Abstract. New and archived observations of VW Hyi in outburst show the occasional presence of optical Dwarf Nova Oscillations (DNOs) over the range of 18 – 40 s. There is a rapid increase in period near the end of outburst, at the same time that the EUV falls almost to zero, which we attribute to propellering. The DNOs return to a shorter period after this phase, but are very incoherent. The DNOs show some modulation by the Quasi-Periodic Oscillations (QPOs) that are also occasionally present in the light curve. We interpret the QPOs as a prograde travelling wave in the inner disc, which obscures and/or reprocesses radiation from the central region. The model is applied to observations of OY Car and WZ Sge.

1. Introduction

The presence of brightness modulations of low amplitude and moderate coherence in Cataclysmic Variables (CVs) was first detected in 1972 (Warner & Robinson 1972). Of similar appearance but much lower stability than the 71 s modulation in the old nova DQ Her, these oscillations are found almost exclusively in dwarf novae during outburst or in nova-like variables. Collectively they have become known as Dwarf Nova Oscillations (DNOs). They are not found in all nova-likes, nor in all dwarf novae in outburst, but they have been found in a total of about 15 of the former and 4 of the latter (see the list given in Chapter 8 of Warner (1995a)). DNOs are also observed in the soft X-ray and EUV regions of some CVs. The shortness of period and the emission of high energy radiation indicate that the origin of the DNOs is at, or close to, the surface of the white dwarf primary. However, the phase shifts seen during eclipse in the optical (e.g. HT Cas: Patterson 1981; UX UMa: Nather & Robinson 1974), which extend right through eclipse, show that the concave surface of the disc reprocesses high energy radiation from a rotating irradiating beam. In the UV the eclipse of the oscillations is of similar duration to that of the white dwarf (Knigge et al. 1998), demonstrating directly that the source of the energy is close to the primary.

The most striking property of the DNOs is that they show a strong period-luminosity relationship during the outbursts of dwarf novae: minimum period corresponds to highest UV luminosity, i.e. to the phase when mass transfer on to the primary is at its maximum. The range of period during this systematic variation can be a factor of two over the few days of an outburst. This is in
strong contrast to DQ Her, which has a time scale $\sim 10^7$ y for change of its period, which is understood in terms of accretion of angular momentum onto the white dwarf. Therefore, if the two phenomena are similar in underlying physics, only a very small fraction of the mass of the white dwarf is participating in angular momentum transfer. Paczynski (1978) long ago proposed that this could be understood if the accreting matter produced a rapidly spinning equatorial band that spun up during the increasing $\dot{M}$ to maximum luminosity and was spun down again in the decline stages of the outburst. Katz (1975) estimated that in order to couple the outer regions to the core of a white dwarf a magnetic field in excess of $10^5$ G is necessary. Freely rotating equatorial belts would therefore only be expected for field strengths lower than this.

Evidence for equatorial belts is now quite strong – in VW Hyi HST spectra have been interpreted as implying a hot equatorial region rotating at nearly the Kepler velocity and lasting for a week or more after outburst (Sion et al. 1996); an equatorial accretion belt has also been deduced for U Gem (Cheng et al. 1997). Possible detection of magnetically controlled accretion flow in VW Hyi during outburst is given by the existence of an inverse P Cygni spectral profile and a truncated disc (Huang et al. 1996).

We therefore favour the interpretation of DNOs as magnetically controlled accretion onto an equatorial belt – it becomes an extension of the standard intermediate polar model to lower field strengths, and because an essential component is the free slipping of the equatorial belt we call the model the Low Inertia Magnetic Accretor (LIMA). This model has already been developed to some extent by Warner (1995b).

Figure 1. The light curve of VW Hyi, taken on 5 February 2000 during the return of VW Hyi to quiescence after a normal outburst. An enlarged view of a small section of the light curve shows the DNOs.
2. New Observations of VW Hyi

In Fig. 1 we show the light curve of VW Hyi at 3 s time resolution that we obtained on 5 February 2000 just as the system was reaching quiescence after a normal outburst. The large amplitude modulation is the normal orbital hump. The inset is a small section of light curve greatly magnified and shows the presence of $\sim$30 s DNOs that persist throughout the run. There is also a $\sim$500 s modulation that we discuss below. The light curve is made up almost entirely of these three modulations – there is very little flickering.

