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Invited Review

Rapid Oscillations in Cataclysmic Variables

Brian Warner

Department of Astronomy, University of Cape Town, Rondebosch 7700, Cape Province, South Africa; warner@physci.uct.ac.za

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ABSTRACT. I give an overview of the rich phenomenology of dwarf nova oscillations (DNOs) and quasi-periodic oscillations (QPOs) observed in cataclysmic variable stars (CVs). The favored interpretation of these rapid brightness modulations (3 to >1000 s timescales) is that they are magnetic in nature—magnetically channeled accretion from the inner accretion disk for DNOs and possible magnetically excited traveling waves in the disk for QPOs. There is increasing evidence for the magnetic aspects, which extend to lower fields the well-known properties of strong field (polar) and intermediate strength field (intermediate polar) CVs. The result is that almost all CVs show the presence of magnetic fields on their white dwarf primaries, although for many the intrinsic field may be locally enhanced by the accretion process itself. There are many behaviors that parallel the QPOs seen in X-ray binaries, with high- and low-frequency X-ray QPOs resembling, respectively, the DNOs and QPOs in CVs.

1. INTRODUCTION

The discovery by Merle Walker (1956) on 1954 July 9 of a 71 s modulation in the light curve of DQ Her, the remnant of nova Herculis 1934, gave notice that not only are cataclysmic variables (CVs) binaries of short orbital period, they are also capable of producing periodic phenomena on what, in 1954, were unprecedentedly short timescales. The rapidity and high stability of the modulation in DQ Her is now attributed to rotation of the white dwarf primary; thus, it was the forerunner of the class of CVs known as intermediate polars (IPs), in which the magnetic field of the primary channels gas from the inner edge of an accretion disk onto spots or arcs on the primary, and of which about 32 are now known (Kuulkers et al. 2003). In the case of DQ Her the optical oscillations have been shown to be due to anisotropic radiation from the primary (located probably at two accretion hot spots, so the rotation period is actually 142 s) sweeping across the accretion disk, deduced from observed phase changes in eclipse of the continuum modulation and from the wavelength dependence of pulsation phase in the emission lines (Warner et al. 1972; Patterson, Robinson, & Nather 1978; Chanan, Nelson, & Margon 1978; Martell et al. 1995; Silber et al. 1996).

In the early searches for further examples of the DQ Her phenomenon (see Warner [1988] for a history of the application of high-speed photometry to CVs) only one more nova, V533 Her, was added (Patterson 1979). However, the same timescale phenomenon, albeit of much lower stability and usually of very low amplitude, was found (Warner & Robinson 1972) to be commonly present in dwarf novae during outburst and also in nova-like variables (i.e., in CVs of high rates of mass transfer, $\dot{M}$). These modulations, with periods initially observed in the range of 8–40 s, became known as dwarf nova oscillations (DNOs). In the optical they are usually of such low amplitude that they appear only in Fourier transforms, but occasionally they reach a few percent amplitude and can be seen directly in the light curve (Fig. 1). In almost all cases they are highly sinusoidal in pulse profile. There is no apparent correlation between amplitude of DNOs and orbital inclination.

The study of such rapid modulations in CV light curves used to necessitate the use of relatively inefficient photomultipliers, but the advent of high quantum efficiency CCDs, and the ability to window and bin their pixels, has made possible studies to much fainter levels, and in particular in crowded fields. An example of such a design and its applications is given in O'Donoghue (1995).

Longer timescale modulations of large amplitude but much lower coherence were identified in CV light curves by Patterson, Robinson, & Nather (1977) and are commonly called quasi-periodic oscillations (QPOs). As discussed below, these may have more than one timescale and physical origin.

Recently, a new type of DNO has been recognized (Warner, Woudt, & Pretorius 2003; hereafter WWP03), similar to the DNOs but having periods typically greater by a factor of about 4. These can coexist with the DNOs and QPOs, and may at times be mistaken for ordinary DNOs.

I examine the general properties of each of these kinds of short timescale modulations. A general review of the literature on oscillations in CVs up to 1995 can be found in Warner (1995a). I omit from discussion here the rapid oscillations that are observed at ∼1 Hz in the accretion columns of strongly magnetic CVs (polars; e.g., Larsson 1992).

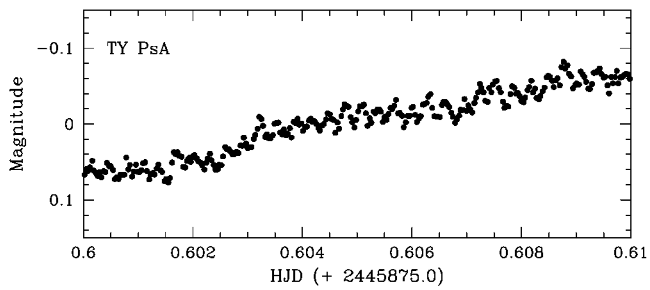

FIG. 1.—Light curve of TY PsA. The DNOs are directly visible in the light curve. Individual points are 3 s integrations. (Adapted from Warner, O'Donoghue, & Wargau 1989.)

2. DNOs

From the time of their discovery it was recognized that, unlike DQ Her, which has $Q = |dP/dt|^{-1} \sim 10^{12}$, DNOs are low-$Q$ modulations. On timescales of hours their periods can change by many seconds, but at other times are stable to milliseconds for many hours, giving $10^3 < Q < 10^7$. Two timescales of variation are known. The first, on an outburst timescale, is a period-luminosity relationship connecting DNO period to optical brightness, but not in a single-valued manner, thus producing "banana loops" in a diagram of $P_{\rm DNO}$ versus m_v (Patterson 1981). Although it was early hypothesized that $P_{\rm DNO}$ would be found to be simply related to accretion luminosity (Bailey 1980) and that this would produce such loops because of the observed time delay between bolometric and optical luminosities (Hassall et al. 1983; Warner 1995b), it was a long time before this could be directly demonstrated as a monotonic relationship between $P_{\rm DNO}$ and EUV luminosity (which is a good monitor of bolometric accretion luminosity; Mauche 1996a). It was even longer before simultaneous observations of DNOs in the optical and EUV would show identical modulations in phase (Mauche & Robinson 2001).

Although covering a smaller range of luminosities, the period-luminosity relationship has been demonstrated for nova-like stars (Warner, O'Donoghue, & Allen 1985). It would be of interest to study any DNOs in nova-like stars that go into states of low $\dot{M}$ (i.e., the VY Scl stars).

The second timescale of variation is very short; even when the DNOs are at their most coherent, changes are seen as sudden small jumps in period (typically ∼0.03 s; i.e., ∼0.1%) that interrupt times of comparative stability lasting for thousands of seconds (Fig. 2). There is evidence that DNOs are most stable at maximum of outburst but that their stability (i.e., coherence length) progressively decreases late in outburst (e.g., Hildebrand, Spillar, & Stiening 1981). The rarity with which any optical DNOs are seen at maximum light in VW Hyi, and their low amplitude (∼1 mmag) when observed (Woudt & Warner 2002a, hereafter WW2a), could indicate that it is high stability that is rare and that the Fourier transform techniques usually employed are inadequate for detecting drifting signals. Similarly, van der Woerd et al. (1987) were successful in detecting DNOs on only two occasions during extensive soft X-ray observations of seven outbursts of VW Hyi, where the modulation is large (∼15%) when present.

The night-to-night change from easy detectability to complete absence of DNOs in nova-like stars (e.g., UX UMa, where DNOs are found in only about half of the optical and *Hubble Space Telescope* [*HST*] observations; Nather & Robinson 1974; Knigge et al. 1998) also indicate cessation rather than reduced coherence. The changes of amplitude of DNOs over a few hours often include disappearance and reappearance.

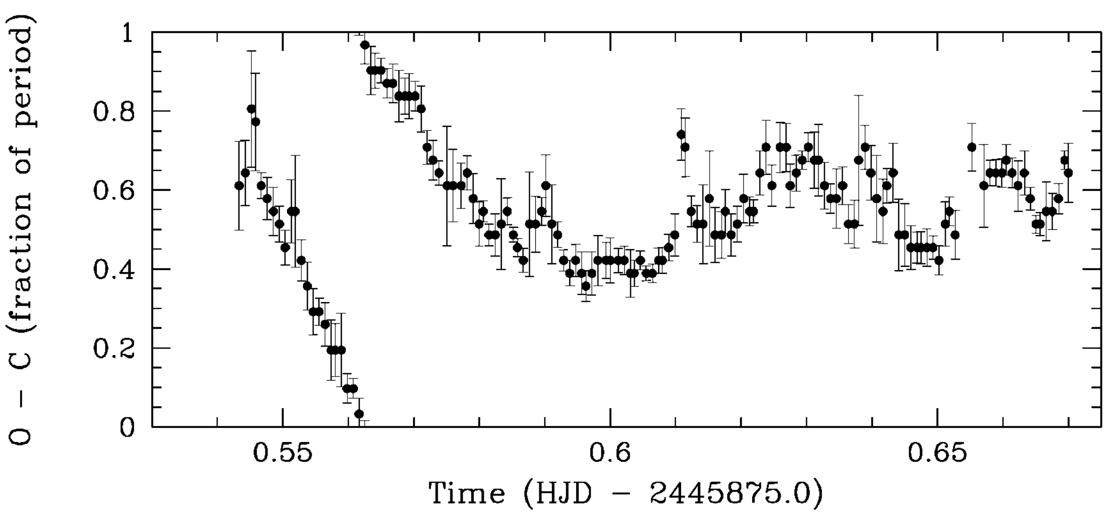

FIG. 2.—$O - C$ diagram of TY PsA. (from observations published in Warner et al. 1989). The observed oscillations are compared with a sine wave of constant period 26.64 s. At the start of the run the period was shorter than this, giving a nearly linear change of phase ($O - C$), but around 0.58 day the period changed to an average of 26.64 s, but with short and often sudden changes of phase (or, equivalently, period). The diagram "wraps around" when the phase exceeds one cycle.

