# Rapid Oscillations in Cataclysmic Variables, and a Comparison with X-Ray Binaries

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**Abstract.** We compare some of the properties of rapid oscillations in cataclysmic variables and X-Ray binaries. In addition to the earlier recognition that both types possess the same correlation between high and low frequency quasi-periodic oscillations, we have now found that the dwarf nova VW Hyi in its late stages of outburst shows the 1:2:3 oscillation harmonics that are seen in some neutron star and black holes X-Ray binaries. We point out that the behaviour of the dwarf nova WZ Sge has some similarities to those of accreting millisecond pulsars.

## INTRODUCTION

The rapid oscillations seen in cataclysmic variables (CVs) and X-Ray binaries (XRBs), although separated by orders of magnitude in time scales, show many common features in their phenomenology. The former have been recognised since the singular discovery of highly stable 71 sec modulations in the optical light curve of DQ Her, exactly 50 years ago, in July 1954 (Walker 1956), followed by the opening of a floodgate of phenomena associated with the discovery of similar but less stable oscillations in outbursting dwarf novae (Warner & Robinson 1972). The first observed XRB rapid modulations date to the days of EXOSAT and the quasi-periodic 5 – 50 Hz flux variations seen in the low mass XRB GX 5-1 (van der Klis et al. 1985). With the advent of RXTE in 1996 the time resolution was increased to where kilohertz oscillations could be detected, with the result that now a quarter of the neutron star XRBs (Swank 2004) and a sixth of the black hole XRBs (McClintock & Remillard 2004) have been observed with quasi-periodic oscillations (QPOs).

## OSCILLATIONS IN CVS

The rich phenomenology of oscillations in CVs has been reviewed recently by Warner (2004). There are at least three distinct types of rapid oscillation in CVs, which can exist separately or simultaneously:

1. Dwarf Nova Oscillations (DNOs). These are oscillations typically in the range 3 – 40 s, usually appearing in high mass transfer ($\dot{M}$) discs, i.e. dwarf novae in outburst and nova-like variables. They have not been observed in all such CVs, and are of varying amplitude, often disappearing altogether. They show a period-$\dot{M}$ relationship, with shortest periods at highest $\dot{M}$, and are of moderate coherence with small

abrupt changes of period and almost continuous phase noise. 'Double DNOs' are occasionally seen, with frequency differences equal to the frequency of the QPO (see (3) below) present at the time. DNOs are sinusoidal modulations; the companion in a double DNO is at longer period and usually possesses a first harmonic (Warner & Woudt 2002, hereafter WW1; Woudt & Warner 2002, hereafter WW2).

2. Longer-period DNOs. These lpDNOs have periods $\sim 4$ times those of DNOs and show little if any variation with $\dot{M}$ (or optical luminosity). They are less commonly present than DNOs, are occasionally seen even in quiescence of dwarf novae, and can also appear doubled on rare occasions (Warner, Woudt & Pretorius 2003, hereafter WWP).

3. Quasi-Periodic Oscillations. The QPOs of interest here are those with periods $P_{QPO} \sim 15 P_{DNO}$ (there are others of longer period probably related to the rotation of the slower rotating primaries - Patterson et al. 2002). These QPOs have a short coherence length, typically growing and decaying in $\sim 5$ cycles, and changing phase or period on that time scale if they are longer lived (WW2).

It is useful to have a model in mind that ties these variations together. The following is the one advanced by WW1, which in its fundamentals was first proposed by Paczynski (1978). This is, in principle, an extension of the standard intermediate polar model (see Chapters 7 and 8 of Warner (1995)) to lower field strengths. The recent discovery of kilogauss magnetic fields in a number of DA stars (Aznar Cuadrado et al. 2004) demonstrates that such low fields are probably common in isolated white dwarfs and therefore also in CVs (though they are below the detection limit of direct measurement).