![Figure 2](image.png)

Figure 2. Evolution of DNO and QPO periods in three outbursts: February 2000 (circles with error bars), December 1972 (triangles), and February 2001 (squares). The top panel shows the ratio of periods in the February 2000 outburst.

The DNOs in this light curve are of relatively large amplitude (most DNOs are only visible in a Fourier Transform) and steadily increase their period through the 5.3 h run. This is shown in Fig. 2, where we have added the DNO behaviour observed at the end of a superoutburst of VW Hyi in December 1972 and at the end of a normal outburst in February 2001. We have also reanalysed our archive of VW Hyi high speed photometry built up over nearly 30 years, and found some previously overlooked DNOs. In particular, we have found a 14.29 s signal near the maximum of the 26 October 1984 superoutburst and a 14.06 s DNO near maximum in the 19 December 1982 superoutburst. These signals,
Figure 3. DNO periods versus V magnitude of VW Hyi. The curved continuous line is the DNO evolution seen in Fig. 2. The range of DNO periods in the various runs is shown by horizontal bars.

at periods nearly half of the shortest periods previously detected in the optical, are pleasingly close to the 14.06 s DNO seen in soft X-rays in the November 1983 superoutburst and the periods of 14.2 to 14.4 s in X-rays at the peak of the October 1984 outburst (van der Woerd et al. 1987). The optical period of 33.9 s seen by Schoembs & Vogt (1980) near maximum of the October 1978 superoutburst is in fact a 14.18 s DNO beating with their integration time of 10 s. The 14.06 s DNO in our data is of very high stability, which enables it to be seen easily in the FT despite having an amplitude of only 0.0012 mag. It is possible that such short very low amplitude DNOs are commonly present but not stable enough to detect with the usual techniques.

These short period DNOs, and others of longer period measured in our archived and recent light curves of VW Hyi, lead to the variation of DNO period with brightness in outburst shown in Fig. 3. The slope of the variation is at first similar to what has been seen in many dwarf novae in outburst, but the rapid increase in period (the continuous curve in Fig. 3, derived from Fig. 2) is anomalous and implies a very rapid deceleration (a factor of 2 in angular velocity in about 10 h) of the equatorial belt in our LIMA model.

In addition to the DNOs discussed above, CVs commonly show far less coherent oscillations with periods an order of magnitude longer – known as Quasi-Periodic Oscillations (QPOs). The oscillations of range \( \sim 0.1 \) mag seen in Fig. 1 are QPOs, and are the first in which a systematic evolution of period has been seen – Fig. 2 shows that their mean period increase from \( \sim 400 \) s to \( \sim 600 \) s during the run. The ratio \( P_{QPO}/P_{DNO} \) remains roughly constant at \( \sim 15 \) during their evolution in both the February 2000 and December 1972 outbursts. One of the features that we have noticed about QPOs is that their minima often appear
as absorption dips, carrying the minima of their modulations below the general lower envelope of flickering and other slower modulations – see Fig. 4.

We have also detected QPOs in VW Hyi in quiescence. This is the first time QPOs in a CV have been found at minimum light. As with other CVs (but see WZ Sge below) we do not find any DNOs during quiescence.

3. Interaction between DNOs and QPOs

In previous studies of VW Hyi (Warner & Brickhill 1978; Robinson & Warner 1984) simultaneous DNOs and QPOs have been observed, and it was noted that at times the QPOs modulate the amplitude of the DNOs. In our new observations and analyses we see further occasional examples of this, but there is a new phenomenon that has important implications for models of DNOs and QPOs.

In part of a run made during outburst on 3 November 1974 there is a double DNO: DNOs are normally monoperiodic (there are a few other cases of double DNOs), but this run has DNOs at 28.77 s and 31.16 s and a strong QPO at 349 s. This QPO period is the beat period between the two DNOs. The shorter period of the DNOs is purely sinusoidal; the longer period has a first harmonic. Average profiles of the three modulations are shown in Fig. 5. The DNO behaviour in VW Hyi is exactly similar to what Marsh & Horne (1998) have found in HST observations of OY Car – there they see two periods near 18 s, separated by 0.22 s, with the longer period having a dominant first harmonic. In addition, Steeghs et al. (2001) found a double DNO in V2051 Oph on the decline from
outburst. In neither of these latter observations is the light curve sufficiently long to enable certain detection of a QPO at the beat period, if one existed.