TABLE 1
Rapid Optical and Ultraviolet Modulations in Cataclysmic Variables

Star	Type	P_{orb} (h)	DNO (s)	lpDNO (s)	QPO (s)	References
SS Cyg	DN	6.60	6.58*–10.9	32–36	83–111,730	1–5
RU Peg	DN	8.99	11.6–11.8	→ ?	~51	
VW Hyi	NL	1.78	14.03–40	~90	400–600	6–8
EM Cyg	DN	6.98	14.6–21.2			
Z Cam	DN	6.96	16.0–18.8			
HX Peg	DN	4.82	16.2–16.4	~83	~340, 800–1900	8–9
WX Cet	DN	1.40	17.4			10
OY Car	DN	1.50	17.6–28.0	47.9, 116	~320, 1500	8, 11
WX Hyi	DN	1.80	19.4		~190, 1140, 1560	8
V436 Cen	DN	1.50	19.5–20.1		475	7–8
HL Aqr	NL	3.25	19.6			
RR Pic	N	3.48	20–40			
HT Cas	DN	1.77	20.2–20.4	~100		1
TU Men	DN	2.82	20.6		313	9
HP Lib	AMC	0.31			~290	12
CR Boo	AMC	0.40	21–23	62	~300	8
AQ Eri	DN	1.46	21.0–23.5	~90	~280	8
AH Hya	DN	…	21.55			9
TY PsA	DN	2.02	21.6, 25.5–30	110	355	9
BR Lup	DN	1.91	21.65			9
SW UMa	DN	1.36	22.3		280–370	13
KT Per	DN	3.92	22.4–29.3	~86, 147		
EC 2117	NL	3.71	22.5–25.5	~95	~500	8
WW Cet	DN	4.22	23.1	103	263	9
SY Cnc	DN	9.12	23.3–33.0			
VZ Pyx	DN	1.78	23.9	112	390, ~3000	8, 14
V803 Cen	AMC	0.28		176		8
V1159 Ori	DN	1.50	24–34	177	→ ?	9, 15
AH Her	DN	5.93	24.0–38.8	~100		1
CN Ori	DN	3.91	24.3–32.6			8
IX Vel	N	4.65	24.6–29.1		~500	16
U Gem	DN	4.25	~25	~146		17
Z Cha	DN	1.79	25.1–27.7		585	8
V893 Sco	DN	1.82	25.2		~350	8, 18
BP Lyn	NL	3.67	25.5			
AM CVn	AMC	0.28	26.3		290, 820	19–22
WZ Sge	DN	1.36	27.87, 28.95, 14.48+others		742	7, 23–33
V2051 Oph	DN	1.50	28.06, 29.77, 42.2		486, 1800	7, 34
UX UMa	NL	4.72	28.5–30.0		~650	3, 35
V3885 Sgr	NL	4.94	29–32			
HP Nor	DN	…	35.2			9
RX And	DN	5.08	36		~1000	8
BP Cra	DN	…	38.6			9
V436 Car	NL	4.21	~40	123		36
V533 Her	N	3.52	63.63		1400	8, 37
YZ Cnc	DN	2.08		~90		
LX Ser	NL	3.80	~140	→ ?		
X Leo	DN	3.95	89–160			9
TW Vir	DN	4.38	112–121		1000	9
V373 Sct	N	…	258.3	→ ?		38
BT Mon	N	8.01			~1800	8, 39
GK Per	N	1.99d	360–380		5000	40–42
KR Aur	DN	3.91			400–900	43
EF Peg	NL	1.92			400, 1080	44
TV Crv	DN	1.50			600	45
RW Sex	NL	5.93			620, 1280	

TABLE 1 (*Continued*)

Star	Type	P_{orb} (h)	DNO (s)	lpDNO (s)	QPO (s)	References
V842 Cen	N	...			750–1300	38
EC 0528-58	NL	...			900–1560	46
TT Ari	NL	3.30			900–1600	47–49
V442 Cen	DN	...			925	
V442 Oph	NL	2.98			1000	48
RX J 1643	NL	2.89			1000	48
BH Lyn	NL	3.74			1030	48
AH Men	NL	3.01			1100	48
V795 Her	NL	2.60			1150	48, 50
WX Ari	NL	3.34			1180	48
SS Aur	DN	4.39			1200–1800	51
V751 Cyg	NL	3.47			1230	52
LS Peg	NL	4.20			1240	53–55
NSV 10934	DN	1.7			1300	56
V426 Oph	DN	6.85			1680	
GO Com	DN	1.58			1980	
V592 Cas	DN	2.76			2160	57
CW Mon	DN	4.23			2200	58
SU UMa	DN	1.83			2280	
MV Lyr	NL	3.20			~3000	59, 60, 61

NOTES.—DN = dwarf nova, N = nova, NL = nova-like, AMC = AM CVn star. Asterisk denotes cases in which a period approximately half that noted was also observed. Arrows (→ ?) indicate that the assignment to type of oscillation in the column to the left is not certain—the oscillation may belong in the marked column.

REFERENCES.—(These references are additional to those given in Table 8.2 of Warner [1995].) (1) Patterson 1981; (2) Mauche & Robinson 2001; (3) Mauche 1996a; (4) Mauche 1997a; (5) Mauche 2002; (6) WW2a; (7) WW2b; (8) WWP03; (9) M. L. Pretorius (2003, unpublished); (10) J. Patterson (2003, private communication); (11) Marsh & Horne 1998; (12) Patterson et al. 2002c; (13) Nogami et al. 1998; (14) Remillard et al. 1994; (15) Patterson et al. 1995; (16) Williams & Hiltner 1984; (17) Long et al. 1996; (18) Bruch, Steiner, & Gneiding 2000; (19) Patterson et al. 1979; (20) Skillman et al. 1999; (21) Patterson et al. 1992; (22) Provencal et al. 1995; (23) K2002; (24) Skidmore et al. 2002; (25) Skidmore et al. 1999; (26) Patterson et al. 1998; (27) Welsh et al. 1997; (28) Skidmore et al. 1997; (29) Provencal & Nather 1997; (30) Patterson et al. 2002a; (31) Provencal & Nather 1997; (32) Araujo-Betancor 2003; (33) W2003; (34) Steeghs et al. 2001; (35) Knigge et al. 1998; (36) Woudt & Warner 2002b; (37) Rodriguez-Gil & Martinez-Pais 2002; (38) Woudt & Warner 2003; (39) Smith, Dhillon, & Marsh 1998; (40) Nogami, Kato & Baba 2002; (41) Morales-Rueda, Still, & Roche 1996; (42) Morales-Rueda, Still, & Roche 1999; (43) Kato et al. 2002; (44) Kato 2002; (45) Uemura et al. 2001; (46) Chen et al. 2001; (47) Kraicheva et al. 1999b; (48) Patterson et al. 2002b; (49) Tremko et al. 1996; (50) Rodriguez-Gil et al. 2002; (51) Tovmassian 1987; (52) Patterson et al. 2001; (53) Taylor, Thorstensen, & Patterson 1999; (54) Rodriguez-Gil et al. 2001; (55) Szkody et al. 2001; (56) Kato et al. 2004; (57) Kato & Starkey 2002; (58) Kato et al. 2003; (59) Pavlenko & Shugarov 1999; (60) Kraicheva, Stanishev, & Genkov 1999a; (61) Skillman, Patterson, & Thorstensen 1995.

In addition to the abrupt changes in period, which are not accompanied by any noticeable change in system luminosity, there are short-lived phase excursions that appear to have no effect on the underlying trend in period. When best defined, the DNOs show the presence of an underlying clock with abrupt changes of period, on which the phase noise seems never to cause loss of knowledge of phase (Warner & Brickhill 1978; Jones & Watson 1992). However, the increasing frequency of the phase and period changes produces reduced coherence in late phases of outbursts. These short-timescale variations are demonstrated in Figure 2.

When sufficient DNO coherence occurs in eclipsing dwarf novae or nova-like stars, phase and amplitude variations can be measured during the eclipses. These show that, as in DQ Her, DNOs are caused by "beams" of radiation carried around by rotation of the primary (Nather & Robinson 1974; Patterson 1981; Petterson 1980). Confirmation comes from Keck time-resolved spectroscopy of V2051 Oph, which has a pulse phase in its emission lines that is wavelength dependent, similar to that of DQ Her (Steeghs et al. 2001).

An inventory of DNO observations[1] is given in Table 1. There are about 50 CVs in which standard DNOs have been

[1] In many cases there has been only one observation of a DNO in a given star, but its persistence for an hour or more is sufficient evidence for its existence. The full range of period is in most cases not yet determined, and therefore the order of stars in Table 1 (where, in the first part, they are listed by increasing minimum observed period) is to some extent arbitrary. In a few cases of very low amplitude, short duration of appearance, or other reasons, I have omitted published claims of DNO detections.

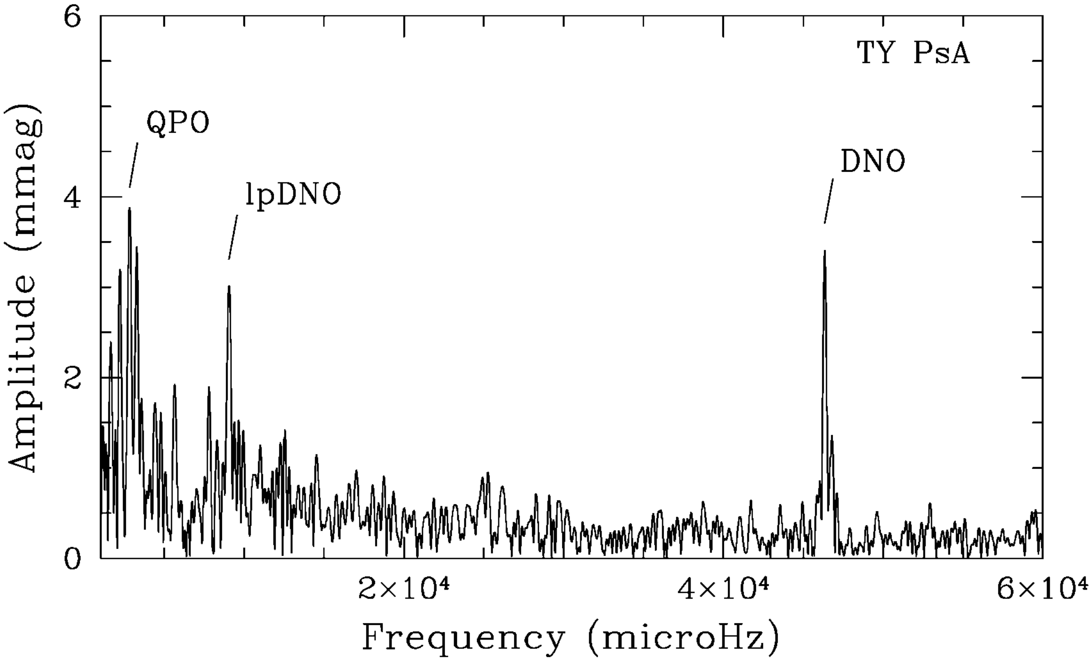

FIG. 3.—Fourier spectrum of TY PsA. The QPO, lpDNO, and DNO are all simultaneously present. (From M. L. Pretorius, [2003, unpublished observations].)

detected, plus a few in which the nature of the DNOs is not yet determined. It is notable that none of the classic IPs appears in this list (an instructive exception is GK Per; see § 4); despite much high-speed photometry, none of these has been reported as having modulations at periods shorter than their primary spin-related periods.