Provided that the primary has a sufficiently weak magnetic field ($\lesssim 5 \times 10^5$ G) accretion through a disc onto its surface generates a freely moving equatorial belt. There is spectroscopic evidence of such a belt after dwarf nova outbursts (e.g. Sion et al. 1996; Godon et al. 2004). If the primary's field is stronger then the system is an intermediate polar with very stable rotation. The rapidly rotating belt will enhance whatever field the primary has, resulting in magnetic channeling of accreting mass even for weak field primaries, but onto the equatorial belt. The low inertia of the belt is what allows it to be spun up and down by magnetic connection to the inner edge of the accretion disc – giving the $\dot{M}$-$P_{DNO}$ relationship seen in outbursting dwarf novae. We refer to this as the Low Inertia Magnetic Accretor (LIMA) model (WW1).

There is a key observation that supports the idea that at least some of the white dwarfs in dwarf novae have magnetic fields strong enough to channel accretion, despite the absence yet of direct detection by spectroscopic or polarimetric means, and this comes from the X-Ray eclipse of OY Car observed shortly after outburst. Wheatley & West (2003) deduce that the X-Ray emitting region is considerably smaller than the white dwarf and is at high primocentric latitude.

The QPOs are thought (by WW1) to be due to a prograde traveling wave at the inner edge of the disc, probably excited by field winding arising from the non-synchronous rotation of the disc and the primary. The traveling wave can intercept and/or reprocess radiation from near the primary, thereby generating the optical QPOs. The revolving anisotropic radiation from the accretion zones on the belt (that causes the DNOs) can sweep across the traveling wave and be reprocessed at the beat period, producing the double DNOs.

The lpDNOs may be an additional channel of accretion from the disc, but along field lines that connect to the body of the primary, rather than to the belt.

Not all CVs in their high $\dot{M}$ phases show DNOs or QPOs. This shows that there is a parameter that determines the presence or absence of oscillations. In the LIMA model this is simply the strength of the magnetic field of the equatorial belt, which is determined by both the field of the primary and any shear enhancement that takes place.

# THE EVOLUTION OF DNOS THROUGH OUTBURST IN VW HYDRI

At maximum luminosity of a VW Hyi outburst DNOs are seen at 14 s, both in soft X-Rays (van der Woerd et al. 1987) and the optical (WW2). Until almost the end of outburst DNOs are seen only intermittently, but when visible they are found to increase slowly and systematically in period to $\sim$ 20 s when the star has descended to $\sim$ 1.5 mag above minimum. At this phase of outburst DNOs are almost always present; as the star continues to fade WW2 discovered that there is a rapid increase in period, doubling to $\sim$ 40 s in about 5 h. This has been ascribed (WW1) to propellering, caused when the equatorial belt with its associated magnetic field is rotating at higher angular velocity than the inner edge of the accretion disc, and is consistent with the near cessation of EUV flux (which is a direct monitor of $\dot{M}$ onto the primary) precisely during the phase of rapid DNO deceleration (Mauche 2002). Following this deceleration phase there has been uncertainty in the evolution of the DNOs. Figure 8 of WW2 showed that the DNO periods at some point decrease by a factor of about two and the oscillations themselves become apparently less coherent. We have gathered more light curves of VW Hyi covering these final phases of outburst, the analysis of which has uncovered a remarkable behaviour.

## Late stage DNOs in VW Hydri

When the DNOs have increased to $P_{DNO} \sim 39$ s there is a sudden frequency doubling – seen in Figure1. We have not managed to be at the telescope, with a clear sky, when this happens, but our various observing runs suggest that it happens in less than $\sim$ 15 min, and (as seen by the later behaviour) may happen essentially instantaneously. As we do not have the crucial information we cannot yet claim that the period exactly halves, but again from subsequent behaviour we can be fairly certain that the fundamental has been replaced by its first harmonic. The period of the now dominant 1st harmonic continues to increase systematically and with little scatter as VW Hyi decreases in brightness until at a period of $\sim$ 28 s a new periodicity appears, which within error of measurement is at a period 2/3rds of the 1st harmonic, so here are sure that we are dealing with a 2nd harmonic.

