DNOs and QPOs in Cataclysmic Variables

Brian Warner and Patrick A. Woudt

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

Abstract. We describe some of the recent observations of Dwarf Nova Oscillations and Quasi-Periodic Oscillations in cataclysmic variable stars. The similarities to high frequency QPOs seen in X-Ray binaries make this an increasingly useful field to explore. Our principal new result is the discovery of 1:2:3 harmonic structure in the DNOs of VW Hyi late in outburst. Similar structure is seen in the QPOs of some black hole and neutron star X-Ray binaries. In VW Hyi there is a sudden frequency-doubling when the DNO period reaches \( \sim 39 \) s. This first harmonic increases in period to \( \sim 28 \) s at which point the second harmonic appears. Both harmonics continue with increasing period, together or separately, with an occasional appearance of the fundamental, until the latter reaches \( \sim 105 \) s, by which time VW Hyi has fallen to its quiescent magnitude. We also report the first extensive observations of DNOs in a dwarf nova (OY Car) in quiescence. These are lpDNOs (longer period DNOs) and show similar short time scale properties to the DNOs and lpDNOs seen in outburst.

1. Introduction

The history of rapid oscillations in CVs started exactly 50 years ago with the discovery of the 71 s brightness modulation in DQ Herculis by Merle Walker in July 1954 (Walker 1956). No further examples were found until the advent of digital photometry, and the associated ease of performing Fourier transforms (FTs), whereupon very low amplitude oscillations were found in many outbursting dwarf novae and some nova-like variables (Warner & Robinson 1972). A recent review gives the total of CVs in which such Dwarf Nova Oscillations (DNOs) have been observed as about 50 (Warner 2004). This enlarged data set confirms most of the earlier general correlations, namely

- The oscillations are usually only present in high \( \dot{M} \) states.
- There is a period-luminosity law, with the minimum of \( P_{DNO} \) occurring at maximum \( \dot{M} \) onto the primary.
- DNOs are maximally coherent at maximum \( \dot{M} \), and may become incoherent – in the sense of short trains of coherence interrupted by small period changes – later in outburst.

2. New Phenomena

Recent studies have added a number of previously unsuspected properties that are making the interpretation of DNOs increasingly complex. In a series of
Figure 1. The light curve of EC2117–54. The lpDNOs with a period of 94.21 s are directly visible in the light curve (from WWP).

papers (Woudt & Warner 2002: WW2; Warner & Woudt 2002: WW1; Warner, Woudt & Pretorius 2003: WWP; Warner & Woudt 2004) inter alia the following additional behaviours have been noted:

- In VW Hyi, in which DNOs are particularly prominent at the very ends of outbursts, the usual slow increase of $P_{DNO}$ with falling brightness is succeeded by a phase of rapid increase, with $P_{DNO}$ doubling in about 5 hours, at the end of which there occurs –

- Frequency doubling of the DNO, i.e. the appearance of the first harmonic, which is in turn superseded by the appearance of the second harmonic. During this late phase, which in effect extends (at least in the optical) into the first day or so of quiescence, the fundamental and 1st and 2nd harmonics can appear in various combinations. More details are given below.

A completely new type of DNO has been discovered – the longer period DNO (lpDNO) which has a period $\sim 3 - 5$ times that of the DNOs and shows little or no dependence on $\dot{M}$. These have been seen in about 17 CVs (Warner 2004) but, as with the normal DNOs, are only intermittently present. DNOs and lpDNOs behave independently of each other, being seen separately or in coexistence and their short time scale variations in period or phase appear not to be correlated. Figure 1 gives an example of lpDNOs that are visible directly in the light curve, and Figure 2 shows an example of a FT containing both a DNO and a lpDNO.