3. LONGER PERIOD DNOs

It has recently been realized from observing the literature as well as the sky that there is another class of DNOs showing coherence levels similar to DNOs but not following the same period-luminosity relationship (in fact, their periods may be independent of $\dot{M}$; WWP03). We have called these "longer period DNOs" (lpDNOs); they have periods typically about 4 times greater than those of DNOs and can coexist with the latter. An example of this is shown in Figure 3. They are mentioned, but without explanation, in a number of early papers on DNOs. Specific examples are in VW Hyi, where a modulation with period averaging ~88 s (in addition to ~28–36 s DNOs) was seen on seven nights of an outburst as the system decreased in brightness from magnitude 10.6 to 13.7 (Haefner, Schoembs, & Vogt 1979; examples of similar, but rare, periodicities in VW Hyi are given by WWP03); in SS Cyg, where ~33 s modulation was present in addition to 10 s DNOs (Robinson & Nather 1979; Patterson 1981); and in HT Cas and AH Her, where ~100 s modulations were seen (the former even in quiescence) but where normal DNOs have much shorter periods (Patterson 1981).

lpDNOs have now been observed in about 17 CVs (Table 1).

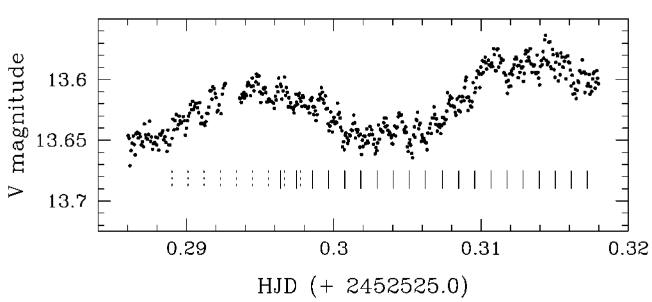

FIG. 4.—Light curve of EC 2117-54 (the first 45 minutes of run S6554). The lpDNO modulation at 94.21 s is clearly visible in the light curve. The lpDNO minima are marked by vertical bars. There is a phase shift around HJD 2,452,525.297. (From WWP03.)

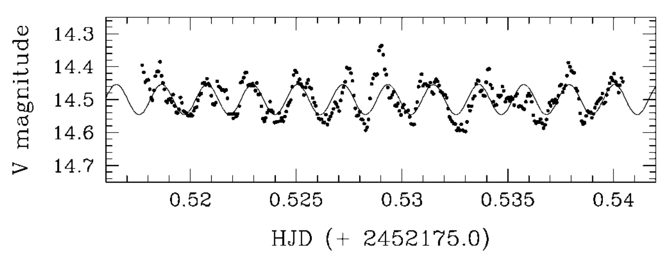

FIG. 5.—Light curve of WX Hyi showing the 185 s QPO clearly. Superimposed is the result from the nonlinear sinusoidal least-squares fit. (From WWP03.)

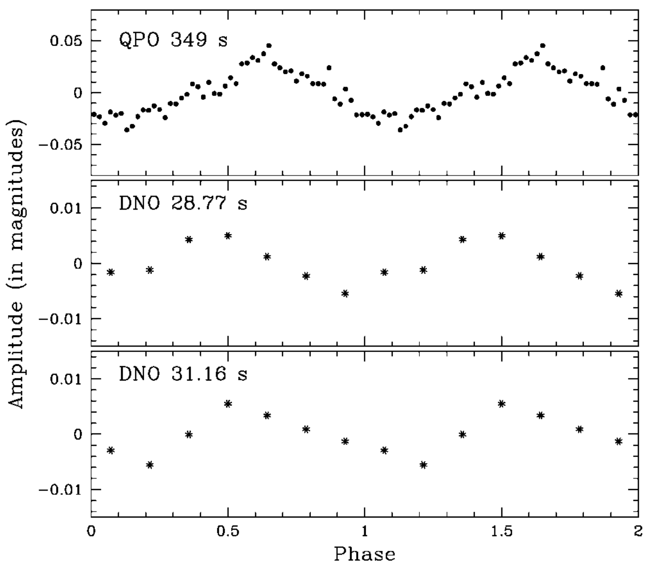

FIG. 6.—Averaged profiles of the DNOs and QPOs present simultaneously in VW Hyi (corresponding to the Fourier spectrum in Fig. 12). (From WW2a.)

These include some reclassifications, and there may be other cases where DNOs have mistaken identity. No studies of phase shifts during eclipse have yet been made, but the existence of double lpDNOs (§ 4.1) indicates that a rotating-beam model is applicable and therefore phase shifts should occur.

As with DNOs, the lpDNOs are not always present. On average they have slightly larger amplitudes than DNOs and are more often seen directly in the light curve (see Fig. 4). For this reason some previously observed lpDNOs were classified as QPOs.

Comparison of the amplitude and phase changes of DNOs and lpDNOs when both are simultaneously present shows that they generally behave independently (WWP03).

Table 1 includes four AM CVn stars—helium-transferring CVs with ultrashort orbital periods. The detection of the various types of rapid modulation in AM CVn stars is made difficult by the presence of strong harmonics to the main orbital/superhump brightness variations. (These harmonics are not independent oscillations in the system; they appear in Fourier transforms merely from the highly nonsinusoidal shapes of the principal modulations.)

Nevertheless, V803 Cen has long been known to possess a modulation at ∼178 s (O'Donoghue, Menzies, & Hill 1987) of unknown origin. It is seen when V803 Cen has a high $\dot{M}$, but not during low states, its period appears independent of luminosity, and there are phase variations on timescales of hours, similar to those of DNOs (WWP03). These are the characteristics of lpDNOs, rather than, e.g., possible pulsations of the primary. No ordinary DNOs have yet been detected in V803 Cen, but its compatriot CR Boo has shown the full set of DNO, lpDNO, and QPO oscillations (WWP03), and the type star AM CVn has shown both ordinary DNOs and two periodicities in the QPO range.

4. QUASI-PERIODIC OSCILLATIONS

Quasi-periodic modulations have orders of magnitude less coherence than DNOs. Because of this they are difficult to recognize in Fourier transforms; their power is spread over a wide band of frequency. They typically have $Q \sim 5$–20. An example of an unusually coherent train of 11 cycles of a QPO is shown in Figure 5; a Fourier transform of this light curve shows that 19.4 s DNOs with a mean amplitude of 3.8 mmag were also present.

In principle there may be more than one kind of variation; e.g., almost constant period but with frequent large phase changes, with perhaps a clear growth and decay in amplitude between the phase jumps, or constantly varying period and amplitude over a limited range. There has as yet been no study or classification of such modulations; their analysis is hampered by the general stochastic flickering arising from accretion processes that is usually present in CVs (although here again some reclassification may be necessary; some of the flickering and flaring commented on in the CV literature has a QPO look about it). More refined definitions and analyses will probably reveal that QPOs are more common than hitherto realized; at present we accept only the QPOs in a light curve that are obvious to the eye.

A glance down the column listing QPO periods in Table 1 will indicate the evident existence of two timescales of QPO. In a few cases (e.g., WX Hyi, VZ Pyx, OY Car, or perhaps V2051 Oph) two quite different periods of QPOs have been observed. For those systems where DNOs and/or lpDNOs are seen, there are often QPOs at ∼15 times the DNO period, or, equivalently, ∼4 times the lpDNO period. Apart from these there is a large number of observations of quasi-periodic modulations with periods in the range of 1000–3000 s (note that GK Per is an exception here; its 5000 s QPO is ∼15 times its optical DNO period). I have to distinguish between these two kinds of QPO here but am reluctant to introduce yet more nomenclature, and so I will simply discuss separately those that are related to DNO/lpDNO periods and those that are not.

4.1. DNO-Related QPOs

A valuable clue to the nature of these QPOs is given by the existence of "double DNOs." Pairs of DNOs with small separations in period were found in V3885 Sgr (29.08 and 30.15 s; Hesser, Lasker, & Osmer 1974), V2051 Oph (29.77 and 28.06 s; Steeghs et al. 2001), OY Car (17.94 and 18.16 s; Marsh & Horne 1998), V436 Cen (19.45 and 20.20 s; WWP03), EC 2117-54 (many examples, typically 22.10 and 23.27 s; WWP03), CN Ori (11.23 and 12.10 s; WWP03), and VW Hyi (see below; WW2a); and there is the case of WZ Sge, which shows stable modulations at 27.87 and/or 28.95 s even in quiescence (Table 1), which I discuss in § 10.