The evolution of the DNOs from this point is complex in the sense that there is a gradual move from dominance by the 1st harmonic to dominance by the 2nd harmonic, with often both being simultaneously present – and, very importantly, there is an occasional
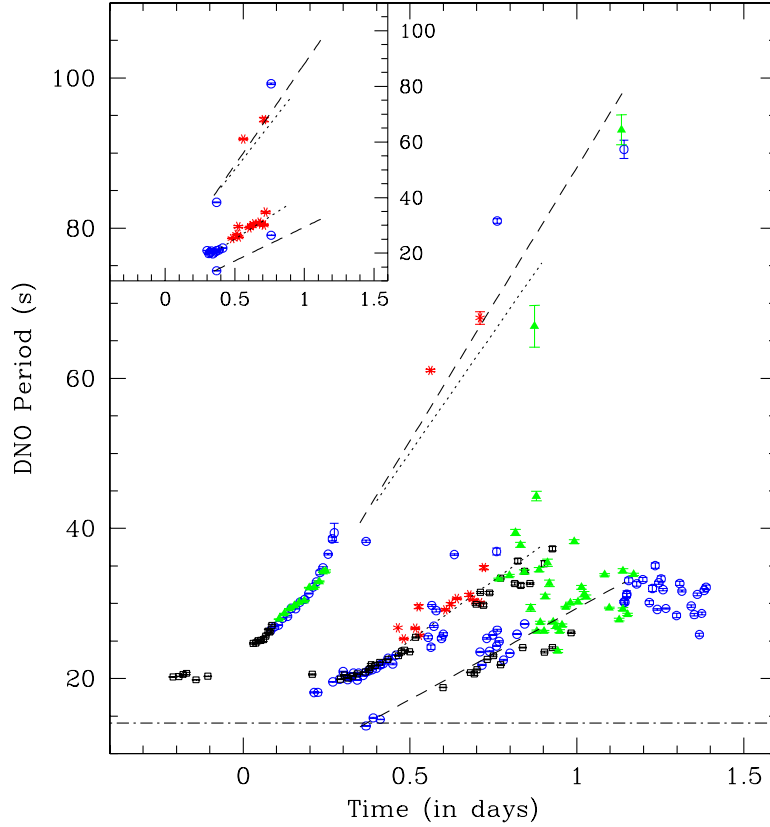
**FIGURE 1.** The evolution of DNO periods at the end of normal and super outbursts of the dwarf nova VW Hyi. Different symbols mark the various kind of outbursts, ranging from short (red asterisks), normal (blue open circles), long (black open squares) to super (green filled triangles) outbursts. The dotted and dashed lines show the results of a least-squares fit to the first and second harmonic, respectively, and are multiplied by a factor of two and three to illustrate the inferred evolution of the fundamental DNO period. The dashed-dotted horizontal line at 14.1 s represents the minimum observed DNO period at maximum brightness. The inset highlights two observing runs in which the fundamental, the first and/or second harmonic of the DNO period were present simultaneously.

appearance of the associated fundamental, showing that the description as fundamental, 1st and 2nd harmonics is quantitatively justified. Figure 2 shows examples of Fourier transforms (FTs) with various combinations of the harmonics present.

In Figure 3 we show a modified form of Figure 1, in which the harmonics have been replaced by their implied fundamentals. From this we see that the fundamental continues to increase at a rapid rate, with increasing scatter, until it reaches $\sim 105$ s, after which VW Hyi has reached quiescence and we have not detected DNOs. The fundamental period increases almost linearly from 30 s to 105 s in $\sim 27.5$ h, i.e. $\dot{P} = 1.06 \times 10^{-3}$.