4. The Nature of QPOs

Because of their low coherence QPOs are often more easily seen in the light curve than in its FT (where they spread over a large range of frequencies). They are rarely seen at high energies, but there are a few convincing cases, for example \( \sim 500 \) s at the end of an outburst of VW H6 by Ginga at 2-10 keV (Wheatley et al. 1996), where we see similar time scale optical QPOs.

A popular theoretical explanation of QPOs is that they arise as non-radial oscillations in the accretion disc. Perturbation analyses, e.g. by Carroll et al. (1985) and Collins, Helfer & van Horn (2000), show that a wide range of periods could exist, but no explanation has been given of what mechanism selects the limited range of periods observed in any individual object. On the other hand, Lubow & Pringle (1993) find that an \( m = 1 \) g-mode in the inner disc is the most likely to be excited. This mode corresponds to a travelling wave.
moving upstream in the Keplerian flow, at an angular frequency slightly less than that of the flow, so it amounts to a prograde slowly travelling wall.

The theoretical models usually aim to explain QPOs in discs as luminosity variations intrinsic to the disc itself (analogous to the kappa or epsilon mechanisms of stellar pulsations). But our observations of absorption dips suggests an alternative reason for the brightness modulations – interception and reprocessing of the high energy radiation coming from the accretion-heated white dwarf surface. If the travelling wall is very near the white dwarf then it will send additional reprocessed light to us when at superior conjunction, and may partially obscure the primary or very innermost part of the accretion curtain when at inferior conjunction. Furthermore, the same interception may occur for the rotating DNO beam, creating DNO sidebands in analogy with intermediate polars. The longer period DNO would be the reprocessed beam for a progradely travelling wall, and would be the one likely to depart from sinusoidality (because of irregular structure of the wall), just as is observed. Variations in the amplitude of the wall will account for the intermittency of production of double DNOs – indeed, it could happen that in some systems the geometry is such that no interception at all of the beam occurs.

The QPOs seen in hard X-rays towards the end of outburst (Wheatley et al. 1996) are probably the result of quasi-periodic obscuration of the central source by the wall.

For the LIMA model, where the inner disc is truncated by the magnetosphere of the primary, the region just outside the inner radius is a likely place for excitation of travelling waves – through the differential winding and reconnection of field lines that couple the inner disc to the primary. This has been hinted at in 2D simulations and 3D extrapolations of disc-magnetosphere interaction (Uzdensky, Konigl & Litwin 2001).

5. The Rapid Deceleration of DNOs

From the energetics of a VW Hyi outburst we can estimate that the accretion onto the primary during a normal outburst is \( \sim 2 \times 10^{22} \) g and \( \sim 8 \) times greater in a superoutburst. The angular deceleration of the equatorial belt then implies an energy extraction of \( \sim 3 \, L_\odot \) for a normal outburst and \( \sim 8 \) times larger for a superoutburst. Yet at this time (the end of an outburst) the total luminosity of VW Hyi is only \( \sim 0.1 \, L_\odot \), so it is clear that the energy loss from the belt is not radiative. The same situation is seen in AE Aqr, where the observed spin-down rate of the primary is equivalent to \( 4 \, L_\odot \) but this is not radiated (de Jager et al. 1994). In the latter star the explanation is that the spin-down torque comes from propelling (e.g., Wynn, King & Horne 1997), and the energy (and angular momentum) extracted from the star goes into gas that is centrifuged away. We propose that the same is happening in VW Hyi during the rapid deceleration phase – but only the equatorial belt is involved. In fact, the time scale for spin-down of the primary in AE Aqr is \( \sim 1.7 \times 10^7 \) y; scaling this by the ratio of the mass of the belt in VW Hyi to the mass of the primary gives a spin-down time scale of \( \sim 10 \) h (for the same applied magnetic and material torques in both cases). This is equal to the time scale that we observe in VW Hyi.
It is understandable that VW Hyi gets itself into a propeller ing state at the end of outburst – as $M$ from the disc falls at the end of outburst the radius of the inner edge of the disc moves outwards. At the same time the spin-down torque acting on the belt is reducing rapidly, and so the belt cannot maintain an equilibrium angular velocity with the inner edge of the disc – it spins more rapidly than the disc and its attached magnetic field centrifuges most of the accreting gas away, losing angular velocity until it again reaches equilibrium with the disc. The stability of mass transfer in these circumstances has been studied by Spruit & Taam (1993); the gas is not ejected from the system, it is merely moved out to a larger radius in the disc.