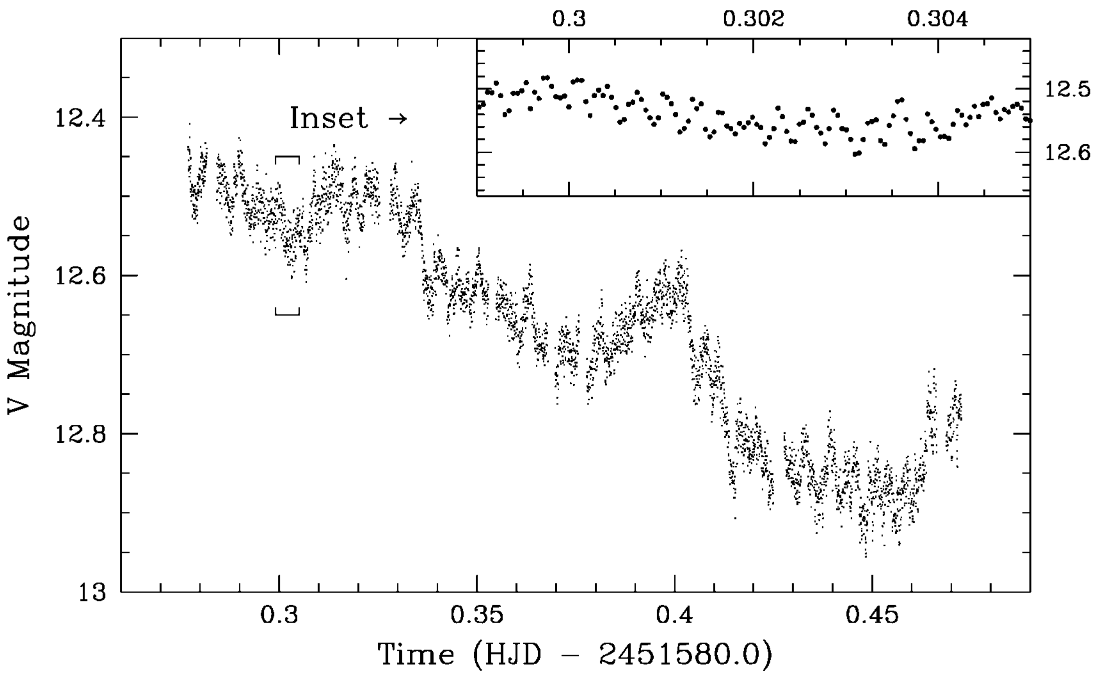

FIG. 7.—Light curve of VW Hyi on 2000 February 5, taken during the late decay phase of this dwarf nova outburst. The inset is an amplified view of a small part showing the DNOs. The large humps are at the orbital period (107 minutes). QPOs are present with a range of ∼0.1 mag and timescale ∼0.006 days. (From WW2a.)

In many of these cases the beat period between the double DNOs corresponds to the period of a QPO present at the same time, including WZ Sge (Warner & Woudt 2002, hereafter WW2b). In Figure 6 the mean pulse profiles of two DNO components and the accompanying QPO are illustrated. An example of a double lpDNO, split at the QPO frequency, has been found in VW Hyi (WWP03).

Another clear example of an interrelationship between DNOs and QPOs is given by the light curve of VW Hyi for 2000 February 5 (Fig. 7), obtained at the end of outburst when large-amplitude DNOs and QPOs typically occur in this star. The fall in brightness by a factor of about 2 during the observation caused steady increases in period for both the DNOs and the QPOs, the first time such an evolution of QPO period had been seen. The ratio P_{QPO}/P_{DNO} remained at about 15 during this evolution (Fig. 8). This is generalized in § 11.

4.2. Other QPOs

Even among the remaining QPOs there may be two or more distinct types. Many of the CVs listed in Table 1 with periods of ∼1000 s are suspected by Patterson et al. (2002b) of being generated by IP structures, as in the case of GK Per, in which the underlying 351 s rotation of the primary is seen as ∼380 s modulation caused by reprocessing of the rotating beam off a varying period QPO source. The periods are characteristic of the "canonical" IPs, which have rotation periods ∼15 minutes and binary periods ∼4 hr. Included among these systems are LS Peg and V795 Her, both of which show polarization modulated at the optical periods (Rodriquez-Gil et al. 2001, 2002) but which have not yet been proved to have the high stability required for definite IP status.

For these systems, therefore, the evidence is accumulating that their QPOs are another manifestation of magnetic primaries and are occurring in IPs for which large-amplitude coherent optical and X-ray modulations are in some way suppressed, perhaps by high $\dot{M}$. These will therefore probably add directly to the tally of IPs.

However, anticipating the model developed in § 6, a CV cannot have DNOs (and/or lpDNOs) and be an IP—the magnetic field is either strong enough to anchor the exterior of the white dwarf to the interior, or it is not—and this exclusivity is indeed demonstrated by the absence of any observed DNOs in known IPs. So we are left with at least a few CVs for which the QPOs cannot have a direct connection with rotation of the primary. In Table 1 these are the systems WX Hyi, VZ Pyx, OY Car, and V2051 Oph, already mentioned above, and there may be others in which only QPOs have so far been detected. The timescales of some of these modulations are comparable to the rotation periods at the outer edges of high-$\dot{M}$ accretion disks (which are ∼0.20 P_{orb}; eq. [8.6] of Warner 1995a), but no definite models accompany this speculation.

Another possible source of brightness variation is modulation of $\dot{M}$ from the secondary, caused by nonradial oscillations of the secondary in a manner similar to that of the ∼5 minute

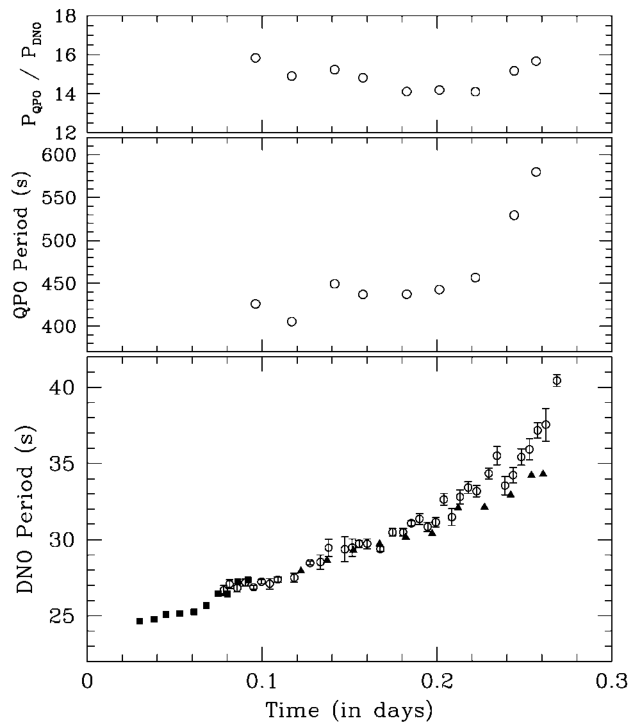

FIG. 8.—Variations with time of the DNO and QPO periods in the normal outburst of 2000 February (*circles with error bars*). DNOs are added for the superoutburst of 1972 December (*triangles*) and the normal outburst of 2001 February (*squares*). The topmost panel shows the ratio of the periods in the 2000 February run. (From WW2a.)

oscillations of the Sun. Small amplitude variations in radius of the secondary would be amplified in $\dot{M}$ by the great sensitivity of Roche lobe overflow.

5. X-RAY OBSERVATIONS

CVs, even nominally "nonmagnetic" ones, are usually detectable in X-rays: the low-$\dot{M}$ systems have hard X-ray emission, and the high-$\dot{M}$, optically thick, systems have soft X-rays. A transition from hard to soft and back is seen during a dwarf nova outburst.

Table 2 lists X-ray observations of DNOs and QPOs in CVs. It includes only the lower Q modulations (i.e., it omits IPs). The best-studied systems are SS Cyg, U Gem, and VW Hyi, which are close enough to the Sun for soft X-rays to be received almost unabsorbed by interstellar gas and are thus very strong sources during outbursts. There appears to be a mixture of DNOs, lpDNOs, and QPOs, but VW Hyi and U Gem in particular have full sets (note that in the case of VW Hyi the DNOs were observed at maximum but the QPOs were at the very end of outburst, so the ratio P_{QPO}/P_{DNO} is not close to the value 15 seen in the optical). In cases in which there is an overlap, it is evident that individual stars show the same modulation timescales in optical and X-ray.

The phase behavior of DNOs is the same in X-rays as in the optical. The most detailed study is that of Jones & Watson (1992); one of their results is shown in Figure 9, which should be compared with Figure 2. The amplitude of modulation in this case averaged about 35% but at times reached nearly 100%. Such large amplitudes are commonly seen in soft X-ray DNOs.

Table 2 shows that ordinary DNOs seen during dwarf nova outbursts occur in soft X-rays but not hard X-rays. This is most notable in the comprehensive study by Wheatley, Mauche, & Mattei (2003, hereafter WMM03) of an outburst in SS Cyg. The few observed hard X-ray DNOs have all occurred at quiescence. WMM03 conclude that the source of the DNOs must lie in the optically thick boundary layer at the surface of the primary. Although "residual" hard X-rays are observed during outburst, these are not modulated as DNOs; but this is in accordance with the interpretation of these X-rays as being coronal in origin (WMM03).

On the other hand, modulations at QPO periods are seen in hard X-rays, most strongly in VW Hyi just as the hard X-rays are turning on at the end of an outburst (Wheatley et al. 1996) and in SS Cyg during the turn-off phase of hard X-rays after the start of outburst and again when they turn on at the end of outburst (WMM03). These phases correspond to the transitions between optically thick and optically thin disks, which themselves are governed by $\dot{M}$ in the inner disk. The QPOs themselves are not accompanied by any hardness variations, thus eliminating temperature variations or photoelectric absorption variations as the source of the oscillations; but it does allow quasi-periodic occultation by a source that is completely opaque at X-ray energies (WMM03).

6. STATISTICAL VERSUS PHYSICAL MODELS

A number of statistical analyses of DNO light curves have been undertaken. Early models included a damped harmonic oscillator excited by white noise (Robinson & Nather 1979; Hildebrand et al. 1981) and a sinusoidal oscillator exercising a random walk in phase (Horne & Gomer 1980; Cordova et al. 1980, 1984). One problem with such approaches is that although they may deliver quantitative values of statistical parameters, these do not necessarily lead to any physical insight. A worse problem arises when it is seen that for the best quality data, such analyses are inappropriate; e.g., Jones & Watson (1992) show that the random walk model does not represent the behavior of the soft X-ray DNOs of SS Cyg. But that should be no surprise, given the systematic behavior seen in the phase diagrams (Figs. 2 and 9).

A more profitable approach, therefore, is to start with the observed properties and try to envisage a model that can reproduce them. In presenting what I think is a viable model, I am influenced by the following facts:

1. At least 10% of single white dwarfs have magnetic fields $>2 \times 10^6$ G, and the limited studies with sensitivities down to $\sim 3 \times 10^4$ G suggest that the total may be significantly higher (Liebert, Bergeron, & Holberg 2003). At least 25% of white

TABLE 2
RAPID OSCILLATIONS IN X-RAYS

Star	Type	P_{orb} (h)	Period (s)	Energy	State	References
SS Cyg	DN	6.60	7.4–10.7	soft	O	1–4
			2.8*	soft	O	5
			155–245	hard	O	6
VW Hyi	DN	1.78	14.06, 14.2–14.4	soft	O	7
			63–68	soft	O	7
			∼60	hard	Q	8
			∼500	hard	O	9
HT Cas	DN	1.77	21.85:	hard	Q	10, 11
U Gem	DN	4.25	25–29	soft	O	2, 12
			121, 135	hard	Q	11
			585	hard	O	11
WZ Sge	DN	1.36	27.8	hard	Q	13
SU UMa	DN	1.83	33.93:	hard	Q	10
YZ Cnc	DN	2.21	222	hard	Q	11
RW Sex	NL	5.93	254	hard		11
AB Dra	DN	3.65	290	hard	O	11
OY Car	DN	1.50	2240	soft	Q	14
GK Per	N, DN	1.99d	3000–5000	hard	O	15, 16

NOTES—O = outburst, Q = quiescence. A colon denotes a less-certain observation; asterisk denotes cases in which frequency doubling had occurred.