We have not detected such 1:2:3 ratios in the DNOs of any CV other than VW Hyi – but VW Hyi is also unique in having DNOs that are most prominent at the end of its outburst.
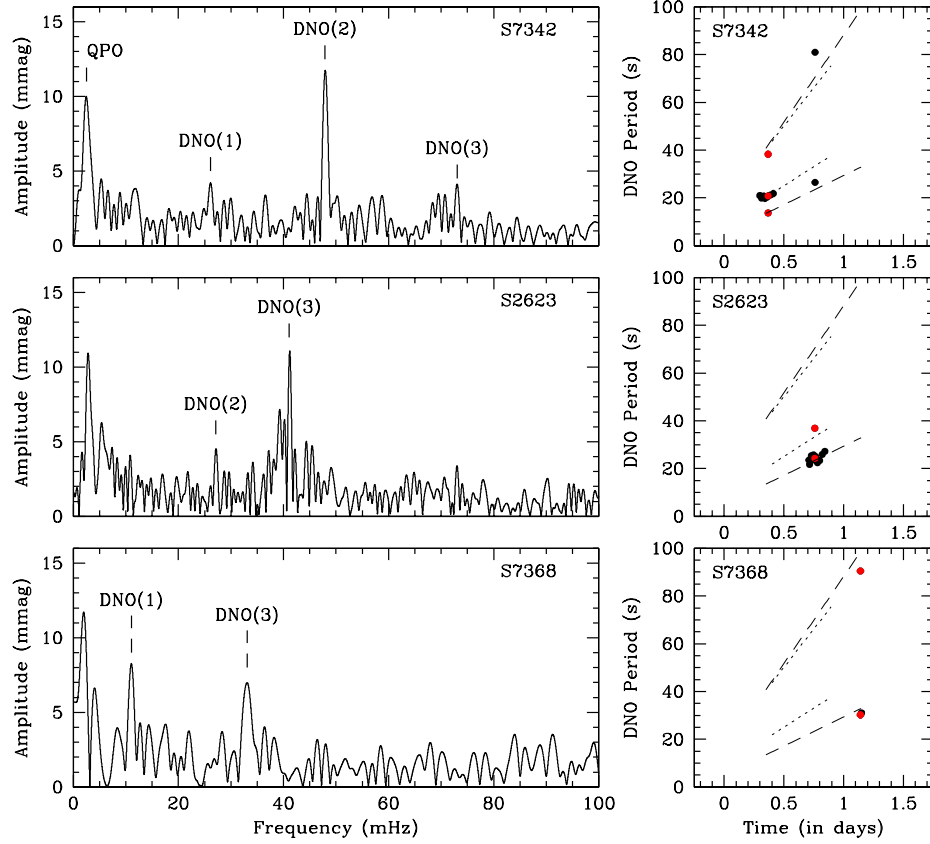
**FIGURE 2.** Examples of Fourier transforms of VW Hyi in which combinations of the fundamental and the first two harmonics of the DNO period are present.

## Similarity to XRBs

As pointed out in WW1 and WWP, CVs and XRBs show the same correlation of their high frequency and low frequency oscillations, viz. the ratio of $\sim 15$. This relationship, which extends over 6 orders of magnitude in frequency, is shown in Figure 4.