There is indirect but strong observational evidence for propelling in VW Hyi. Over precisely the $\sim 0.5$ day range in which we see the rapid deceleration, Mauche, Mattei & Bateson (2001) find that the EUV flux of VW Hyi drops precipitately almost to zero and recovers afterwards. As the EUV flux is a monitor of the accretion flow onto the primary, this shows that gas is being prevented from accreting.

6. Other Systems

Our proposals for interpreting the rich phenomenology of VW Hyi, of which we have given an outline above (more extensive and quantitative results are contained in two papers currently in press in MNRAS), enable us to achieve understanding of observations of DNOs and QPOs in some other systems, of which we give only two examples here.

**OY Car.** As already pointed out above, the double DNOs seen in OY Car (Marsh & Horne 1998) are analogous to what we see in VW Hyi and can be interpreted as a DNO with a QPO sideband. Although the beat period of $\sim 1500$ s is not visible in the short observing run containing the double DNO, a QPO at $\sim 2240$ s has been seen in X-Ray observations of OY Car about two days after a normal outburst (Ramsay et al. 2001), with the properties of a periodically obscuring source, and is probably a longer period evolution from the putative $\sim 1500$ s QPO during outburst.

**WZ Sge.** WZ Sge is a very long interval SU UMa star which has brightness modulations at quiescence with periods of 27.868 s and 28.952 s. It has often been claimed that the shorter period has orbital sideband structure like an intermediate polar and that therefore 27.868 s is the rotation period of the white dwarf (Patterson 1980; Warner, Tout & Livio 1996). The measured $v \sin i$ of the primary (Cheng et al. 1997) and the recently favoured mass of the primary of $\sim 1.0$ M$_\odot$ give $P_{\mathrm{rot}}$ for the primary of 28 $\pm$ 8 s, which is compatible with this proposal.

However, the 28.952 s period does not fit the scheme of orbital sidebands. In the light of the double DNOs seen in VW Hyi and OY Car, and the occasionally observed first harmonic of the 28.952 s modulation (Provenca & Nather 1997), it seems probable that the longer period of the two oscillations is caused by reprocessing off a travelling wall. The beat period of the DNOs (as we shall now call them) is 744 s. Such a reprocessing model had already been proposed by Lasota, Kuulkers & Charles (1999), who assumed that the wall must be rotating in the disc at a radius where the Keplerian period is 744 s – which puts it at
the outer rim of the accretion disc (but that needs to be revised with the larger primary mass now deduced). We propose that the reprocessing wall is a slowly travelling wave close to the primary – if it is at the inner edge of the truncated disc, then the observed DNO period puts the inner edge very close to the surface of the primary.

With this model we could hope to see the 744 s beat period in the light curve as the travelling wall reprocesses or obscures radiation from the central source. We have found just such a signal in a high quality light curve of WZ Sge provided by Dr. Janet Wood. The principal obscuration caused by the wall is the long known dip of variable depth that occurs in the vicinity of orbital phase 0.3 (Patterson 1980); the other dips are less easily recognised because some of them occur near to eclipse or the deep minimum at orbital phase 0.5.

7. X-ray Binaries

The DNO and QPO phenomena in CVs have numerous analogues among the X-ray binaries. In particular, the ratio $P_{\text{QPO}}/P_{\text{DNO}} \sim 15$ seen in VW Hyi is the same as the ratio of the two QPOs commonly seen in X-ray binaries (see Fig. 2 of Psaltis, Belloni & van der Klis 1999) over a wide range of frequencies. The CV behaviour is an extrapolation of this to frequencies two orders of magnitude lower.