REFERENCES.—(1) Cordova et al. 1980; (2) Cordova et al. 1984; (3) Watson, King & Heise 1985; (4) Jones & Watson 1992; (5) van Teeseling 1997; (6) WMM03; (7) van der Woerd et al.1987; (8) Pandel et al. 2003; (9) Wheatley et al. 1996; (10) Eracleous, Patterson, & Halpern 1991; (11) Cordova & Mason 1984; (12) Mason et al. 1988; (13) Patterson et al. 1998; (14) Ramsay et al. 2001; (15) Watson, King, & Osborne 1985; (16) Ishida et al. 1996.

dwarfs in CVs have detectable or directly inferable fields (i.e., they are polars or IPs), despite the fact that the current lower limit for detection in these systems is $\sim 7 \times 10^6$ G (Wickramasinghe & Ferrario 2000). But here there may be a selection effect operating: most strongly magnetic CVs have been found from X-ray surveys, which probe to greater distances than extant optical surveys (although the Sloan Digital Sky Survey may eventually remove this bias). On the other hand, at least some of the high-$\dot{M}$ IPs avoided detection until recently (e.g., the SW Sex systems LS Peg and V795 Her). It has been suggested that in the common-envelope phase, magnetic fields are generated and amplified within the differentially rotating envelope (Regos & Tout 1995), so it would not be surprising to find that CV primaries are systematically more magnetic than isolated white dwarfs.

2. Given this, we may suspect that not only are there many primaries in CVs with fields $< 7 \times 10^6$ G, but they may even constitute a dominant fraction of the apparently "nonmagnetic" majority. The DNO model that I favor is based on this expected extension of the distribution of magnetic fields of primaries to values lower than those in IPs.

7. A MAGNETIC MODEL FOR DNOs AND lpDNOs

The observed period-luminosity relationship for DNOs prompted Paczynski (1978) to suggest that magnetically channeled accretion was responsible, but onto an equatorial belt that slips on the surface of the primary, rather than onto the body of the primary itself. This was developed by Warner (1995b) and more recently in WW2b. Direct evidence for long-lived, rapidly rotating equatorial belts on the primaries of dwarf novae after outburst has come from *HST* observations (Sion et al. 1996; Gänsicke & Beuermann 1996; Cheng et al. 1997; Szkody et al. 1998; Sion & Urban 2002) in which spectra are found to be composite, comprising a white dwarf in relatively slow rotation plus a hot belt rotating at a rate comparable to the Keplerian velocity at the surface of the primary.

I describe the model briefly and show how it relates to the principal observed properties of DNOs, lpDNOs, and QPOs.

An accretion torque applied to the surface of a star can only be communicated to the bulk of the star if the viscosity of the interior of the star is large enough. Degenerate material is notoriously slippery, so a white dwarf behaves like a solid body only if it is permeated by a strong enough magnetic field (Durisen 1973). "Strong enough" turns out to be $B > 1 \times 10^5$ G (Katz 1975; WW2b). For accretion to be magnetically controlled near the surface of the primary, B must also be strong enough, depending on $\dot{M}$ and the geometry of the field. For $\dot{M} \sim 5 \times 10^{17}$ g s^{-1}, probably the maximum reached in dwarf novae in outburst, the requirement (for a multipole field) is $B > 2 \times 10^4$ G (eq. [16] of WW2b).

There is, therefore, a window of opportunity: even high-$\dot{M}$ accretion onto low-field primaries can be magnetically controlled by whatever field the freely slipping equatorial belt has. The field within the belt itself will be enhanced during accretion by differential shearing of the field lines, which aids magnetic channeling (this may also explain why dwarf novae in quiescence in general do not show DNOs). CVs with very low

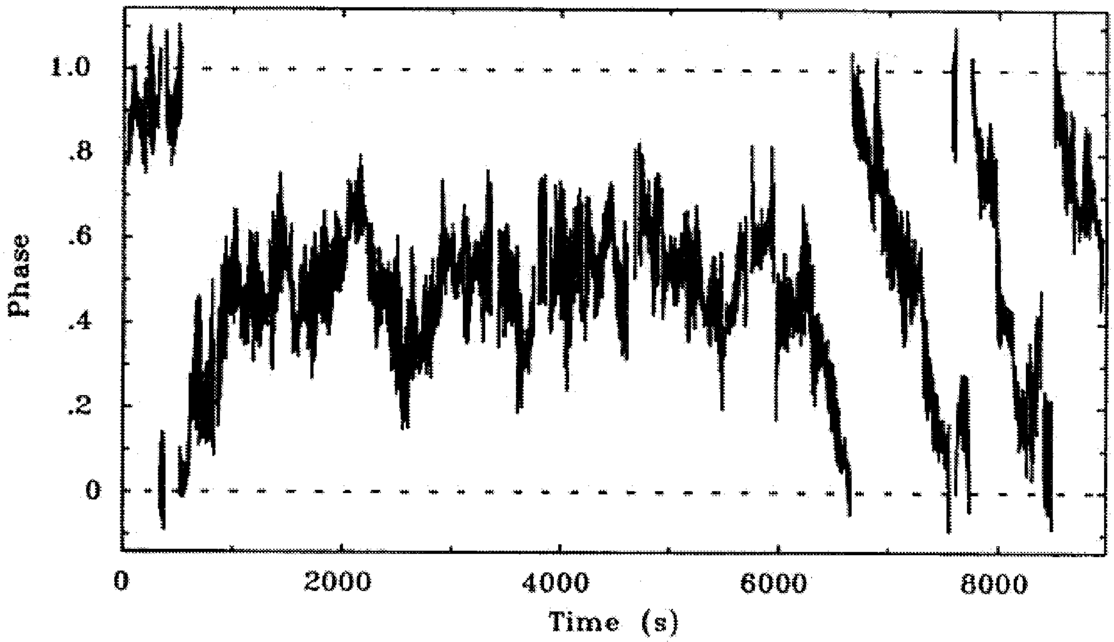

FIG. 9.—Phase behavior of DNOs in SS Cyg in X-rays (adapted from Jones & Watson 1992). This is the same kind of diagram as Fig. 2, displaying $O-C$ phase relative to a constant period.

intrinsic fields should never show DNOs: several dwarf novae and nova-like stars have been extensively observed with high time resolution without any sign of DNOs (Patterson 1981 and Warner 1995a list examples); these constitute genuine non-magnetic CVs.

The model is therefore similar to that for an IP but is of low Q: the mass of the belt accreted during a dwarf nova outburst (obtained by measuring the total energy radiated, $\sim10^{39}$–10^{40} ergs and ascribing it to released gravitational energy) is $\sim10^{22}$ g (cf. 10^{33} g for the whole primary) and can thus be easily tugged around by magnetic coupling to the accretion disk. It spins up as $\dot{M}$ increases on the rising branch of outburst, which compresses the magnetosphere of the primary and decreases the period at the inner radius of the disk. Because $\dot{M}$ varies with time during an outburst, no equilibrium is reached. As the inner radius of the disk steadily decreases, the minimum energy state for accretion is constantly being sought, so field lines reconnect between the equatorial belt (which has differential rotation in latitude as well as in depth) and the disk, resulting in accretion along field lines connected to zones of slightly different periods of rotation. This search for equilibrium causes the sudden jumps of DNO period as matter is transferred from one magnetic channel to another; they are least frequent at maximum luminosity when $\dot{M}$ passes through its turning point and hence is most constant.

After maximum luminosity, $\dot{M}$ decreases steadily, and at some point the inner edge of the disk retreats so rapidly that the belt is not able to slow its rotation period rapidly enough to maintain near equilibrium. Then gas attaching itself to the field lines anchored in the belt is centrifuged outward, stopping most of the accretion onto the primary and extracting angular momentum from the belt.

Evidence for such "propellering" is seen in VW Hyi. The variation in DNO period as a function of brightness on the descending branch of outburst is shown in Figure 10. The general correlation between period and brightness for $8.3 < V < 12.3$ is an example of the ubiquitous period-luminosity relationship referred to above. But that is succeeded by a phase of extremely rapid increase in period, during which the DNO period doubles in about 6 hr. This phase is concomitant with cessation of EUV flux (Fig. 11). Since EUV flux is a competent monitor of $\dot{M}$ onto the primary, it can be seen that accretion is reduced to a trickle at exactly the time that the deduced rapid deceleration of the equatorial belt is occurring.

What about lpDNOs? Their independence from accretion luminosity puts them in a different category from ordinary DNOs, but in other aspects they behave like magnetically channeled accretion, including the existence of double lpDNOs split at the QPO frequency (§ 4.1). A clue to the cause of their longer periods comes from observed rotationally broadened spectra of some CV primaries. Taking the observed projected rotational velocities (Sion 1999) and adopting measured or estimated masses and inclinations (details are given in WW2b and WWP03) we find the following rotation periods (all with at least 20% uncertainty): VW Hyi, 140 s; SS Cyg, 63 s; OY Car, >260 s. These rotation periods are roughly twice the observed lpDNO periods, which would occur for accretion onto two regions of the primary. I suggest, therefore, that lpDNOs

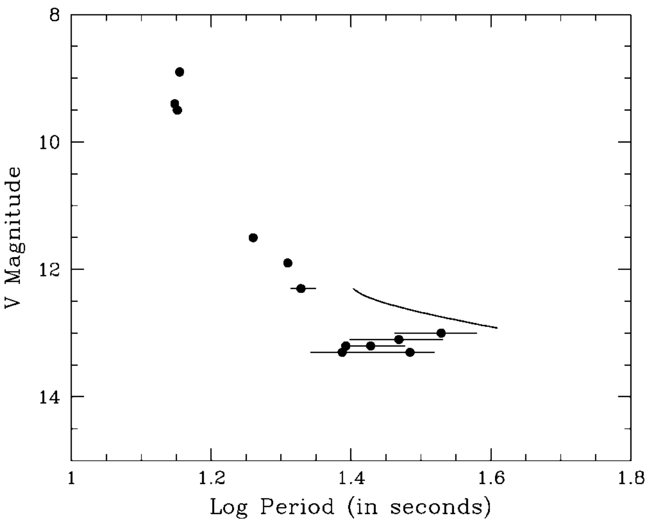

FIG. 10.—DNO periods as a function of the V magnitude of VW Hyi. The curved solid line corresponds to the DNO evolution seen in Fig. 8. The horizontal bars show the range of DNO periods in each of the runs illustrated. (From WW2a.)

