end of a normal outburst), which contains two oscillations, near 85 s and 94 s. These lpDNO detections are distributed from maximum light almost to quiescence, and include normal and superoutbursts. The oscillation in S2243 is relatively strong (amplitude 1.3 mmag) and is from early in the same 1975 December superoutburst that Haefner et al. (1977, 1979) saw the ∼88 s modulations. The amplitudes of the oscillations in S6184 are 1.3 mmag, made when VW Hyi was a factor of 10 less luminous than in S2243. There is a tendency for the periods in our runs to increase through the outburst (from 75.9 s at maximum to 93.1 s at the end of outburst), but this may be small-number statistics (the Haefner et al. observations do not show this) and in any case the oscillations come from six different outbursts.

We get a clue to what the ∼70–93 s periodicities in VW Hyi may be by noting that Sion et al. (2001) have measured $v \sin i = 500$ km s^{-1} and log $g = 8.0$ for the primary of VW Hyi, and that Sion et al. (1996) found $v \sin i = 300$ km s^{-1} from a different set of spectra. With an inclination $i = 65°$ and the standard white dwarf mass/radius relationship, these give $M(1) = 0.6$ M$_\odot$ and a rotation period $P_{\rm rot} \sim 120$–165 s for the primary. The observed periods may therefore be associated with the bulk rotation of the white dwarf – which is certainly a short-period clock available in the system. This suggests that some mass accretion on to two magnetic poles on the primary is at times taking place (as well as on to the belt). Unlike an IP, in a low-field CV the angular momentum accreting at the equator will be distributed in latitude as well as radially; the outer layers of the primary will therefore rotate differentially and it follows that the accretion regions may not always have exactly the same angular velocity.

4.1.2 Phase and amplitude diagrams

To investigate these lpDNOs more thoroughly, we have computed FTs for subsets of the data and have also produced phase/amplitude diagrams. In such diagrams the formal errors, derived from least-squares fits, are sometimes very large. This is particularly the case where there are large-amplitude QPOs or flickering that has not been filtered out. We start by describing the behaviour of VW Hyi in run S6133. The FT in the vicinity of 100 s for the entire run, shown in Fig. 10, has three strong periodicities. Using pre-whitening and multiple sinusoidal non-linear least-squares fitting, we find these are best represented by oscillations at 84.44 s and 85.70 s, with an amplitude of 1.7 mmag and 1.5 mmag, respectively, and 94.13 s with amplitude 1.6 mmag. The doublet at 85 s is strong only in the first half of the run, which is not long enough to resolve it fully; in the second half of the run it appears as a single peak at 85.3 s. The separation of the doublet is therefore not well determined; although formally it corresponds to a beat period of 5740 s, we found periods up to 6200 s while analysing the data in various ways. The orbital period of VW Hyi is 6173 s, so we suggest, in analogy with IPs, that the 85 s doublet consists of a rotating beam with a period of 84.4 s and an orbital sideband produced by reprocessing by the secondary or by the vertical thickening of the disc where the stream impacts.

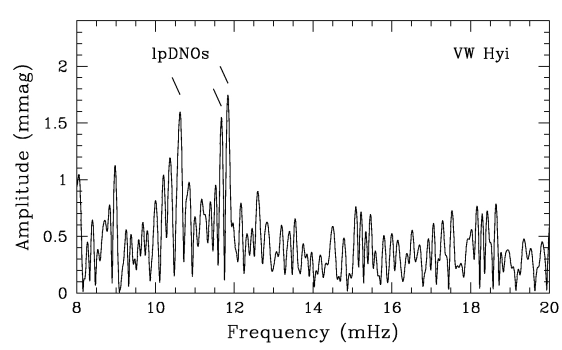

Figure 10. The Fourier transform – truncated at the lowest frequencies – of VW Hyi (run S6133). The lpDNO frequencies are marked.

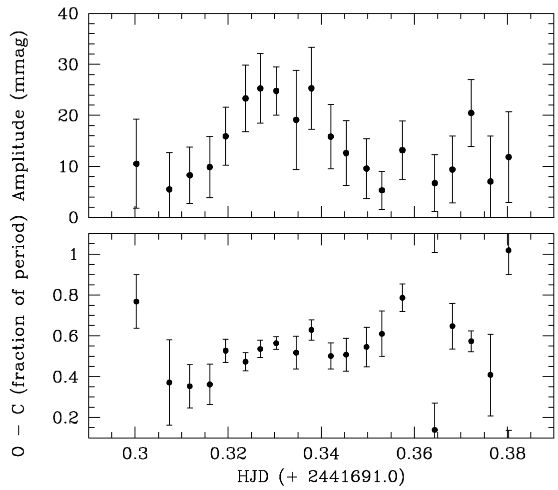

Figure 11. Amplitude/phase diagrams for the lpDNO in run S0129 of VW Hyi. For the lpDNO a mean period of 93.1 s is taken, and each dot represents ∼7 lpDNO cycles; there is a 50 per cent overlap.

If the 94 s modulation is also a reprocessed signal then, by analogy with the model for double DNOs, it implies a prograde travelling wave with a period of 820 s. There is no peak in the FT at this period, but shadowing of the disc and shadowing in our direction can be very different for a system that is not of high inclination.

Of the other runs with lpDNOs in them, all but one have narrow spikes in their FTs. The 93 s peak in the FT of run S0129 is too broad to be a single period, and its phase/amplitude diagram shows a sinusoidal modulation suggesting the presence of two unresolved periodicities beating together – see Fig. 11. The sine wave fitted to the amplitude modulation has a period ∼5100 s, but is uncertain because only one cycle is observed. This is of a similar time-scale to the doublet separation in run S6133.

The occasional presence of unresolved doublets in the FT could account for some of the spread in the lpDNO periods seen in VW Hyi by Haefner et al. (1977, 1979).

4.2 EC 2117−54

4.2.1 DNOs

In Section 3.2 we gave the first evidence that the ∼23 s oscillations are DNOs. To study this further, we have computed amplitude/phase diagrams for all of the runs, some of which are shown in Fig. 12. The variations seen [for example the change of slope in the O–C diagram from negative to positive in run S6551 at HJD 245 2552.335 (bottom left panel of Fig. 12), which is caused by a change in period from 22.66 s to 22.74 s] are characteristic of DNOs (see Paper I). There is no systematic variation of DNO phase with orbital phase of the kind seen in DQ Her (O'Donoghue 1985). Phase changes in the DNO (as illustrated in Fig. 12) occur at different times as phase changes in the lpDNO, and the two oscillations appear to be independent.