Acknowledgments. Our research has been supported by grants from the University of Cape Town. We are grateful to Chris Mauche for supplying his EUVE observations of VW Hyi and to Janet Wood for allowing us to analyse her light curve of WZ Sge.

References

Carroll, B.W., Cabot, W., McDermott, P.N., Savedoff, M.P., & van Horn, H.M. 1985, ApJ, 296, 529
Collins, T.J.B., Helfer, H.L., & van Horn, H.M. 2000, ApJ, 534, 934
Cheng, F.H., Sion, E.M., Szkody, P., & Huang, M. 1997, ApJ, 484, 149L
de Jager, O.C., Meintes, P.J., O’Donoghue, D., & Robinson, E.L. 1994, MNRAS, 267, 577
Huang, M., Sion, E.M., Hubeny, I., Cheng, F.H., & Szkody, P. 1996, ApJ, 458, 355
Katz, J.I. 1975, ApJ, 200, 298
Knigge, C., Drake, N., Long, K.S., Wade, R.A., Horne, K., & Baptista, R. 1998, ApJ, 499, 236
Lasota, J.-P., Kuulkers, E., & Charles, P.A. 1999, MNRAS. 305, 473
Lubow, S.H., & Pringle, J.E. 1993, ApJ, 409, 360
Marsh, T.R., & Horne, K. 1998, ApJ, 299, 92
Mauche, C.W., Mattei, J., & Bateson, F.M. 2001, in “Evolution of Binary & Multiple Star Systems”, eds. P. Podsiadlowski, et al. (Bormio, Italy), in press
Nather, R.E., & Robinson, E.L. 1974, ApJ, 190, 637
Paczynski, B. 1978, in “Nonstationary Evolution of Close Binaries”, ed. A. Zytkowski (Polish Sci. Publ.: Warsaw), 89
Patterson, J. 1980, ApJ, 241, 235
Patterson, J, 1981, ApJS, 45, 517
Paczyński, B. 1978, in “Nonstationary Evolution of Close Binaries”, ed. A. Zytkow (Polish Sci. Publ.: Warsaw), 89
Psaltis, D., Belloni T., & van der Klis M. 1999, ApJ, 520, 262
Patterson, J. 1980, ApJ, 241, 235
Patterson, J, 1981, ApJS, 45, 517
Psaltis, D., Belloni T., & van der Klis M. 1999, ApJ, 520, 262
Ramsay, G., Poole, T., Mason, K., Córdova, F., Priedhorsky, W., Breeveld, A., Much, R., Osborne, J., Pandel, D., Potter, S., West, J., & Wheatley P. 2001, A&A, 365, 288L
Robinson, E.L., & Warner, B. 1984, ApJ, 277, 250
Schoembs, R., & Vogt, N. 1980, A&A, 91, 25
Sion, E.M., Cheng, F.H., Huang, M., Hubeny, I., & Szkody, P. 1996, ApJ, 471, 41L
Spruit, H.C., & Taam, R.E. 1993, ApJ, 402, 593
Steeghs, D., O'Brien, K., Horne, K., Gomer, R., & Oke, J.B. 2001, MNRAS, in press
Uzdensky, D.A., Königl, A., & Litwin, C. 2001, ApJ, in press
van der Woerd, H., Heise, J., Paerels, F., Beuermann, K., van der Klis, M., Motch, C., & van Paradijs, J. 1987, A&A, 182, 219
Warner, B. 1995a, Cataclysmic Variable Stars (Cambridge University Press: Cambridge)
Warner, B. 1995b, in ASP Conf. Ser. 85, Cape Workshop on Magnetic Variables, eds. D.A.H. Buckley & B. Warner (San Francisco: ASP), 343
Warner, B., & Brickhill, A.J. 1978, MNRAS, 182, 777
Warner, B., & Robinson, E.L. 1972, Nature Phys. Sci., 239, 2
Warner, B., Tout, C.A., & Livio, M. 1996, MNRAS, 282, 735
Wheatley, P.J., Verbunt, F., Belloni, T., Watson, M.G., Naylor, T., Ishida, M., Duck, S.R., & Pfefferman, E. 1996, A&A, 307, 137
Wynn, G.A., King, A.R., & Horne, K. 1997, MNRAS, 286, 436