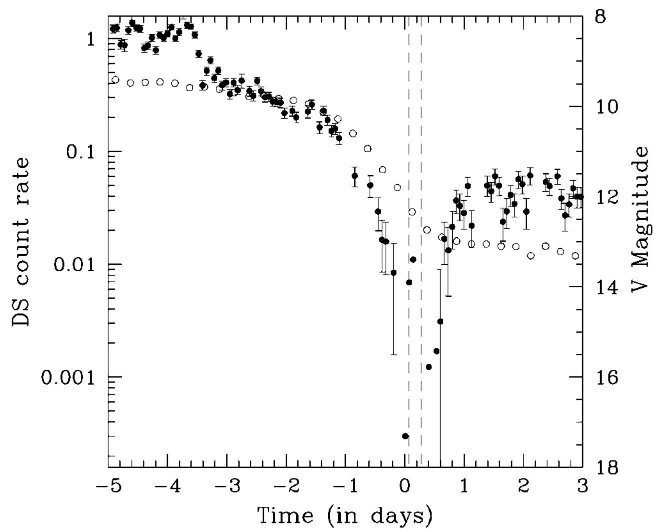

FIG. 11.—Comparison of EUV flux (DS count; *filled circles*) at the end of a superoutburst in VW Hyi with the average optical light curve (*open circles*). The vertical dashed lines show the range over which the DNOs in Fig. 8 were observed. EUV data are from C. W. Mauche (2002, private communication); optical data are from the Royal Astronomical Society of New Zealand (2002, provided by F. Bateson).

are literally connected to the primary's rotation, which will be differential in latitude as material accreted at the equator spreads out across the surface. This explains why, unlike DNOs, lpDNO periods are not correlated with $\dot{M}$ and behave independently of DNOs.

If this interpretation is correct, then the lpDNOs allow an extension of knowledge of rotation periods—from the IP region to primaries of lower field strength. The definite lpDNOs in Table 1 cover the range of 33–177 s. If we exclude AE Aqr, then the known IPs have rotation periods that range from the 142 s of DQ Her to 4021 s for EX Hya. The reason for omitting AE Aqr is because the field of $\sim 3 \times 10^5$ G deduced for it (Wynn, King, & Horne 1997; Choi & Yi 2000) is at the bottom end of the range of IP fields and may not be quite large enough for the primary to behave as a solid body. This in turn calls into question the high spin-down power that is deduced from the observed large $dP_{\rm rot}/dt$ in AE Aqr (de Jager et al. 1994). Indeed, the rapid spin-down may be simply because only the inertia of the outer layers of the primary is coupled to the retarding torque (which, because of the high rotation rate, is largely due to propellering).

The existence of two clear groups—rapidly rotating primaries with signatures of weak fields, and slower rotating IPs with quite strong fields—constitutes a correlation between magnetic field strength and rotation period of the primary. This is related to the fact that the stronger the field, the larger the radius of the magnetosphere and the longer the IP equilibrium period. But $\dot{M}$ also plays a role: the larger the $\dot{M}$, the smaller the equilibrium radius of the magnetosphere. And from the observed timescales $P_{\rm rot}/|dP_{\rm rot}/dt| \sim 10^6$ yr in IPs, we see that it is the average $\dot{M}$ over the past millions of years that determines the current value of $P_{\rm rot}$. Such a timescale probably includes several nova explosions and may include long periods of very low $\dot{M}$ (hibernation; see § 9.4.3 of Warner 1995a), so the apparent correlation between field strength and spin period means either that the present weak-field CVs have preferentially had historic high $\dot{M}$, or that all CVs experience roughly similar average $\dot{M}$ and that their spin periods are solely a result of their weaker fields. The latter scenario seems more probable and, indeed, if measurements of B can be made, offers a way to estimate long-term average values of $\dot{M}$.

I have suggested that DNOs and lpDNOs are the signatures of magnetically channeled accretion onto regions that are rotating respectively with maximum angular velocities close to the equatorial Keplerian velocity and at roughly one-eighth (for two-pole accretion) of that velocity. According to Kippenhahn & Thomas (1978) the large specific angular momentum of material accreted at the equator onto a nonmagnetic primary results in very slow mixing to higher latitudes: the timescale is much greater than the time between nova eruptions (but note that this computation includes only mixing via the Richardson instability; coupling of parts of the surface by closed-loop magnetic fields will also distribute angular momentum). They find that the latitudinal width of the equatorial belt, caused by mixing and defined as that latitude where the velocity falls to half of the equatorial velocity, is $\sim 20°$ (beyond which it falls very rapidly). They also find that 10^4 yr of accretion at $10^{-9}\ M_\odot\ {\rm yr}^{-1}$ results, after mixing with surface material, in a belt with an angular velocity of 0.22 of the Keplerian velocity in the equatorial plane—and therefore ~ 0.11 at latitude 20°. In the suggested

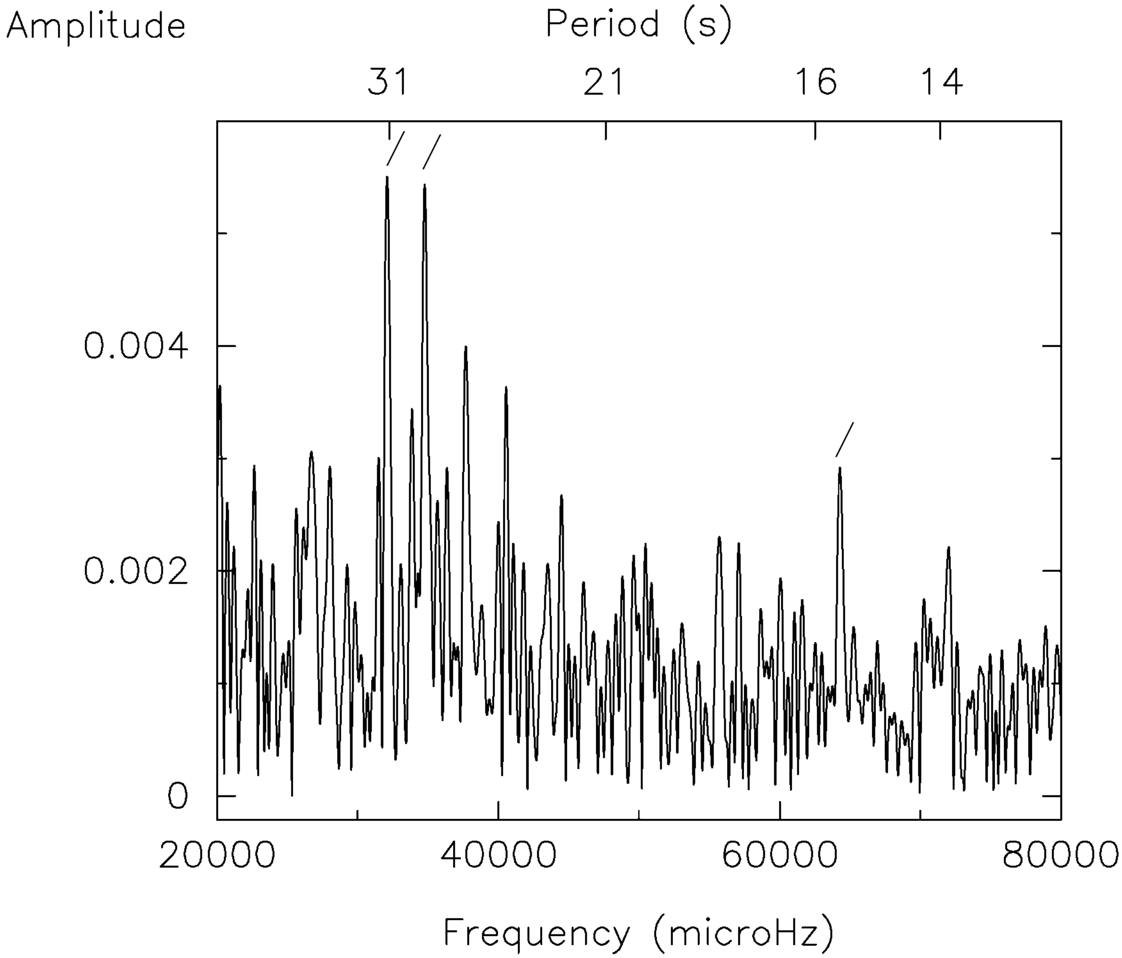

FIG. 12.—Fourier spectrum of a light curve of VW Hyi during outburst showing double DNO and harmonic to the lower frequency (*indicated by bars*). (From WW2a.)

model for lpDNOs this would mean that the body of the primary (or, at least where accretion onto it occurs) has acquired a rotation period close to that of the belt at its outer edge.

Perhaps the most direct evidence so far for magnetically controlled accretion in a dwarf nova comes from the analysis of *XMM-Newton* observations of OY Car just after an outburst. Wheatley & West (2003) show that the eclipse implies that the X-ray emitting region is noticeably smaller than the surface of the primary and is away from the equator (at latitude ~50° in their diagram). It is the presence of such accretion that may account for the rare 48 s QPOs observed in OY Car during quiescence (WWP03) and the 60 s X-ray QPOs seen in VW Hyi in quiescence (Pandel, Cordova, & Howell 2003).

Almost equally direct evidence is given by the presence of a variable-strength inverse P Cygni feature observed in the spectrum of VW Hyi during outburst, which has been interpreted as structured inflow of gas from the inner edge of a truncated disk (Huang et al. 1996).