The interpretation of the 11.02 s period in run S6599 given in Section 3.2 above enables us to explain the existence of the 12.78 s period in run S6555. The integration time for this run was 6 s, so an 11 s periodicity would lie above the Nyquist frequency. If 12.78 s is the beat frequency with the integration length (see RU Peg, Section 2.1), then we are detecting a first harmonic modulation at 11.31 s, implying a fundamental at 22.62 s, which is within the

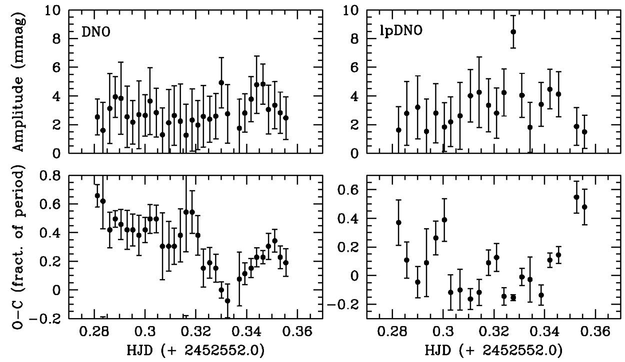

Figure 12. Amplitude/phase diagrams for the DNO (left panels) and lpDNO (right panels) in run S6551 (sections I, II and III, see Table 2) of EC 2117−54. For the DNO a mean period of 22.69 s was taken, and each dot represents ∼18 DNO cycles. The lpDNO is plotted against a mean period of 95.5 s, and each dot represents ∼6 lpDNO cycles. In both cases there is a 50 per cent overlap.

range of P_{DNO} seen in other runs. In the FT there is no sign of the fundamental.

The same explanation holds in run S6634, where the observed 13.2 s modulation of very small amplitude is really an 11.0 s periodicity, implying a fundamental at 22.0 s and a pseudo-QPO period ∼400 s. There is nothing significant in the FT at this latter period.

4.2.2 lpDNOs and QPOs

It can be seen in Table 2 that, in addition to the regular DNO and QPO modulations, a period around 94 s frequently appears in the light curve. For example, in addition to its double DNO, run S6544 has a sinusoidal modulation at a period near 94 s seen in Fig. 2. [Note that the mean amplitude, derived from fitting to a sinusoid, especially one that is not quite constant in period (see below), is much smaller than the range of the largest cycles, which are the ones most readily seen in the light curve.]

The lpDNO oscillations are also easily visible in the light curve of run S6551, but this run has the added interest that in one section the

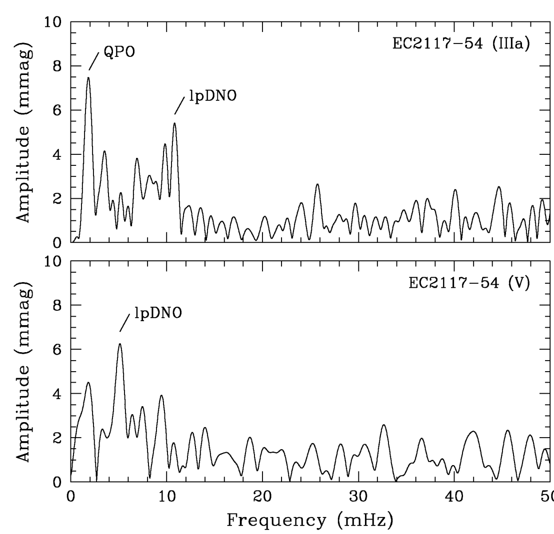

Figure 13. The Fourier transform of sections IIIa (upper panel) and V (lower panel) of run S6551 of EC 2117−54.

period doubles (Fig. 13), which could signify a temporary change from two-pole to single-pole accretion.

In addition, in EC 2117−54 there are regular QPOs with periods ∼500 s that are easily seen in some sections of the light curves.

The suite of periods in EC 2117−54 is remarkably similar to that seen in VW Hyi late in its decline from outburst. In the latter, QPOs with $P_{\mathrm{QPO}} \sim 400$ s and DNOs with $P_{\mathrm{DNO}} \sim 22$ s occur when the system is about 1 mag above its quiescent brightness (Paper I). Furthermore, the ∼94 s periodicities that we have seen in EC 2117−54 are similar to those in VW Hyi at ∼88 s (see Section 4.1.1).

4.2.3 Some detailed examples

The richness of the observational material for EC 2117−54 enables us to make a detailed analysis of the behaviour of the lpDNOs and compare them with the DNOs. As these are a newly recognized class of oscillation, we present more detail than might otherwise be justified. We will start by featuring two light curves where the lpDNOs are particularly prominent.

Fig. 14 shows the first 45 min of the light curve obtained in run S6544. The FT of this section of S6544 has already appeared in Fig. 2 and was discussed above. A phase shift around HJD ∼ 245 2525.297 is present, illustrated by the two sets of vertical bars marking the lpDNO minima in Fig. 14; the dotted bars fit the first part of the light curve well, and the solid bars fit the minima after the phase shift. This illustrates the lack of complete stability in lpDNOs.

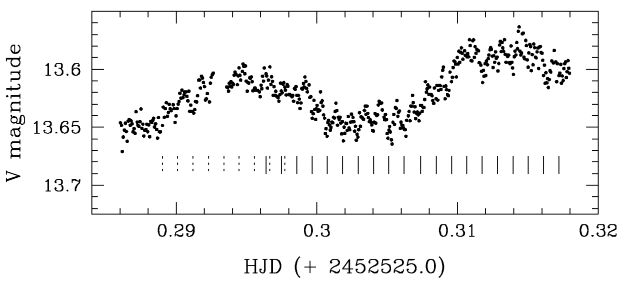

Figure 14. The light curve of EC 2117−54 (the first 45 min of run S6544). The lpDNO modulation at 94.21 s is clearly visible in the light curve. The lpDNO minima are marked by vertical bars. There is a phase shift around HJD ∼ 245 2525.297.

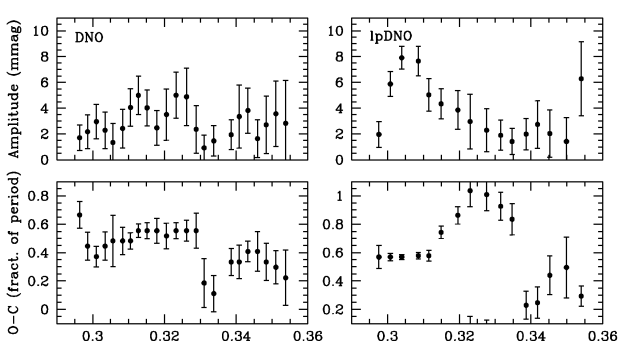

Figure 15. Amplitude/phase diagrams for the DNO (left panels) and lpDNO (right panels) in run S6544 (sections I, II and III, see Table 2) of EC 2117−54. For the DNO a mean period of 23.27 s was taken, and each dot represents ∼18 DNO cycles. The lpDNO is plotted against a mean period of 94.21 s, and each dot represents ∼6 lpDNO cycles. In both cases there is a 50 per cent overlap.

Another example of the independent behaviour of the DNOs and lpDNOs is given in Fig. 15, where the amplitude and phase of the DNO and lpDNO in run S6544 (sections I–III) is plotted.

