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Absolute magnitudes of cataclysmic variables

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Summary. Absolute magnitudes M_V of the accretion discs (with allowance for effects of inclination) of stars in the principal classes of cataclysmic variable stars are derived from a variety of techniques. For dwarf novae, whose distances are found mostly from infrared observations of their secondaries, a tight relationship is found between M_V(max) at maximum of outburst and orbital period:

$M_V(\mathrm{max})=5.64-0.259\ P(\mathrm{hr})$.

Use of this equation provides M_V(min) at minimum light for further dwarf novae without known distances. For many of these stars it is possible also to derive M_V(mean), averaged over the outburst cycle.

Analysis of this extensive data set discloses that M_V(min) and M_V(mean) are functions of orbital period P and mean time T_n between normal outbursts. T_n is shorter for the brighter systems. The Z Cam stars have M_V(mean) close to the theoretical value for stable (rather than episodic) mass transfer through accretion discs. Above that critical level all observed discs are stable.

An amplitude – T_n (Kukarkin–Parenago) relationship is found to exist for the dwarf novae. Together with the above results it leads, through a simple model for disc instabilities, to a predicted relationship between duration of dwarf nova outbursts and P which is verified by observation.

Absolute magnitudes of classical novae at minimum light, derived from application of the M_V(max) – rate of decline relationship, average M_V=4.4 which is close to the luminosity of dwarf novae during outburst. Nova-like variables have similar luminosities. Together these results suggest the possibility of an upper limit to the rate of mass transfer in an accretion disc.

A scenario is given in which recent suggestions on cyclical evolution through classical novae, dwarf novae and nova-like variables are shown to agree qualitatively with the systematics found here. A relatively short interval ($\sim 10^3$ yr) between successive nova outbursts appears likely.

The Appendix lists cataclysmic variables which are nearer than 300 pc, which should be targets for trigonometrical parallaxes.

1 Introduction

Current studies of cataclysmic variable stars (CVs) are aimed at improving our knowledge of their structure and evolution. Crucial parameters in the modelling of a CV are the rates of mass transfer (i) from the secondary, (ii) through the disc, (iii) on to the white dwarf primary and (iv) out of the system as a whole. Although much can be learned from the overall flux distribution, which, apart from effects of interstellar absorption, is independent of distance, quantitative modelling of the X-ray, UV, visible and IR emissions, the emission-line fluxes and radio frequency flux, requires estimates of the rates of mass transfer which can only be obtained if the distance to the CV is known.

There is still much to be gained from a general survey of absolute magnitudes of CVs, comparing results from the techniques that are common to all CVs and those that are specific to subclasses. Such a survey may help to evaluate the reliability of a particular technique or it may draw attention to systematic differences between techniques; it can also reveal similarities or differences between the various CV subclasses.

Many of the currently known CVs lie at distances $50<d<300$ pc which in principle makes them accessible to trigonometric parallax determinations or at least statistical derivations of group parallaxes from proper motions and radial velocities. Although the faintness of the CVs has deterred efforts of an astrometric nature, it remains the case that any future assistance in distance determinations from this direction will come from the large astrometric reflectors more than from small-aperture astrometric satellites. There has been little improvement in the astrometric data base since 1965 when Luyten & Hughes (1965) found a mean absolute magnitude $M_V \simeq 4$ from proper motions of classical nova (CN) remnants and Kraft & Luyten (1965) found $M_V=7.8\pm0.7$ from proper motions and velocities of dwarf novae (DN). The number of radial velocity measurements for CVs has greatly increased since 1965, but concomitantly there has been a realization of the uncertainties of interpretation of the emission-line profiles which can leave even the systemic velocity ill-determined. For a few of the CVs reliable velocities can be obtained from the absorption-line spectra of the secondaries, but these do not cover all subclasses and all orbital periods. The number of CVs for which the systemic velocity is known to an accuracy of ±5 km s^{-1} is very small.

We will consider a number of other methods of determining distances, always keeping in mind that the motivation is principally that of estimating physically significant parameters such as the rates of mass transfer. There has been a tendency in recent years to reduce the emphasis placed on basic absolute magnitudes in favour of the physical properties of accretion discs. Empirical relationships such as the variation of mass transfer rate in the disc, $\dot{M}_d$, as a function of orbital period P (e.g. Patterson 1984), or the relationship between $\dot{M}_d$ and radius R_d of the accretion disc (e.g. Smak 1982) use derived parameters which are highly model-dependent. It is our philosophy here to retain as far as possible the observational data and empirical calibrations (although some of the latter inevitably are interpretive and model-dependent). The principle is the same as that adopted in studies of colour–magnitude diagrams of clusters: the basic observational V, $B-V$ diagram is presented (or, perhaps, an M_V, $B-V$ diagram , where M_V-V has been obtained from a model-dependent fit to a theoretical main sequence), not transformed to a log L, log T_e diagram through uncertain $M_V(L, T_e)$ and $T_e(B-V)$ relationships. The observational diagram may be calibrated from theoretical interpretations (e.g. lines of constant radius in the M_V, $B-V$ diagram, or lines of constant $\dot{M}_d$ in CV diagrams) but hopefully the underlying observational data remain relatively invariant to improvements in theory.

Three techniques are widely used to obtain absolute magnitudes or distances of CVs. The expansion-parallax method applies only to CN and will be discussed later. From fits of the flux distribution, $\dot{M}_d$ and distances may be obtained. However, the differences between the model fluxes (Williams 1980; Tylenda 1981; Williams & Ferguson 1982; Wade 1982, 1984) and in the fits to the observations (Kiplinger 1979, 1980; Hassall 1985; Berriman, Szkody & Capps 1985), suggest that this method should not be accepted as a fundamental one – it would be preferable to find distances by an independent method and use these to assist the flux modelling.