A third type of rapid modulation in CVs is that called Quasi-Periodic Oscillation (QPO), which was first recognised by Patterson, Robinson & Nather (1977), and is of very low coherence, typically changing period or phase after only a few cycles. A new appreciation of these oscillations has emerged from the realisation that the periods of many QPOs and DNOs are related through $P_{QPO} \sim 15 \times P_{DNO}$, as maintained in VW Hyi during its rapid deceleration phase (WW2) and seen in numerous other CVs. The fact that the same relationship is found (Psaltis, Belloni & van der Klis 1999) in the rapid oscillations of X-Ray Binaries (XRBs) shows a connection of phenomena across six orders
of magnitude in frequency, and links CVs to the neutron star and black hole XRBs. The current standing of this relationship is shown in Figure 3.

Occasionally double DNOs are observed, split by the frequency of the QPO present at the time.

3. The Magnetic Model for DNOs and QPOs

A magnetic accretion model for DNOs has been developed (Warner 1995; WW1), based on an original proposal by Paczynski (1978). In essence it is a modification of the standard intermediate polar structure, allowing an independently rotating equatorial accretion belt to be set up because the magnetic field of the primary is insufficient to couple its outer layers to the interior. The optical DNOs are the result of seeing the accretion curtain attached to the belt, and/or reprocessing by the disc of the anisotropic radiation carried around by the belt. This Low Inertia Magnetic Accretor model has had some success in explaining the behaviour of normal DNOs (WW1). From this model, however, there is no immediate expectation of DNO harmonics, so we need to describe these in detail and suggest how further consideration of the LIMA model might explain them.

The lpDNOs, because of their insensitivity to $\dot{M}$, are hypothesized (WW1) to be caused by part of the accretion flow onto the primary being channeled along magnetic field lines of the primary itself (which will be differentially rotating because of the angular momentum that is fed in at the equator, and therefore some variation in period of the lpDNOs is to expected according to which field lines are fed from the disc).

The QPOs are thought to be caused by interruption and reprocessing by a traveling wave at the inner edge of the accretion disc, of radiation from the centre of the system, moving slowly in a prograde direction (WW1), for which
there is some theoretical expectation (Lubow & Pringle 1993). It is reprocessing of the rotating DNO beam by the traveling wave that causes the double DNOs.

4. Details of the Harmonic Structure in VW Hyi

In the earlier analysis of DNO evolution in VW Hyi near the end of outburst (WW2) it was pointed out that the rapid increase of $P_{DNO}$, during which the period doubles in only five hours, is followed by DNOs that have evidently halved in period; but there were insufficient data to analyse this fully. In the past year we have concentrated on acquiring more VW Hyi light curves during this final phase of outburst, and find that there is a systematic effect present that if not fully sampled can lead to the perplexing, apparently chaotic variations in period that we had previously deduced.

The behaviour of the DNOs is shown in Figure 4 (the zero of outburst phase is defined in WW2). It should be remembered that what we are displaying here are the periodic components derived from Fourier transforms (FTs) of subsec-
Figure 4. The evolution of DNO periods at the end of normal and super outbursts in the dwarf nova VW Hyi. The different symbols indicate the various different kinds of outbursts (short: asterisk, normal: open circles, long: open squares, and super outbursts: filled triangles). The dotted and dashed lines show the result of a least-squares fit to the first and second harmonic, respectively, and are multiplied by a factor of two and three to show the evolution of the fundamental DNO period. The inset highlights two observing runs in which the fundamental, first and second harmonic of the DNO period were present simultaneously. The horizontal dotted-dashed line illustrates the minimum DNO period (14.1 s) observed at maximum brightness.

The steady increase of $P_{DNO}$ from 20 s onwards continues to $\sim 39$ s, at which point frequency doubling occurs and what we consider to be the 1st harmonic takes over the general increase of period. We have not yet been able to observe at the precise moment of transition, but we have bracketed it in separate outbursts; it seems to take place in less than $\sim 15$ min and may well be almost instantaneous. The 1st harmonic sets out at $\sim 19$ s and increases until it reaches $\sim 28$ s, but the first appearance of an additional oscillation, the second harmonic, occurs already when the 1st harmonic is at $\sim 21$ s. Initially the 2nd harmonic is rarely seen, but as the periods lengthen it eventually becomes the
Figure 5. Examples of Fourier transforms of VW Hyi in which combinations of the fundamental and the first two harmonics of the DNO period are present simultaneously.