8. THE NATURE OF QPOs

The observational evidence available at present (WW2b) shows that when a double DNO occurs, then it is the shorter of the two periods that is at the expected DNO period—and the profile of that signal is sinusoidal. The longer period often has a significant first harmonic (e.g., Marsh & Horne 1998; Fig. 12). The fact that the DNO frequency is accompanied by only one sideband shows that this is not a case of modulation of the DNO at the QPO frequency; rather, it is similar to the dominant sideband seen in IPs, which is caused by “reflection” (more correctly, reprocessing) of the rotating beam off the secondary (or other structure, such as a thickening of the disk at stream impact, revolving at the orbital frequency). By analogy, we conclude that the lpDNO component is generated by the rotating DNO beam being reprocessed by a structure revolving in a prograde direction around the primary at the QPO period. The irregular profile of this structure causes the harmonics in the reprocessed signal.

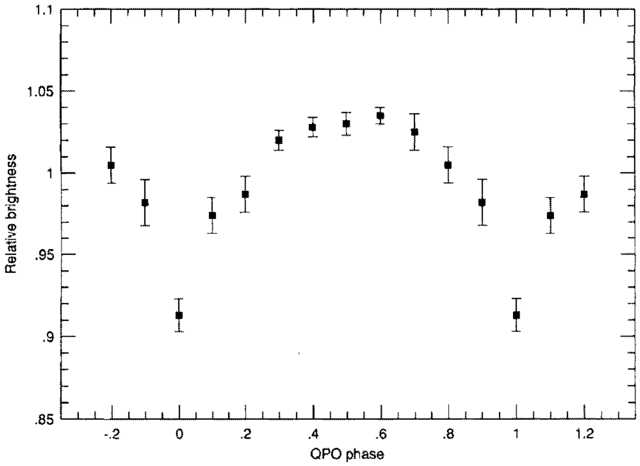

FIG. 13.—Mean light curve of the ~370 s QPO in SW UMa (from Kato, Hirata, & Mineshige 1992). Individual cycles of the QPOs, at higher time resolution, show that the low point is caused by a shallow eclipse.

The periods of most QPOs are so short (relative to the orbital period) that the accretion disk is the only possible location for the reprocessing site. If revolving at the Keplerian period, the site would be in the outer region of the disk and would have to have a very large vertical height in order to intercept enough of the rotating DNO beam. This is not out of the question, but perturbation analyses of accretion disks show that there are a number of oscillatory modes available and that a slowly moving prograde traveling wave in the inner disk is the most likely to be excited (Lubow & Pringle 1993). Such a traveling wave, excited by a process of magnetic winding and reconnection, has been proposed as the structure that generates the double DNOs (WW2b). The QPOs themselves are then the result of reprocessing and/or obscuration of the radiation from the hot inner regions by the traveling wave.

The obscuration aspect of QPOs is demonstrated by the occasional presence of deep dips at the minima of the QPO modulations, which pull the light curve well below its interpolated lower envelope (see, e.g., Fig. 2 of WW2b). A particularly interesting QPO profile is shown by SW UMa, in which the minimum of the ~370 s modulation is deepened by an apparent shallow eclipse of ~70 s duration, which is probably a partial eclipse of the primary (Fig. 13).

This model for optical QPOs—simple reflection and obscuration by an excited mode of the accretion disk—differs greatly from some earlier proposals that also invoke oscillation modes of disks. In those (nonmagnetic) studies (e.g., Carroll et al. 1985; Collins, Helfer, & van Horn 2000) the QPOs are supposed to be oscillations of the intrinsic luminosity of the disk itself. This is a viable option for nonmagnetic primaries, but it remains to be demonstrated observationally that such oscillation modes are excited and generate detectable QPOs.

The QPOs observed in the hard X-ray emission of SS Cyg during outburst are not entirely compatible with the above

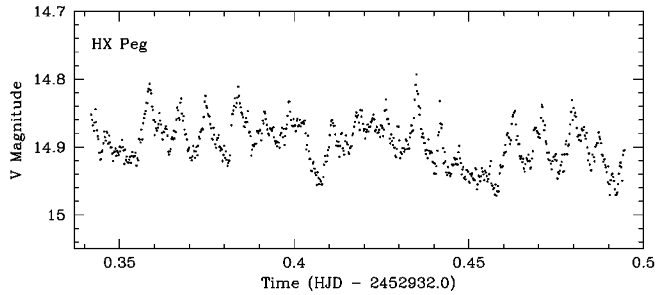

FIG. 14.—Light curve of HX Peg in outburst. The original data have been binned to 20 s integrations. (Courtesy M. L. Pretorius [2003, unpublished observations]).

model. Although deep dips that appear to be obscurations accompany the QPOs (Fig. 9 of WMM03), the quasi-periodic peaks cannot be due to a reflection effect. The overall effect looks more like QPOs of $\dot{M}$ at the inner boundary layer.

In this regard it is of interest to note parallel studies in other fields of astrophysics that have relevance to the QPOs in CVs. Quasi-periodic accretion and ejection of dense knots of gas in young stellar objects (YSOs) has been modeled as an interaction between a magnetic star and its accretion disk. The inner boundary of the disk undergoes quasi-periodic radial oscillations, each of which strips a ring of gas that falls onto the star (Goodson, Böhm, & Winglee 1999; Goodson & Winglee 1999). In the application to YSOs, appropriate parameters lead to an estimate of the oscillation period as $\sim 100/2\pi$ times the Keplerian period at the inner edge of the disk. It can be shown that the same mechanism applied to high-$\dot{M}$ CV disks and $B \sim 10^6$ G produces a similar result, which we can interpret as $P_{\rm QPO}/P_{\rm DNO} \sim 100/2\pi \sim 16$. Such modulation of accretion onto low-field CV primaries is therefore another mechanism that could produce QPOs at the observed periods. These would probably look more like flares than sinusoidal modulations. A possible example is shown in Figure 14, where recurrent flares with a quasiperiod of ~750 s are seen. In this light curve, low-amplitude ordinary QPOs at 347 s were also present, demonstrating the permitted coexistence of the two types of QPO.

In similar modeling by Uzdensky (2002) and Uzdensky, Königl, & Litwin (2002) of accretion from a disk into the magnetosphere of an aligned magnetic rotator, it is found that field winding and reconnection can lead to quasi-periodic accretion. The first results of three-dimensional modeling of accretion onto an inclined dipole rotator have recently appeared in which short-timescale QPOs also are found (Romanova et al. 2003).

9. FREQUENCY DOUBLING AND ALIASING

DNOs in the EUV region of SS Cyg have been observed in several outbursts (Mauche 1996b, 1997b, 1998, 2002) and constitute the most complete coverage of the evolution of DNOs in this wavelength region. The DNOs were found to be mostly sinusoidal in profile, except that at the brightest parts of outbursts in 1993 August and 1994 June, a noticeable first harmonic appeared. Then, in the 1996 October outburst, with SS Cyg at its brightest, the fundamental disappeared and the signal doubled in frequency to become entirely first harmonic (i.e., with a period of ∼3 s). The next outburst was observed in soft X-rays and was also found to have a 2.8 s DNO (van Teeseling 1997).

Before discussing possible physical causes of the frequency doubling, it is useful to point out that such short oscillation periods have implications for optical photometry of DNOs. For example, the 9.735 s DNO observed in SS Cyg by Patterson, Robinson, and Kiplinger (1978) at the unprecedentedly low amplitude of 0.02 mmag is now seen (as was allowed by the authors at the time) to be a beat between a true period of 6.790 s (or its first harmonic) and the photometric integration time of 4 s. If undersampled in such a way, a sinusoidal signal is reduced in amplitude by a factor of $\sin x/x$, where $x = \pi\, dt/P_{\rm DNO}$, and dt is the integration time. For the case under consideration, the true amplitude of the 6.79 s DNO would therefore have been 0.04 mmag, or 0.14 mmag if frequency doubling had occurred.

Another interesting example is given by the "type star" for QPOs, namely, RU Peg. The Fourier transform for RU Peg computed by Patterson et al. (1977) shows a QPO centered on 50 s and a 0.6 mmag DNO at 11 s; their integration time was 4 s. From the discussion in § 4 we would expect DNOs at ∼50/15 ∼ 3.3 s, not at 11 s. One possibility, therefore, is that the observed signal at 11 s was a beat with the integration time and that the true signal was 2.97 s with an amplitude of 2.8 mmag. This opens the further possibility that RU Peg had undergone frequency doubling at that time. Yet another possibility is that the observed 11 s signal was a low-amplitude lpDNO and there was no ordinary DNO detected at all.

The lesson to be learned from this is that it is necessary either to carry out photometry of DNOs with integration times of 1 s or less, or alternatively to split up the observations using noncommensurate integration times (e.g., alternate runs with 4 and 5 s integrations).

The physical cause of frequency doubling is not yet clear; it is a topic to be explored that could lead to greater insight into normal DNO behavior. A transition from single-pole to two-pole accretion is an obvious possibility. As $\dot{M}$ increases to a maximum value, the magnetosphere is squashed close to the surface of the white dwarf, at which point higher multipole components of the magnetic field geometry become more resilient than the dipole component (Lamb 1988), and what may have been a single visible accretion region could become two or more accreting zones (although only one or two are likely to capture most of the accretion flow).

Another possible model results from the change in viewing geometry when the inner radius of the disk approaches the surface of the primary. At moderate to high orbital inclinations, the primary obscures the inner part of the rear of the disk, and the front side of the disk, with its accretion curtain, can obscure the lower hemisphere and perhaps even part of the equatorial accretion zone. Furthermore, accretion columns or curtains are often of lowest optical thickness perpendicular to the accretion flow, which produces a fan beam. In either case the maximum direct visibility of an accretion zone may be near each limb of the rotating primary, the result being that a single bright region will be seen twice per rotation.

It would be helpful to have simultaneous EUV/X-ray and optical observations—the different wavelength regions give different points of view, the former showing what happens as seen directly from the center of the system, and the latter showing largely what the disk sees. It is possible that frequency doubling could occur at the short wavelengths but not at visible wavelengths.

An instructive example of a powerful effect of geometry is given by the IP XY Ari, in which the amplitude (in X-rays) of the 206 s periodic pulse is ∼20% and is double-peaked in quiescence but ∼90% and single-peaked in outburst. This is an example of period doubling rather than frequency doubling during outburst, the interpretation of which is that in quiescence there are two almost equal and 180° out-of-phase pulses coming from two-pole accretion, but during an outburst the inner edge of the disk moves so close to the primary that the lower pole is obscured, removing the filling-in effect of the other pole (Hellier, Mukai, & Beardmore 1997).