4.2.4 Discussion

EC 2117−54 has an orbital period that places it in the 3–4 h range where most, perhaps all, nova-like variables experience states of low $\dot{M}$ and are known as VY Scl stars. DNOs have not been observed in any recognized VY Scl stars but they have in two nova-likes that will probably show low states if observed sufficiently: HL Aql, $P_{\mathrm{DNO}} = 19.6$ s, $V = 13.5$ (Haefner & Schoembs 1987); and BP Lyn, $P_{\mathrm{DNO}} = 25.5$ s, $V = 14.2$ (Ringwald 1992). Thus the DNOs and QPOs have yet to be followed into and out of low states – it will be very instructive to observe the evolution of the oscillations during these transitions; all three of the above-mentioned objects should be bright enough in their low states for such observations to be made.

Some of the nova-likes in this same period range are classified as eclipsing SW Sex stars, two of which have been shown to have periodically modulated circular polarization – LS Peg at 29.6 min (Rodríguez-Gil et al. 2001) and V795 Her at 19.54 min (Rodríguez-Gil et al. 2002) – and are IPs. If our interpretation of EC 2117−54 is correct, it is a similar system, probably with a weaker magnetic field, and with a rotation period (deduced from the lpDNOs) of ∼3.2 min.

4.3 SS Cyg

Another star for which longer-period DNOs have been seen is SS Cyg. Patterson (1981, see also Robinson & Nather 1979) observed what he described as QPOs in the range 32–36 s in two different outbursts of SS Cyg, occurring on three nights in the 1978 September outburst when there were also ∼10 s normal DNOs present. There have been no other reports of modulations near this period. Sion (1999) finds $v \sin i = 300$ km s^{-1} for SS Cyg; with a mass of 1.20 M$_{\odot}$ and a (rather uncertain) inclination of 50°, this gives a rotational period ∼63 s, which again could give the observed modulation if there is two-pole accretion.

4.4 HT Cas

Patterson (1981) reported ∼100 s QPOs in outbursts of HT Cas, which has typically ∼20 s normal DNOs during outbursts. The QPOs are said to be often seen also during quiescence, and therefore represent an invariant period in the system, unlike the DNOs. We classify them as lpDNOs.

4.5 AH Her

Patterson (1981) also found ∼100 s QPOs in AH Her, whose normal DNOs range from 24 to 39 s.

The HT Cas and AH Her periodicities may be further examples of lpDNOs, and therefore possibly associated with the rotation of the primary (rotational velocities are not available for these two stars).

4.6 OY Car

One section of run S6724 shows a quite coherent modulation with a mean amplitude of 9.5 mmag and a period of 116 s. The FT is shown in Fig. 16 and represents 10 cycles of this lpDNO. No other long-lived lpDNOs appear in our light curves.

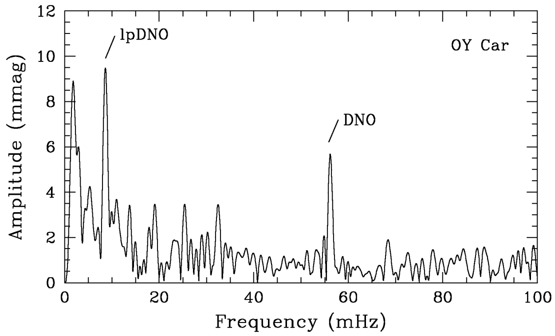

Figure 16. The Fourier transform of a section of ∼20 min of run S6724 of OY Car during superoutburst. The lpDNO and DNO frequencies are marked.

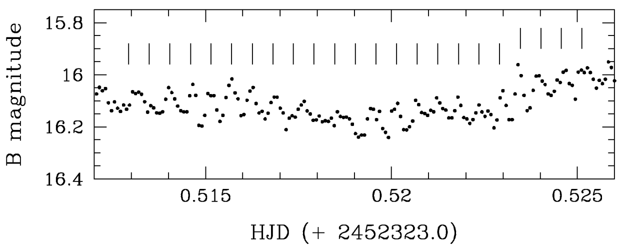

Figure 17. A section of the light curve of OY Car (run S6488) during quiescence, in which a clear ∼48 s periodicity is present (the vertical bars mark the maxima of this coherent signal).

OY Car has $v \sin i \leqslant 200$ km s^{-1} (Sion 1999), a mass of 0.68 M$_\odot$ and $i = 83°$ (Wood et al. 1989), which leads to $P_{\rm rot} \geqslant 260$ s. An lpDNO at 116 s is therefore just compatible with a two-pole accretor.

We have one run (among many others obtained over past years) of OY Car in quiescence (S6488) that shows a coherent signal. The light curve is given in Fig. 17 and shows a period of 47.9 s. This unusual period is perhaps an evolution from the DNOs seen during outbursts.

4.7 AQ Eri

In addition to the QPOs and DNOs described in Section 3.7 we observe lpDNOs in AQ Eri. In Fig. 6 there are two spikes near 100 s which are at 75.7 (±0.3) s and 106.3 (±0.5) s with mean amplitudes of 2.5 and 2.6 mmag, respectively (derived from non-linear least-squares fits). The frequency difference between these corresponds to a QPO period of ∼265 s, which is similar to the observed period (Section 3.7). These appear to be direct and reprocessed lpDNOs as in VW Hyi (Section 4.1.2).

In run S6516 a single strong lpDNO at 73.6 (±0.1) s and mean amplitude of 2.0 mmag is present. The amplitude/phase plot for this lpDNO is shown in Fig. 18, which may be compared with that for the DNO that is present simultaneously (Fig. 7). The lpDNO has greater coherence than the DNO.

The next night, despite the absence of DNOs or QPOs, there is a prominent lpDNO in the last half of the light curve, being most prominent in the final section as shown in Fig. 19. The period is 108.6 (±0.8) s and the mean amplitude is 5.2 mmag, and corresponds to the reprocessed lpDNO that appears in Fig. 6 as discussed above.

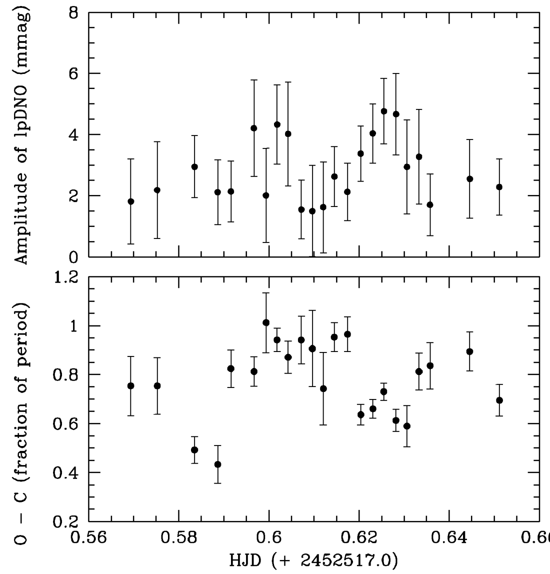

Figure 18. The O–C diagram (lower panel) of the 73.6 s lpDNO in AQ Eri (run S6516). The upper panel shows the amplitude variations of the DNO.