The 3:2:1 period ratios seen in VW Hyi are similar to those already known for a few years in XRBs (McClintock & Remillard 2004). For example, for black hole binaries, 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; GRO J1655-40 has 450 and 300 Hz oscillations (Remillard et al. 2002); and 240 and 160 Hz (ratio 3:2) are present in H1743-322 (Homan et al. 2004). For the neutron star XRB, Sco X-1, Abramowicz et al. (2003) claim a 3:2 period ratio.
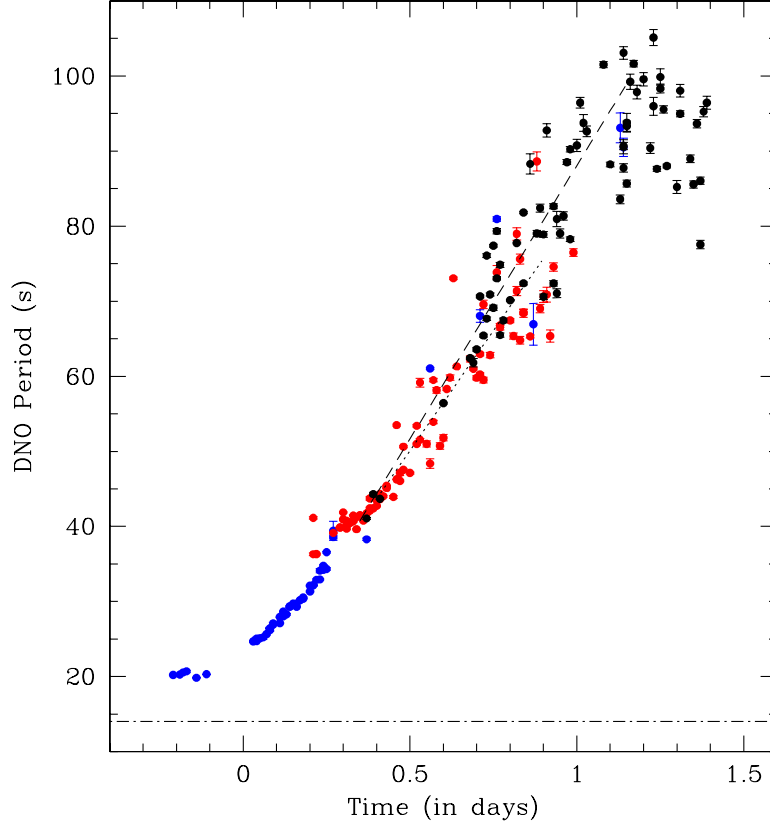
**FIGURE 3.** The evolution of the fundamental DNO period in VW Hyi at the end of normal and super outbursts. The different colours indicate the observed fundamental (blue), first harmonic (red) – multiplied by two –, and second harmonic (black) – multiplied by three. The dotted, dashed and dashed-dotted lines are as in Figure 1.