The most prominent oscillation, and it persists later in the outburst than either of the other components.

Occasionally both harmonics are present together, and there are very occasional appearances of the fundamental. Frequently there are alternations between the occurrences of the harmonics. Our FTs show that the fundamental and harmonics are in the ratios 1:2:3 within error when they appear together. An example of FTs containing the two harmonics is shown in Figure 5. When the 1st harmonic has also reached a period of $\sim 40$ s it in turn disappears and usually only the 2nd harmonic is present (but with infrequent appearances of the fundamental).

Figure 6 shows a modified form of Figure 4, where the harmonics have been multiplied by appropriate factors of 2 or 3 to generate the implied but unobservable fundamental. The fundamental itself is, however, occasionally visible, and when it gets to $\sim 80 - 90$ s there is potentially some ambiguity with the lpDNOs that have periods near those values in VW Hyi. But the lpDNOs are usually pure sine waves, so when any of the harmonics are present the period of the fundamental can be predicted precisely and this eliminates the confusion. Figure 6 shows that the deduced period of the fundamental continues to increase steadily, reaching $\sim 105$ s before it cannot any longer be detected (we have examined FTs of runs taken shortly after that outburst phase without success).
5. Comparison with XRBs

The importance of the 1:2:3 period ratios seen in VW Hyi is that these are the first observations in a CV of a phenomenon known for a few years in XRBs (McClintock & Remillard 2004). In particular, the black hole binary XTE J1550-564 has strong X-Ray signals at 276 and 184 Hz and a weak signal at 92 Hz, which are in the ratio 3:2:1, and GRO J1655-40 has 450 and 300 Hz oscillations (Remillard et al. 2002). The interpretation of these harmonic ratios in XRBs has usually required the tools of General Relativity (see review by McClintock & Remillard (2004)), but it is possible that less exotic models might suffice. There certainly should be no recourse to GR to explain the harmonic structure in VW Hyi, and we note that the work of Robertson & Leiter (2002, 2003, 2004) shows that magnetically channeled accretion, as occurs in CVs, may be possible even from discs around black holes.
6. A Possible Model for the Harmonics in CVs

Possible models for the DNO behaviour in VW Hyi will be explored in more detail elsewhere, but here we indicate a way in which the harmonics may be produced.

At maximum of outburst DNOs are rarely seen, but when they are they are at 14.1 s, seen both in optical (WW2) and soft X-Rays (van der Woerd, Heise & Bateson 1986). This suggests that the magnetosphere is generally squashed down to the surface of the primary, but that occasionally \( \dot{M} \) reduces sufficiently to allow some magnetically channeled accretion. From this, and assuming that only one accreting zone is visible, we can deduce the keplerian velocity at the surface of the primary, and hence the mass (0.7 \( M_\odot \)) of the primary.

Near the end of outburst, \( \dot{M} \) onto the primary falls as the disc returns to its quiescent state. The ram pressure on the primary’s magnetosphere is reduced and the inner radius of the truncated disc consequently increases. For small inner radii the primary hides the inner parts of disc on its far side; but for an inclination of \( \sim 63^\circ \) and the above white dwarf mass the far side becomes visible when the keplerian period of the inner edge is \( \sim 45 \) s. We ascribe the appearance of the first harmonic at \( P_{DNO} \sim 40 \) s to this change in geometry – the “upper” accretion curtain is now visible to us on both sides of the primary. Possibly also the lower curtain becomes visible at this time, accreting \( \sim 180^\circ \) out of phase with the upper curtain.