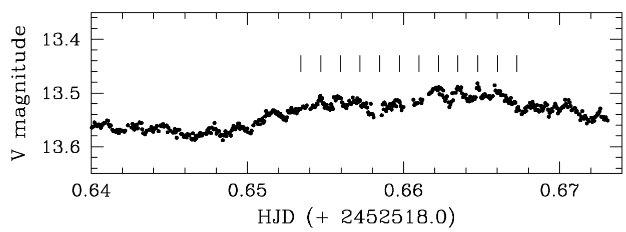

Figure 19. The light curve of AQ Eri on 2002 August 31 (run S6520). The lpDNO modulation at ∼108.6 s is visible in part of the light curve, and the most prominent cycles are marked by the vertical bars.

Our quiescent light curve (S6159) shows large-scale flickering but there is a possible lpDNO of high coherence at 87.0 (±0.2) s and mean amplitude 7.7 mmag.

4.8 U Gem

The soft X-ray observations by Cordova et al. (1980); Cordova et al. (1984), Cordova & Mason (1984) and Mason et al. (1988), referred to in Section 2.13 above, revealed a suite of modulations. In addition to the 21 s DNO and 585 s QPO there were observed periodicities at ∼121 s and ∼135 s in quiescence and possibly ∼152 s in outburst. Robinson & Nather (1979) observed low-coherence optical modulations near 146 s and its first harmonic during an outburst. These oscillations appear to have the properties of lpDNOs, in which case U Gem is the first CV to show all three types of oscillation in the X-ray region.

Sion et al. (1998) find $v \sin i \sim 100$ km s^{-1} for the primary and a mass of 1.1 M$_\odot$, which with $i = 67°$ give $P_{\rm rot} \sim 275$ s, and we again find that two-pole accretion on to the primary will provide the observed lpDNO periods.

4.9 VZ Pyx

In the FT of the last half of the run S6066 (see Fig. 20), a coherent signal is present at 112.4 (±0.6) s, with a mean amplitude 6.2 mmag.

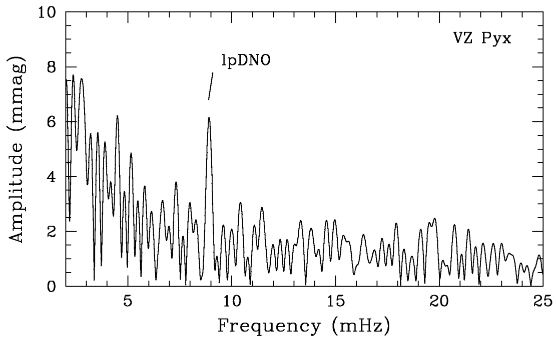

Figure 20. The Fourier transform (truncated at the lowest frequencies) of the last ~1 h of run S6066 of VZ Pyx during outburst. The lpDNO frequency is marked.

No DNOs or QPOs are seen during this run. Given the suite of DNO and QPO frequencies already identified in Section 3.1, we associate the coherent 112.4 s signal with an lpDNO.

4.10 HX Peg

HX Peg is a dwarf nova with an orbital period of 4.82 h and frequent outbursts (recurrence time ~30 d) taking it from a minimum $V \sim 16.5$ to maximum at $V \sim 12.9$. We have observed parts of three outbursts (Table 1).

Late in the 2002 July outburst there is a clear signal (run S6475) with a period of 112.3 (±1.1) s and mean amplitude 2.6 mmag, illustrated in Fig. 21. On the late rise of the 2002 October outburst (run S6584) a similar signal is seen in the first half of the run: 114.8 (±0.7) s with an amplitude of 3.1 mmag. Just after maximum of the 2002 November outburst (run S6656) there is an obvious modulation in the light curve (Fig. 22), which the FT shows is the result of two oscillations, with periods 83.4 (±0.5) s and 111.1 (±1.0) s with amplitudes of 4.8 and 4.2 mmag, respectively. The

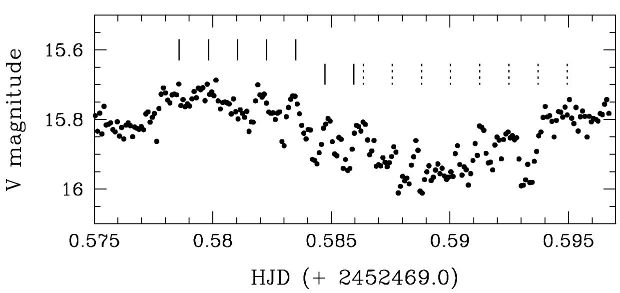

Figure 21. The light curve of HX Peg (the last ~30 min of run S6475). The lpDNO modulation at ~112 s is clearly visible; the maxima are marked by vertical bars. There is a phase shift around HJD ~ 245 2469.586.

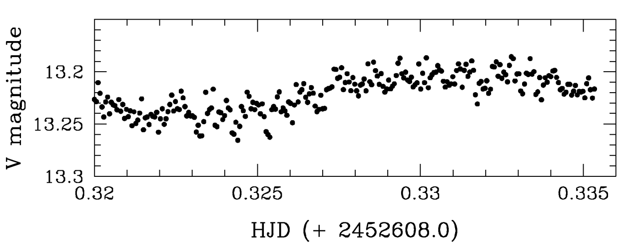

Figure 22. The light curve of HX Peg (the last ~23 min of run S6656).

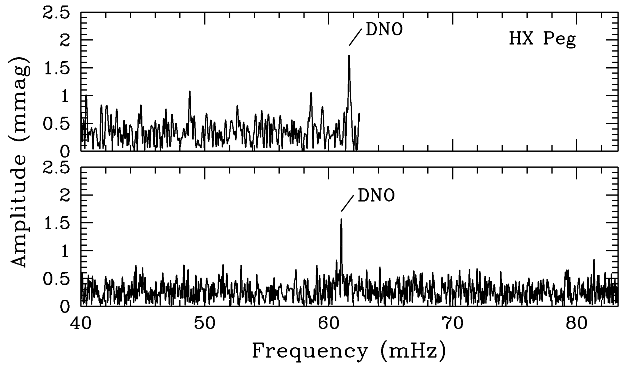

Figure 23. The Fourier transform (truncated at the lowest frequencies) of runs S6646 (upper FT) and S6650 (lower FT) of HX Peg during outburst. The DNO frequencies are marked.

beat period between these oscillations is 335 s and there is a peak in the FT near this period.

The above properties, especially the similarity of the periods near 112 s despite a brightness range of ~2.7 mag (Table 1), suggest an lpDNO in which the true period is ~83 s and the ~112 s is a reprocessed signal. In none of the runs discussed so far is there any sign of a normal DNO. However, runs S6646 and S6650, made at the maximum of the 2002 November outburst, have distinct signals at 16.22 s and 16.39 s, with mean amplitudes of 1.7 mmag and 1.6 mmag, respectively – seen in the FTs in Fig. 23. Combined with the QPO observed a few days later in the same outburst (see above), we have $R = 20.6$.