## A MODEL FOR HARMONICS IN VW HYI

A possible explanation of the appearance of harmonics in the DNOs of VW Hyi is as follows. At high $\dot{M}$, i.e. maximum of outburst, the DNOs are rarely present, but when they are they are seen (in different outbursts) at 14.1 s. We identify this as the minimum period of the equatorial belt – i.e. the keplerian period at the surface of the primary, which leads to a mass of 0.70 $M_\odot$. At high $\dot{M}$ the inner edge of the disc is close to the primary and we can see only the upper accretion zone once per rotation. But, at an orbital inclination of $\sim 63°$ for VW Hyi, the inner edge of the disc eventually retreats (with lowering $\dot{M}$) sufficiently for us to see the zone on the far side (i.e., no longer hidden by the primary); when this happens the keplerian period at the inner edge (which will be similar to the rotation period of the magnetically coupled equatorial belt), with the above parameters, should be $\sim 45$ s. This accounts for the observed frequency doubling at $P_{DNO} \sim 40$ s.
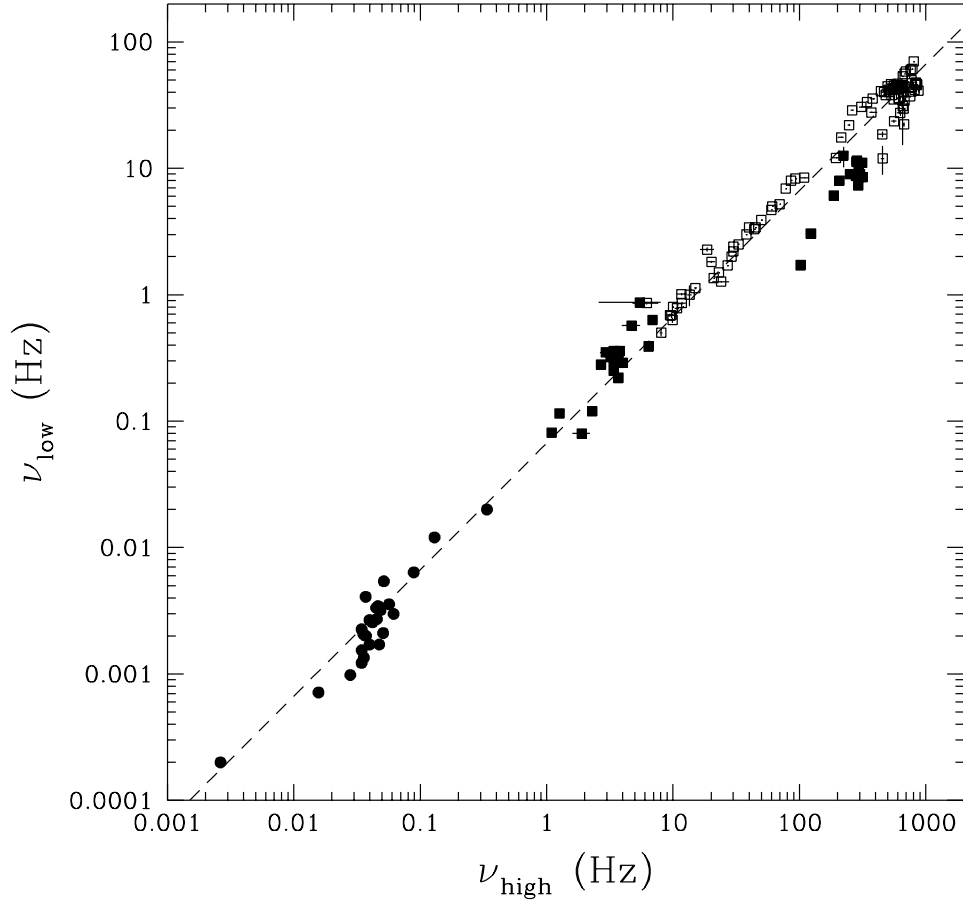
**FIGURE 4.** The Two-QPO diagram for X-ray binaries (filled squares: black hole binaries, open squares: neutron star binaries) and 26 CVs (filled circles). Each CV is plotted only once. The X-Ray binary data are from Belloni et al. (2002) and were kindly provided by T. Belloni. The dashed line marks $P_{QPO}/P_{DNO} = 15$ (From WWP).

As the inner parts of the disc are cleared out by the expanding magnetosphere, eventually the observed DNO should become the reprocessed beam – the traveling (QPO generating) wave subtends the largest and nearest reprocessing site. The frequency of the observed DNO would then be the first harmonic of the difference between the frequencies of the equatorial belt and the traveling wave, which we can call $\tilde{\omega}$.

The traveling wave (according to WW1) is a region of deceleration and pile-up of disc material, and therefore constitutes a region of higher density at the inner edge of the disc. The magnetic field of the equatorial belt sweeps across this at frequency $\tilde{\omega}$, thereby modulating $\dot{M}$ onto the primary. This is an application of the beat-frequency model, first introduced for CVs (Warner 1983) and later independently for XRBs (Alpar & Shaham 1985; Lamb et al. 1985). The outcome is that the first harmonic, at frequency $2\tilde{\omega}$ will have sidebands at $\pm\ \tilde{\omega}$, i.e. the amplitude modulated frequency set $\tilde{\omega}$, $2\tilde{\omega}$ and $3\tilde{\omega}$. The modulations at $\tilde{\omega}$ and $2\tilde{\omega}$ will have additional components, of other amplitudes and phases, so their relative amplitudes will not be that of simple amplitude modulation,

and may vary with time. Similar effects are seen in the orbital sidebands of intermediate polars (Warner 1986).