If there is a thickening of the disc in the form of the QPO traveling wall then the strongest magnetic field lines sweeping around the inner boundary of the disc will accrete at a variable rate, i.e., \( \dot{M} \) will be modulated at the beat frequency \( \omega = \omega_{rot} - \omega_{qpo} \) of the rotation frequency \( \omega_{rot} \) of the equatorial belt and the frequency \( \omega_{qpo} \) of the QPO wall. The effect of this modulation on the first harmonic of the direct (or disc reprocessed) beam will be to generate frequency components \( \omega_{rot} + \omega_{qpo}, 2\omega_{rot} \) and \( 3\omega_{rot} - \omega_{qpo} \). These are close to, but are not exactly in the ratios 1:2:3. On the other hand, if what is being observed is DNOs reprocessed off the wall itself, then the components will be \( \omega_{rot} - \omega_{qpo}, 2(\omega_{rot} - \omega_{qpo}) \) and \( 3(\omega_{rot} - \omega_{qpo}) \), which have exactly the frequency ratios of interest. It is possible that both processes could be present simultaneously, where part of the DNO beam is reprocessed from the disc and part from the wall. We have some evidence that the vertical scatter in Figure 4 is caused partly by such an effect. The fact that the 2nd harmonic does not make its appearance until the 1st harmonic is already in operation is compatible with the hypothesis of rotationally modulated \( \dot{M} \).

7. lpDNOs and QPOs in Quiescence

From the time of the earliest studies of DNOs it has been realised that they rarely if ever occur in quiescence of dwarf novae. However, although uncommon, lpDNOs can exist in these low \( \dot{M} \) states. The observational evidence for quiescent rapid oscillations is discussed in Warner (2004). In hard X-Rays, DNOs with periods respectively of \( \sim 60 \) s, 21.8 s and 33.93 s have been seen in VW Hyi (Pandel, Cordova & Howell 2003: PCH), HT Cas (Cordova & Mason 1984) and SU UMa (Eracleous, Patterson & Halpern 1991). The VW Hyi DNOs also
appear in soft X-Rays. The HT Cas and SU UMa observations are currently the only direct evidence for possible DNOs, rather than lpDNOs, in quiescent dwarf novae.

In the optical, quiescent DNOs with period $\sim 50\, \text{s}$ were reported in OY Car and $87.0\, \text{s}$ in AQ Eri by WWP. Previously $\sim 100\, \text{s}$ oscillations were observed in HT Cas in quiescence (Patterson 1981). In the latter two stars the periods are $\sim 4$ times those of their DNOs and therefore fit the notion that they are lpDNOs, but our observations of OY Car need more explanation.

The DNOs in OY Car were illustrated in figure 17 of WWP with 20 mins of light curve in which the oscillations were readily visible in the light curve. In fact the oscillations were present, but at lower amplitude, throughout the remainder of that 2 h run and showed quite large abrupt changes in period similar to those seen in outburst. These are illustrated in Figure 7. We find that these are the first harmonic of oscillations at $\sim 100\, \text{s}$ – we see oscillatory power also present in the 100 s region of the FT – and are therefore lpDNOs rather than ordinary DNOs. We have found similar lpDNOs in other runs of OY Car in quiescence – they are difficult to detect because of low amplitude and the variations in period. We expect that some other quiescent dwarf novae, if looked at in the correct way, will also be found to have lpDNOs.

It is of interest that it is in OY Car that Wheatley & West (2003) find that the hard X-Rays emitted in quiescence are located at a high latitude region of the white dwarf surface and from an area small compared with that of the white dwarf. This has the signature of magnetic accretion and must be onto the body...
of the white dwarf itself, rather than onto an equatorial belt. This is in accord with the hypothesis of WW1.

The claim by PCH that the X-Ray DNOs in VW Hyi are highly unstable, changing period every $\sim 2$ cycles, is based on the width of the peak in the FT. It is more likely that these are lpDNOs, are relatively coherent (as in OY Car) and also changed their period during the observation. It has been pointed out by Jones & Watson (1992) and reiterated by Warner (2004) that, given the behaviour of DNOs (and lpDNOs) seen in the relatively high signal/noise light curves in some optical observations, statistical tests based on the assumption of random or stochastic noise are entirely inappropriate; in fact, such results are misleading.

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