In addition to the suite of periodicities described above, HX Peg frequently shows very large QPOs with periods over the range of 1400–1900 s. It was our early observations of these, combined with the ~112 s oscillations that we now recognize to be lpDNOs, that led us to combine these into the value $R \sim 16$ announced earlier (Warner & Woudt 2003). We now consider that the ~1800 s QPOs arise from a different physical mechanism, perhaps connected to the rotation period of the outer edge of the accretion disc (see section 8.7 of Warner 1995a).

4.11 AM CVn stars

AM CVn stars are very short orbital period, helium-transferring doubly degenerate CVs. DNOs at 19–22 s and 26.2 s respectively have been observed in the high state of CR Boo (Patterson, private communication) and in AM CVn (Patterson et al. 1979, 1992). In most of the AM CVn stars the dominant modulation is a non-sinusoidal superhump that has strong harmonics to fifth order or higher; this makes the detection of QPOs very difficult. Nevertheless, Patterson et al. (2002) have observed ~5 min QPOs in HP Lib, which is an AM CVn star in the high state.

4.11.1 V803 Cen

V803 Cen is an AM CVn star with high and low states of mass transfer. O'Donoghue, Menzies & Hill (1987) observed brightness modulations with a mean period near 175.8 s during the high state of 1986 July 2–5; the period changed only slightly (to 178.8 s) on July 7 when the star had faded by two magnitudes. The 176 s modulation was seen again in a high state in 1987 (O'Donoghue & Kilkenny 1989), and we have detected it, as described below, but it has not been seen in the very low state (O'Donoghue et al. 1990). From these observations alone we can already say that the range of the oscillations and their insensitivity to luminosity are characteristic of lpDNOs.

An alternative interpretation, as a DB pulsator, does not seem viable for V803 Cen. Although there is one DB pulsator, PG 1351+489 that has most of its power in one oscillation mode (at a period of 490 s) and appears almost monoperiodic (Winget, Nather & Hill 1987), it and all other members of the class are in fact multiperiodic. The range of brightness of V803 Cen is over 4 mag, showing that accretion luminosity dominates in the high state. That implies that any pulsations of the primary would be most visible in the low state; but the reverse is the case. Furthermore, the modulation is not always present at high state, which is a characteristic of DNOs, but not of pulsations of a degenerate star.

We can demonstrate further aspects of the pulsations in V803 Cen that are in accord with DNO behaviour and not with DB pulsations. Table 1 lists observations that we have obtained in the high state; in addition to these we have drawn on archived observations published in O'Donoghue et al. (1987) and O'Donoghue & Kilkenny (1989). FTs and amplitude/O–C diagrams were computed for all of these runs. An example is given in Fig. 24 and shows the occasional short-term instability of the pulsation, which is uncharacteristic of oscillations in degenerate pulsators.

In Fig. 25 we illustrate a light curve (run S4035 of O'Donoghue & Kilkenny 1989) of V803 Cen observed when the 176 s modulation was particularly prominent. In order to show this clearly we have pre-whitened the light curve at the dominant 1611 s superhump modulation and its first three harmonics. The FT of the light curve shown in Fig. 25 is shown in Fig. 26. It shows how easy it is to detect the 176 s modulation when it is present at full amplitude. The first and second harmonics are very weakly present and appear in the mean profile of the modulation as a slight non-sinusoidality. Greater departure from sinusoidal shape is seen in some other runs, with higher harmonics present, but we have not found any light curves where the first harmonic alone is very prominent – as would be the case for dominant two-pole accretion. Nor have we seen a

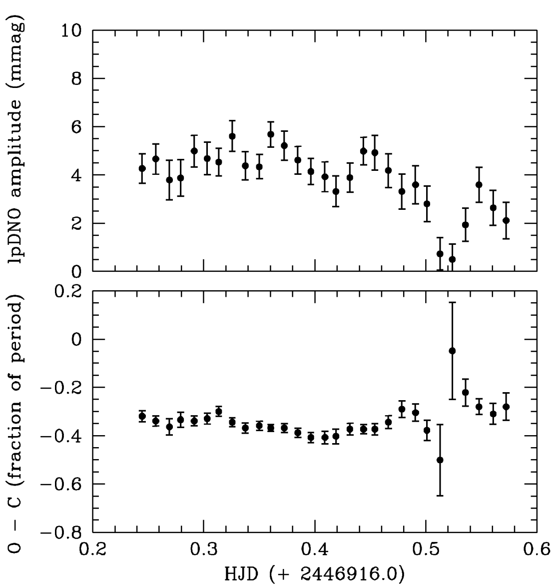

Figure 24. The O–C diagram (lower panel) and amplitude diagram (upper panel) of the 176 s photometric modulation seen in V803 Cen (run S4038 of O'Donoghue & Kilkenny 1989).

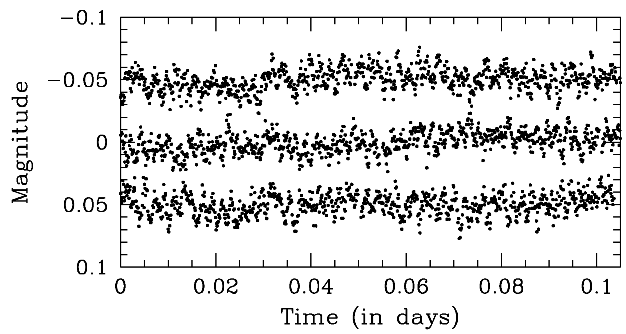

Figure 25. The light curve of run S4035, for V803 Cen, pre-whitened at the superhump frequency and the first three harmonics. The data shown represent a continuous light curve of length 0.315 d, split up into three segments. The first and last segments are displaced vertically, by −0.05 and +0.05 mag, respectively, for display purposes. The mean magnitude of V803 Cen during this run was $B \sim 13.3$ mag.

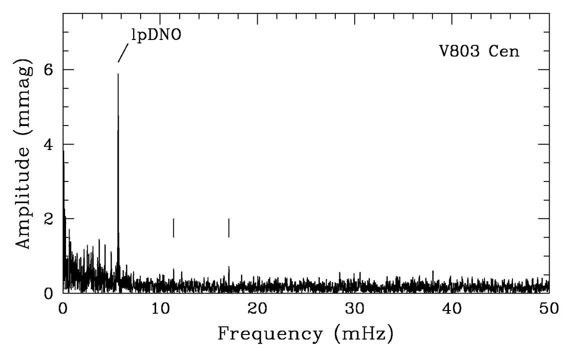

Figure 26. The FT of run S4035, for V803 Cen, pre-whitened at the superhump frequency and the first three harmonics. The peak corresponding to the 175.8 s modulation is marked by 'lpDNO' and the first two harmonics of this modulation are indicated by vertical bars.