It should be noted that in this model there is no physical oscillation at the second harmonic, $3\tilde{\omega}$, it is purely a Fourier component in the light curve, as actually observed.

## THE ROBERTSON-LEITER MODEL

As black holes are not supposed to have magnetic fields it is not automatically obvious that the same magnetically channeled accretion model for CVs and neutron stars is applicable to black hole XRBs. However, in a series of papers Robertson & Leiter have suggested that all of the central objects in galactic black hole candidate XRBs have magnetic moments. The evidence comes from (1) the conclusion that in neutron star binaries the power-law part of the X-Ray flux spectrum arises in the neutron star magnetosphere, where calculations and observations are in close agreement, and the recognition that the same model works for black hole XRBs (Robertson & Leiter 2002); (2) the realisation that a magnetic star collapsing towards its event horizon can be slowed by the radiation pressure ensuing from pair annihilation that itself is a result of pair production by the compressed magnetic field – such a "Magnetospheric, Eternally Collapsing Object" maintains an intrinsic magnetic moment outside its event horizon for orders of magnitude longer than a Hubble time (Robertson & Leiter 2003); (3) models of jets that arise from thin disc interaction with MECOs produce the Radio-IR correlation with Mass and X-Ray luminosity observed in neutron star and Black Hole binaries (and also in AGNs) (Robertson & Leiter 2004).

This recognition that black holes can have magnetospheres that interact with accretion discs permits a unified model that may explain the similarity of behaviour of DNOs and QPOs in CVs and X-Ray binaries seen in Fig. 4.

## WZ SAGITTAE

In quiescence the dwarf nova WZ Sge has optical modulations at 27.87 and 28.95 s; their beat period at 744 s is commonly seen in the light curve and is responsible for recurring absorption dips. These have been interpreted in terms of the LIMA model (WW1), where the magnetic field of the primary is strong enough to prevent easy slippage of the equatorial belt in quiescence (Warner 2004), in which case the 27.87 s period should be thought of as an lpDNO.

During outburst weak oscillations near 6.5 s have been detected (Knigge et al. 2002), which may be the DNOs associated with the lpDNOs (i.e. with rotation of white dwarf itself, and also oscillations at 15 s that increased to 18 s (Welsh et al. 2003), which could be from a spun-up equatorial belt.

The reason for including WZ Sge here is because it appears to be an analogue of the accreting millisecond pulsars (MSPs) in X-Ray binaries, where $\dot{M}$ is very low, the spin rate is relatively high (a factor of only a few above rotational break-up period), and only a small amount of gas manages to leak onto the primary (Galloway et al. 2002; Rappa-

port, Fregeau & Spruit 2004). X-Ray transients containing MSPs have disc instabilities just as in dwarf novae. $\dot{M}$ during outburst is directly measured from the X-Ray flux; the millisecond flux pulsations are sinusoidal and are present during the whole factor of $50 - 100$ of $\dot{M}$ variation during outburst. Optical and UV DNOs are present during superoutbursts of WZ Sge, and in quiescence, but their behaviour is complicated by reprocessing of the high energy rotating beam off various stationary and moving components in the binary system. The magnetic field of the primary in WZ Sge appears not to be strong enough to prevent a freely moving equatorial band from developing during the highest $\dot{M}$ delivered in outburst. In contrast, in the MSP XRBs the pulses are monoperiodic and have small but measurable period derivatives, but here there is no free equatorial belt and we observe only the X-Rays from the accretion region itself.

## CONCLUSIONS

CVs show an increasing range of rapid modulation phenomena that have analogues among the XRBs. It appears increasingly likely that magnetically channeled accretion is the underlying cause for these properties, implying magnetic moments for some stellar mass black holes.

## ACKNOWLEDGMENTS

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