But there may be other reasons for frequency doubling, especially when we note that QPOs can also double (or halve) their frequencies. The QPOs in VW Hyi appear to double in frequency (WW2b) when the system is approaching quiescence, when the inner edge of the disk must be well above the surface of the primary and cannot be responsible for any geometric effects. Frequency doubling of QPOs in KT Per has been reported (Robinson & Nather 1979). The claimed steady decrease in period of QPOs in EF Peg (Kato 2002) is probably more realistically interpreted as an approximate frequency doubling near the middle of the train of oscillations. These may be understood as switches to and from predominantly fundamental and first harmonic excitations of the QPO traveling wave, but the cause for this remains unknown.

10. WZ Sge

WZ Sge is of particular interest because it seems to be an IP while in quiescence and a DNO machine when in outburst, a result of the primary having a magnetic moment almost strong enough to anchor the exterior to the interior. I use "almost" because in quiescence prior to the 1978 outburst, $P/\dot{P} \sim 1 \times 10^5$ yr (see Fig. 7 of Patterson 1980), which is too short a timescale to be a spin- down of the entire primary.

10.1. WZ Sge in Quiescence

The connection between WZ Sge and DNO/QPO phenomena has taken a long time to demonstrate convincingly. Patterson et al. (1998) reviewed the optical observations and added *ASCA* hard X-ray observations showing modulation at 27.87 s, which are characteristic of magnetic channeling onto a white dwarf. *HST* observations also show the dominance of 27.87 s (Skidmore et al. 1999). The observed $v \sin i$ (Cheng et al. 1997) for the primary of WZ Sge leads to a rotation period of 28 ± 8 s, which is in agreement with the magnetic accretor model.

The presence of an additional persistent 28.952 s modulation, which bears no simple relationship to that at 27.87 s, led some workers to suggest that it may be a nonradial oscillation of the primary (e.g., Robinson, Nather, & Patterson 1978). Patterson (1980) originally pointed out that the 28.95 s period could be due to reprocessing of a 27.87 s rotating beam from a thickening of the disk moving in the prograde direction. Lasota, Kuulkers, & Charles (1999) suggested that this reprocessing site could be at the outer rim of the accretion disk, moving at the Keplerian period, but WW2b suggested, in analogy to their findings in outbursting dwarf novae, that the site is near the inner edge of the disk. The existence of the hypothesized disk thickening, moving with a revolution period of 744 s (the beat period between the two short periods), has in fact been directly demonstrated (WW2b). Fourier transforms of some of the light curves show that there is a 744 s period present (it is probably there at all times, but the large variation of amplitude from one cycle to the next makes it difficult to detect in the Fourier transform). In the light curve it appears as recurrent dips of variable depth, the most prominent of which is around orbital phase 0.25 and has been seen in almost all optical curves from the earliest observations (Krzeminski & Kraft 1964). The obscuring source produces the deepest dip when it transits across the bright spot as seen from behind; it does not transit the bright spot when seen from the front, so there is no corresponding deep dip near phase 0.75.

The infrared (*K*-band) light curve of WZ Sge is far less variable than the light curves at shorter wavelengths and is largely due to the modulation caused by viewing the bright spot through an optically thin disk (Skidmore et al. 2002). Interestingly, no QPO dips are seen in the IR (Ciardi et al. 1998; Skidmore et al. 2002), so we deduce that the traveling wave responsible for the QPO dip obscures only the hotter central region of the bright spot, and not the extended cooler region.

To be consistent with the interpretation used earlier, we should classify the 27.87 s modulation as an lpDNO, related to rotation of the main body of the primary, not a DNO. The 27.87/28.95 s pair constitutes a double lpDNO. More specifically, WZ Sge is an IP of the DQ Her subclass (Warner 1995a) but is of lower Q than typical IPs.

10.2. WZ Sge in Outburst

The 2001 superoutburst of WZ Sge provided an opportunity to observe how the short-period oscillations behave during times of greatly increased $\dot{M}$. DNOs were detected only 1 month after the peak of outburst (Knigge et al. 2002, hereafter K2002), and later from 2 to 5 months after peak brightness (Welsh et al. 2003, hereafter W2003). As pointed out by the latter authors, the temperature of the primary fell from 29,000 K to 18,000 K during that time, yet the modulations did not change their character appreciably (this is a characteristic of DNOs rather than white dwarf pulsations).

The earliest observed oscillations (K2002) have periods near 15 s and show changes in amplitude and phase that are characteristic of DNO behavior. There were also weak oscillations with periods near 6.5 s. In the later observations (W2003) the 28.96 s oscillation was present with some stability, but not the 27.87 s one. In addition, there was an 18 s oscillation of lower coherence, characteristic of a DNO.

If we allow that the magnetic field of WZ Sge is barely strong enough to couple the white dwarf's exterior to its interior (i.e., $B \sim 5 \times 10^5$ G), then we would expect that the very large $\dot{M}$ during superoutburst would squash the magnetosphere to the surface of the primary. But field enhancement in the equatorial belt could allow at least some of the accretion to be magnetically channeled. The equatorial belt would start with the spin period of the primary itself (i.e., 27.87 s) and would be spun up from there, perhaps producing the 15 and 18 s DNOs, which appear correlated in the usual way with luminosity of the system. For lpDNOs of 28 s we would expect, from the relationships found for other dwarf novae (§ 3), DNOs at about one-quarter of that period (i.e., 6 s, which is close to the observed 6.5 s DNOs).

Therefore, phenomenologically, WZ Sge behaves in outburst in ways similar to other weakly magnetic dwarf novae. Nevertheless, the appearance of the reprocessed signal at 28.96 s so early in the outburst decline, which implies the existence of the 744 s traveling wave in the model outlined above, requires its excitation process and period to be amazingly robust—and apparently independent of the $\dot{M}$ passing through the inner disk.

11. A CONNECTION WITH X-RAY BINARIES

Many of the phenomena exhibited by CVs also appear in X-ray binaries (XRBs), which have neutron stars and black hole (BH) candidates accreting from companions. Rapid modulations are among the common properties, although in the XRBs the signals appear at hard X-ray energies where the flux is low, and until recently, the oscillations were only detectable in Fourier transforms of many thousands of cycles. An overview of QPOs in XRBs is given by van der Klis (2000).

Some specific similarities to CV behavior are seen in the phase variations in the 5 Hz QPOs in the Rapid Burster (Dotani et al. 1990), the double QPOs at kHz frequencies, and the frequency dependence on accretion luminosity. But a striking result is that the ratio of low- to high-frequency QPOs that appear in the XRBs is close to the value 15 seen in CVs. By considering the CV QPOs and DNOs as low- and high-fre-

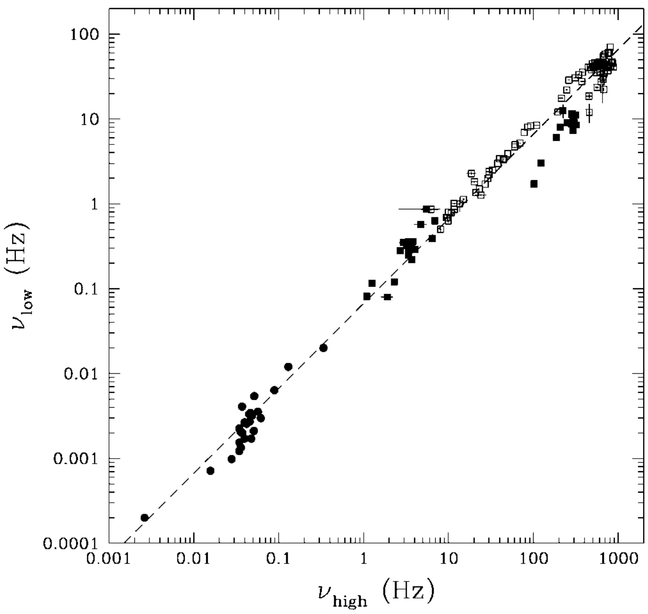

FIG. 15.—Two-QPO diagram for X-ray binaries (*filled squares*, black hole binaries; *open squares*, neutron star binaries) and 26 CVs (*filled circles*). Each CV is only plotted once in this diagram. The X-ray binary data are from Belloni et al. (2002) and were kindly provided by T. Belloni. The dashed line marks $P_{\rm QPO}/P_{\rm DNO} = 15$. (From WWP03.)

quency QPOs, we can place them on the same diagram as XRBs (Fig. 15). The correlation is seen to extend over nearly 6 orders of magnitude in frequency. This does not necessarily mean that exactly the same physics is in operation over the entire range, but certainly the same ratio of timescales appears everywhere.

Furthermore, during X-ray bursts, oscillations that lie between the high- and low-frequency QPOs are often seen. They vary in frequency and are thought to be caused by hot expanding gas on the surface of the neutron star that slips relative to the underlying surface (van der Klis 2000). They are closely related to the rotation period of the star itself and thus resemble the lpDNOs in CVs described in this review.

A recent important development in the study of X-ray binary QPOs is an analysis of the signal in the neutron star system 4U 1608-52 (Barret, Olive, & Kluzniak 2003), in which much higher time resolution has been achieved. What had been thought to be high-frequency (800 Hz) QPOs with $Q \sim 10$ have now been shown to be short (hundreds of cycles) trains of higher Q (>200) cycles and jumps in frequency of up to ~0.5% between the bursts of QPOs. Apart from the implication that the QPO amplitudes are typically several times what had previously been deduced, the high stability for so many cycles eliminates many models of X-ray QPOs (e.g., blobs of accreting gas that would be sheared out of existence after only ~10 cycles). During the phases of high stability the average profile of the QPO is closely sinusoidal.

Consequently, the high-frequency X-ray QPOs now look even more like CV DNOs, with period jumps after ~100 cycles. Among the CVs there are examples of DNOs that are present for only part of the time (i.e., a short duty cycle), but also ones (e.g., VW Hyi just before quiescence) in which a high amplitude is maintained for at least thousands of cycles.

The similarities between CV, neutron star, and BH rapid oscillations may have profound implications. Robertson & Leiter (2003), in gathering evidence that some BHs may have magnetic moments, cite these similarities in their compilation. They reason that BHs forming from magnetic stars are prevented within a Hubble time from reaching their event horizons by the radiation pressure that results from pair creation in the greatly compressed and intensified internal magnetic fields. If this is the case, then magnetic stars collapsing toward the BH end point have observable magnetic moments and hence have more in common with magnetic neutron stars and white dwarfs than has been previously realized.

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