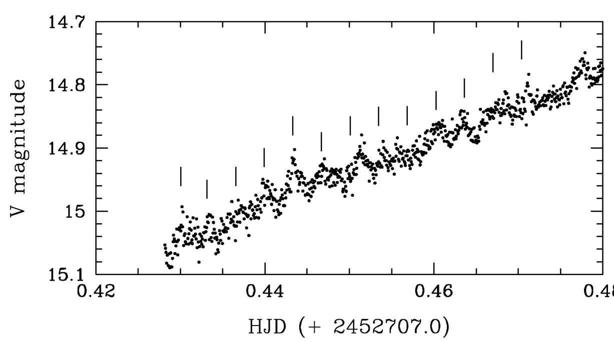

Figure 27. The light curve (the first ~70 min of run S6852) of CR Boo. The QPO maxima are marked.

subharmonic at ~352 s, so we infer that the rotation period of the primary is ~176 s.

4.11.2 CR Boo

The dominant modulation in CR Boo when in a high state is at 1490 s, with considerable power in the first, second and third harmonics (Patterson et al. 1997). We have two long runs on CR Boo (Table 1), the second (S6862) of which shows a light curve and FT similar to

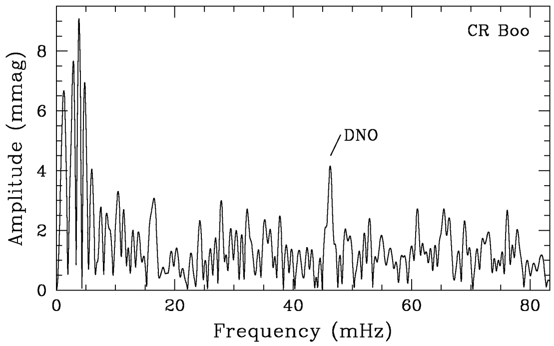

Figure 28. The Fourier transform (data length ∼25 min) of a section of run S6852 of CR Boo. The DNO frequency is marked.

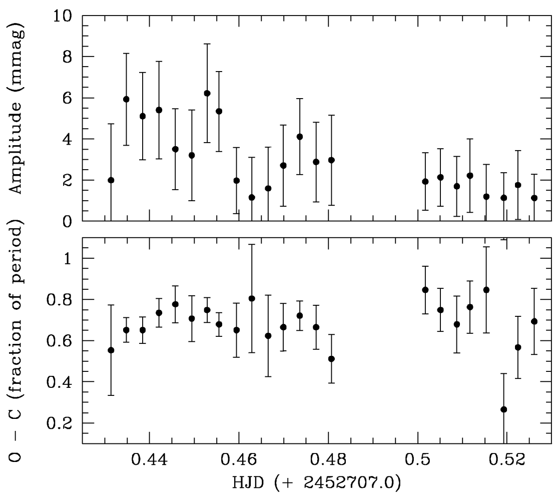

Figure 29. The O–C diagram (lower panel) and amplitude diagram (upper panel) of the 61.9 s lpDNO seen in CR Boo.

the common type, but the first (S6852) has both DNOs and QPOs, as seen in the light curve and FT (Figs 27 and 28).

The QPO signal is near, but not at, the fourth harmonic. The latter would be at 298 s, but the peak in the FT is at 291 s, which is distinctly different. Furthermore, the apparent QPO has large amplitude in the first half of the run, but disappears in the latter half, which is unlike the behaviour of fourth harmonics seen in AM CVn stars (e.g. AM CVn itself: Skillman et al. 1999).

In the same run a DNO is present at 21.6 s, as seen in Fig. 28. This gives $R = 13.5$. The DNO seen in run S6852 is an independent confirmation of DNOs observed on three consecutive nights at ∼22 s in CR Boo during the 1996 CBA campaign on CR Boo (Patterson, private communication).

In addition to the DNO and QPO observed in CR Boo (run S6852), there is an lpDNO at 61.9 s in the same run. Fig. 29 shows the phase/amplitude diagram for the 61.9 s periodicity over the first ∼2.3 h of run S6852.

5 FURTHER COMPARISON BETWEEN QPOs IN CVs AND X-RAY BINARIES

With our extended data set, obtained from observing the literature and the sky, we can generate a more detailed comparison between DNO and QPO periods in CVs. In Fig. 30 we show this on the same two-QPO correlation diagram produced for X-ray binaries (Belloni, Psaltis & van der Klis 2002); the latter distinguishes between neutron star and black hole candidates. Some of the scatter in the CV part of the correlation may arise through ambiguities of period – i.e. whether we are observing the primary periods or their first harmonics. Other scatter comes in a few cases from lack of simultaneity in observations of the DNOs and QPOs. However, the correlation is quite clear, and the whole relationship can be described by $P_{\mathrm{QPO}} \sim 15 P_{\mathrm{DNO}}$ for both CVs and X-ray binaries, over a range of nearly six orders of magnitude in period or frequency. This correlation is not yet understood; Mauche (2002) has shown that many popular models for QPOs in X-ray binaries are excluded by this relationship.

We are conscious of the possibility of bias in our selection of DNOs and QPOs that have been ‘accepted’ into our list, but it was while attempting to avoid such a bias that we realized that there is strong evidence for an additional set of DNOs – the lpDNOs described above. We currently see no clear evidence for maverick DNOs that fit neither of these categories.

There is a possible additional similarity between CV and X-ray binary oscillations. During X-ray bursts in the latter, pulsations are seen that lie in the frequency range 300–600 Hz (see table 1 of van der Klis 2000), which increase in frequency slightly during the burst, and are attributed to hotspots on the neutron star where gas expands and slips relative to the rotation of the underlying atmospheric layers. It is argued (van der Klis 2000) that at least in some cases there are two hotspots. If that were generally the case, then the true rotation frequencies would actually lie in the range 150–300 Hz. The high-frequency QPOs (plotted on the abscissa of Fig. 30) in these same stars (table 3 of van der Klis 2000) lie in the range 500–1100 Hz and are thus ∼4 times the supposed star rotation frequencies. This is the same relationship as seen in CVs, where the lpDNOs (interpreted above as white dwarf body rotation) have approximately four times the periods of the DNOs. The additional factor ∼4 between the periods of lpDNOs and QPOs in CVs is matched by the ratio of frequencies of rotation to low-frequency QPOs in the X-ray binaries.

On the other hand, as can be seen in Table 2, there are examples in CVs where the first harmonic rather than the fundamental appears, and this can lead to $P_{\mathrm{QPO}} \sim 2 P_{\mathrm{lpDNO}}$, as seen in many of the X-ray binary equivalent oscillations described above.

The evolution of burst millisecond oscillations shows phase drifts and often sudden phase shifts that are similar to those of the lpDNOs (Muno, Chakrabaty & Galloway 2002).

6 DISCUSSION AND CONCLUSION

In this paper we have extended the already rich phenomenology of CV DNOs and QPOs to include the recognition of a new type of DNO, the lpDNO. We have detected some double lpDNOs, whose splitting, as with the double DNOs, suggests reprocessing off a travelling wave moving with the QPO period. We have a possible first indication of such a sideband at the orbital frequency. As the lpDNOs are a newly identified phenomenon we have taken care to illustrate them extensively in this paper. It is probable that there are many more aspects still to be uncovered.

The differences in behaviour for outbursts of the same dwarf nova have yet to be understood. Why, during the 1975 December superoutburst of VW Hyi, the ∼88 s lpDNOs were so prominent for a week but only very occasionally and intermittently present in other outbursts, is a mystery. We note, however, that Hartmann et al. (1999) have found that the X-ray properties of VW Hyi also differ greatly from outburst to outburst. Both the X-rays and the DNOs are

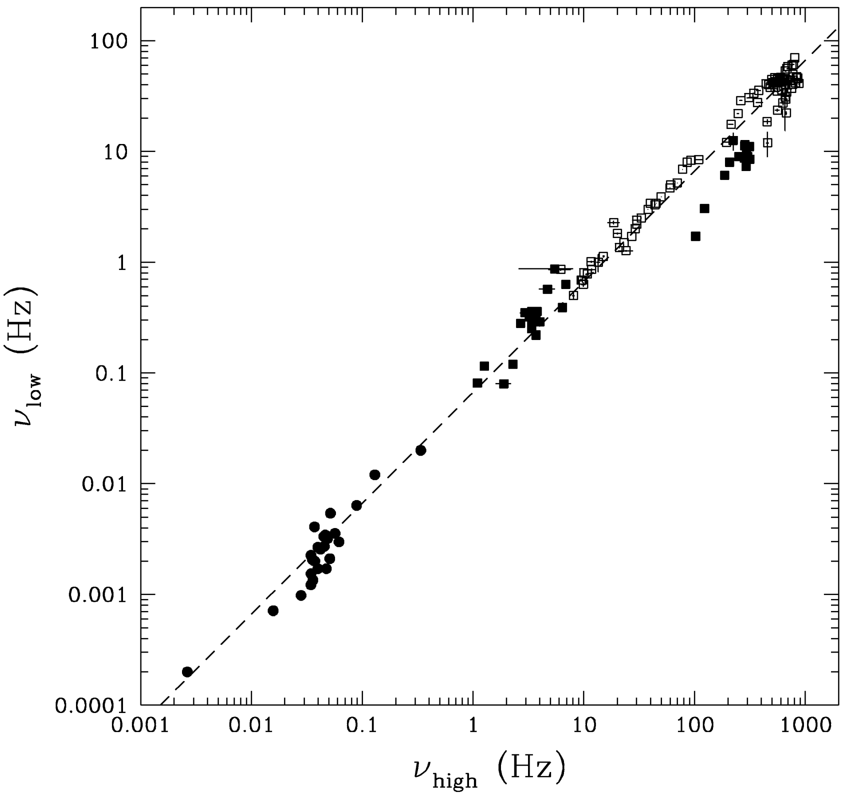

Figure 30. The two-QPO diagram for X-ray binaries (filled squares: black hole binaries; open squares: neutron star binaries) and 26 CVs (filled circles). Each CV is only plotted once in this diagram. The X-ray binary data are from Belloni et al. (2002) and were kindly provided by T. Belloni. The dashed line marks $P_{\rm QPO}/P_{\rm DNO} = 15$.

associated with the inner disc and boundary layer, and both will be affected by the structure and strength of magnetic field connections from the disc to the primary and its equatorial belt, so this is where the differences are probably generated.

Inter alia, we have shown that the helium-transferring systems in some cases have DNO and QPO properties similar to those of the hydrogen-rich CVs. This is first evidence, even if indirect, that the helium primaries of the AM CVn stars can be magnetic.

An advantage that CV observations have over those of X-ray binaries is that in CVs we often easily see the trains of DNO and QPO modulations, and can study the properties of individual cycles, whereas in the X-ray binaries the low fluxes require statistical analyses to extract average properties. If the phenomena really do have the same origin, then further observations of CVs even with small and modest size telescopes are likely to assist understanding of the higher-energy analogues.

At present the interpretation of the CV rapid oscillations in terms of magnetic accretion is speculative – but we note that the behaviours are so complex that no simple explanations (e.g. white dwarf or accretion disc pulsations) are likely to be adequate. The existence of magnetically controlled accretion is in principle testable by the detection of polarization modulated at the DNO period – this might be accomplished for VW Hyi during the large-amplitude DNOs at the end of outburst, which occur at roughly monthly intervals, but will probably require the use of a large telescope observing in the near-infrared. Currently the situation is similar to that of the early development of the intermediate polar model (Patterson & Price 1981; Warner, O'Donoghue & Fairall 1981), which for a few years gave satisfactory explanations of the observed multiple photometric modulations but the magnetic nature was only verified by the discovery of circularly polarized *I*-band flux in 1986 (Penning, Schmidt & Liebert 1986).

van der Klis (2000), in connection with the two-QPO correlation in X-ray binaries and the concomitant variations of the frequencies, remarked that they 'essentially imply that the phenomena are generated in the accretion disc around any low-magnetic field compact object'. Our observations of similar phenomena in (presumably) low-field CVs appear to make this conclusion even more widely applicable.

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REFERENCES

Barrett P., O'Donoghue D., Warner B., 1988, MNRAS, 233, 759
Barwig H., Wimmer W., Bues I., 1993, IAU Circ., 5689
Belloni T., Psaltis D., van der Klis M., 2002, ApJ, 572, 392
Bruch A., Steiner J. E., Gneiding C. D., 2000, PASP, 112, 237
Cordova F. A., Mason K. O., 1984, MNRAS, 206, 879
Cordova F. A., Chester T. J., Tuohy I., Garmire G. P., 1980, ApJ, 235, 163

Cordova F. A., Chester T. J., Mason K. O., Kahn S. M., Garmire G. P., 1984, ApJ, 278, 739
Friend M. T., Martin J. S., Smith R. C., Jones D. H. P., 1990, MNRAS, 246, 654
Goodson A. P., Winglee R. M., 1999, ApJ, 524, 159
Gosh P., Lamb F., 1979, ApJ, 232, 259
Haefner R., Schoembs R., 1987, MNRAS, 224, 231
Haefner R., Schoembs R., Vogt N., 1977, A&A, 61, L37
Haefner R., Schoembs R., Vogt N., 1979, A&A, 77, 7
Hartmann H. W., Wheatley P. J., Heise J., Mattei J., Verbunt F., 1999, A&A, 349, 588
Hesser J. E., Lasker B. M., Osmer P. S., 1974, ApJ, 189, 315
Kato T., Nogami D., 1997, PASJ, 49, 481
Kato T., Hirata R., Mineshige S., 1992, PASJ, 44, L215
Knigge C., Drake N., Long K. S., Wade R. A., Horne K., Baptista R., 1998, ApJ, 499, 429
Long K. S., Mauche C. W., Raymond J. C., Szkody P., Mattei J. A., 1996, ApJ, 469, 841
Marsh T. R., Horne K., 1998, MNRAS, 299, 92
Mason K. O., Cordova F. A., Watson M. G., King A. R., 1988, MNRAS, 232, 779
Mauche C. W., 1998, in Howell S., Kuulkers E., Woodward C., eds, ASP Conf. Ser. Vol. 137, Wild Stars in the Old West. Astron. Soc. Pac., San Francisco, p. 113
Mauche C. W., 2002, ApJ, 580, 423
Morales-Rueda L., Still M. D., Roche P., 1996, MNRAS, 283, L58(MSR)
Morales-Rueda L., Still M. D., Roche P., 1999, MNRAS, 306, 753(MSR)
Muno M. P., Chakrabaty D., Galloway D. K., 2002, ApJ, 580, 1048
Nather R. E., Robinson E. L., 1974, ApJ, 190, 637
Nogami D., Kato T., Baba H., 2002, PASJ, 54, 987
O'Donoghue D., 1985, in Szkody P., ed., Proc. 9th North American Workshop on Cataclysmic Variables. Univ. Washington, Seattle, p. 98
O'Donoghue D., 1995, Baltic Astron., 4, 517
O'Donoghue D., Kilkenny D., 1989, MNRAS, 236, 319
O'Donoghue D., Menzies J. W., Hill P. W., 1987, MNRAS, 227, 347
O'Donoghue D. et al., 1990, MNRAS, 245, 140
Paczyński B., 1978, in Zytkow A., ed., Nonstationary Evolution of Close Binaries. Polish Scientific Publ., Warsaw, p. 89
Patterson J., 1979, ApJ, 233, L13
Patterson J., 1981, ApJS, 45, 517
Patterson J., 1994, PASP, 106, 209
Patterson J., Price C., 1981, ApJ, 243, L83
Patterson J., Robinson E. L., Nather R. E., 1977, ApJ, 214, 144
Patterson J., Robinson E. L., Nather R. E., Handler F., 1979, ApJ, 232, 819
Patterson J., Sterner E., Halpern J. P., Raymond J. C., 1992, ApJ, 384, 234
Patterson J. et al., 1997, PASP, 109, 1100
Patterson J. et al., 2002, PASP, 114, 65
Penning W. R., Schmidt G. D., Liebert J., 1986, ApJ, 301, 881
Psaltis D., Belloni T., van der Klis M., 1999, ApJ, 520, 262
Remillard R. A., Bradt H. V., Brissenden R. J. V., Buckley D. A. H., Schwartz D. A., Silber A., Stoozas B. A., Tuohy I. R., 1994, ApJ, 428, 785
Ringwald F., 1992, PhD thesis, Dartmouth College
Robinson E. L., Nather R. E., 1979, ApJS, 39, 461
Robinson E. L., Nather R. E., 1983, ApJ, 273, 255
Robinson E. L., Zhang E.-H., Stover R. J., 1986, ApJ, 305, 732
Robinson E. L., Shafter A. W., Hill J. A., Wood M. A., 1987, ApJ, 313, 772
Rodríguez-Gil P., Martinez-Pais I. G., 2002, MNRAS, 337, 209
Rodríguez-Gil P., Casares J., Martinez-Pais I. G., Hakala P., Steeghs D., 2001, ApJ, 548, L49
Rodríguez-Gil P., Casares J., Martinez-Pais I. G., Hakala P., 2002, in Gänsicke B. T., Beuermann K., Reinsch K., eds, ASP Conf. Ser. Vol. 261, The Physics of Cataclysmic Variables and Related Objects. Astron. Soc. Pac., San Francisco, p. 533
Schoembs R., 1977, in Kippenhahn R., Rahe J., Strohmeier W., eds, IAU Colloq. 42, The Interaction of Variable Stars with their Environment. Schadel Druck, Bamberg, p. 218
Schoembs R., 1986, A&A, 158, 233
Schoembs R., Vogt N., 1980, A&A, 91, 25
Sion E. M., 1999, PASP, 111, 532
Sion E. M., Cheng F. H., Huang M., Hubeny I., Szkody P., 1996, ApJ, 471, L41
Sion E. M., Cheng F. H., Szkody P., Sparks W. M., Gänsicke B., Huang M., Mattei J., 1998, ApJ, 496, 449
Sion E. M., Cheng F. H., Szkody P., Gänsicke B., Sparks W. M., Hubeny I., 2001, ApJ, 561, L127
Skillman D. R., Patterson J., Kemp J., Harvey D. A., Fried R. E., Retter A., Lipkin Y., Vanmunster T., 1999, PASP, 111, 1281
Smith D. A., Dhillon V. S., Marsh T. R., 1998, MNRAS, 296, 465
Steeghs D., O'Brien K., Horne K., Gomer R., Oke J. B., 2001, MNRAS, 323, 484
Stobie R. S. et al., 1997, MNRAS, 287, 848
Szkody P., 1976, ApJ, 207, 190
Szkody P., Silber A., 1996, AJ, 112, 289
Titarchuk L., Wood K., 2002, ApJ, 577, L23
Uzdensky D. A., 2002, ApJ, 572, 432
van der Klis M., 2000, ARA&A, 158 233
van Teeseling A., 1997, A&A, 324, 73
Warner B., 1975, MNRAS, 173, 37P
Warner B., 1995a, Cataclysmic Variable Stars. Cambridge Univ. Press, Cambridge
Warner B., 1995b, in Buckley D. A. H., Warner B., eds, ASP Conf. Ser. Vol. 85, Cape Workshop on Magnetic Variables. Astron. Soc. Pac., San Francisco, p. 343
Warner B., Nather R. E., 1972, MNRAS, 159, 429
Warner B., Robinson E. L., 1972, Nat. Phys. Sci., 239, 2
Warner B., van Zyl L., 1998, in Deubner F.-L., Christensen-Dalsgaard J., Kurtz D., eds, Proc. IAU Symp. 185, New Eyes to See Inside the Sun and Stars. Kluwer, Dordrecht, p. 321
Warner B., Woudt P. A., 2002a, MNRAS, 335, 84 (Paper II)
Warner B., Woudt P. A., 2002b, in Gänsicke B. T., Beuermann K., Reinsch K., eds, ASP Conf. Ser. Vol. 261, The Physics of Cataclysmic Variables and Related Objects. Astron. Soc. Pac., San Francisco, p. 406
Warner B., Woudt P. A., 2003, in Cropper M., Vrielmann S., eds, IAU Colloq. 190, Magnetic Cataclysmic Variables. Astron. Soc. Pac., San Francisco, in press
Warner B., O'Donoghue D., Fairall A. P., 1981, MNRAS, 196, 705
Warner B., O'Donoghue D., Allen S., 1985, MNRAS, 212, 9P
Warner B., O'Donoghue D., Wargau W., 1989, MNRAS, 238, 73
Watson M. G., King A. R., Osborne J., 1985, MNRAS, 212, 917
Williams G. A., Hiltner W. A., 1984, MNRAS, 211, 629
Winget D. E., Nather R. E., Hill J. A., 1987, ApJ, 316, 305
Wood J. H., Horne K., Berriman G., Wade R. A., 1989, ApJ, 341, 974
Woudt P. A., Warner B., 2002, MNRAS, 333, 411 (Paper I)

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