The third technique, which in principle is applicable to all classes of CVs, depends on observations of the secondary star, which, even though the secondaries in CVs may not be identical to main-sequence stars, may be easier to interpret and calibrate than the disc fluxes. In a few cases the secondary is observable in the visible part of the spectrum (e.g. SS Cyg: Kiplinger 1979) and can provide quite accurate distances. In general, however, the secondary contributes significantly only in the IR and its properties must be deduced from broad-band photometry.

Bailey (1981) pointed out that the surface brightness in the *K*-band of a cool star is insensitive to its temperature or luminosity. *K*-band magnitudes of CVs are, however, contaminated by IR emission from the extensive outer cool regions of the accretion discs. The relative proportions of secondary and disc contributions are not in general unambiguously determined from consideration of the IR colours (Berriman *et al.* 1985) so the distances found from applications of Bailey's method (Bailey 1981; Sherrington & Jameson 1983; Sherrington, Bailey & Jameson 1984; Berriman *et al.* 1985) are often lower limits to the distances, although in general they are thought not to be serious underestimates (Berriman *et al.* 1985).

In a few cases the 'ellipsoidal' (more correctly, Roche distortional) variations of the secondary are detectable in the IR; for such stars the contribution of the secondary is more reliably extracted (but in a model-dependent way, as are almost all of the interpretations of the IR measurements).

Despite the uncertainties inherent in the IR determinations of distances they are currently the most widely applicable and (except for the CN where the expansion-parallax method excels) acceptable distances.

A small number of CVs are members of clusters, moving groups, or have common proper motion companions. For these stars the independent measurements of absolute magnitude therefore available may be used to evaluate the distance scales produced by other means. So far, however, there is little overlap between stars observed by the various techniques, so comparisons can only be made through the systematics of absolute magnitudes among the various CV subclasses.

2 Absolute magnitudes

Bailey's method (Bailey 1981) is based on the equation

$$\log d = \frac{K}{5} + 1 - \frac{S}{5} K + \log (R_2/R_\odot), \tag{1}$$

where S_K is the surface intensity in the *K*-band. To apply this equation we need the radius of the secondary R_2. Berriman *et al.* (1985) were reluctant to apply the results obtained from the Roche geometry of CVs on the grounds that there is evidence (Wade 1981; Young & Schneider 1981) that the secondaries in CVs do not follow the main-sequence mass–radius relationship. However, Patterson (1984) has shown that this belief arose from comparisons of M_2 and R_2 in CVs with *theoretical M–R* relationships for dwarfs, whereas observationally there is good agreement between the *empirical M–R* relationship for the main sequence and that found for CVs. Consequently equation (1) can be supplemented with Patterson's empirical equation

$$R_2/R_\odot = 0.427\, P_4^{1.073} \qquad (P_4 = P/4 \text{ hr}) \tag{2}$$

which is applicable for $P \lesssim 6.5$ hr, where P is the orbital period. Also for $P \lesssim 6$ hr it is possible to take $S_K=4.55$, in which case equations (1) and (2) give

$$\log d\,(\mathrm{pc})=\frac{K}{5}-0.93+1.073\log P(\mathrm{hr}) \qquad P<6.5\ \mathrm{hr}. \tag{3a}$$

For $P \gtrsim 6.5$ hr, however, S_K is not independent of spectral type. From Bailey's (1981) fig. 1 and the calibrations given by Patterson (1984) we find

$$S_K \simeq 10.31-7.81\log P(\mathrm{hr}) \qquad 12 \gtrsim P \gtrsim 5.5\ \mathrm{hr}$$

and

$$R_2/R_\odot=0.113\,P(\mathrm{hr})$$

and therefore

$$\log d\,(\mathrm{pc})=\frac{K}{5}-2.14+2.56\log P(\mathrm{hr}) \qquad 12>P>6.5. \tag{3b}$$

To progress from a distance estimate to the absolute magnitude of a CV – particularly if what is wanted is the absolute magnitude of the accretion disc alone – a number of additional data and corrections are required. To apply equation (3) we need the orbital period or a good approximation to it. For those systems where P has not been directly measured an estimate may be obtained from the *UBV* colours at minimum (Echevarria & Jones 1984) or at maximum (Vogt 1981) or from the rate of decline of dwarf nova outbursts (van Paradijs 1983) or from other correlations between outburst properties of dwarf novae and their orbital periods (Szkody & Mattei 1984).

Apparent magnitudes at maximum light, minimum light or standstill (for Z Cam stars) are not all immediately available in catalogues. For our purposes mean visual magnitudes for each of the above states would be preferable. The compilation of photoelectrically measured magnitudes given by Bruch (1984) must be used with circumspection as some measurements are averages over long time bases, whereas others are short time averages or even individual observations. For most dwarf novae magnitudes are best obtained from the long-term observations of the AAVSO or the Variable Star Section of the RAS of New Zealand. All too often the only magnitudes available are the photographic determinations in the *General Catalogue of Variable Stars* (Kholopov 1985) which does not, for example, distinguish between ordinary and supermaxima in SU UMa Stars. In many of our applications we are aided by the fact that $B-V \sim 0$ at maximum of outburst of CVs, so $m_{pg} \sim m_V$ at this time, and the range of outburst $m_V(\mathrm{min})-m_V(\mathrm{max})$ is independent of interstellar absorption A_V. Values of A_V that have been measured photoelectrically are given by Bruch (1984) and Duerbeck (1981).

Allowing for projected area and limb darkening, the correction to be made to produce the (apparent) visual absolute magnitude of an optically thick disc from its direction-average luminosity is (Paczynski & Schwarzenberg-Czerny 1980):

$$\Delta M_V(i)=-2.5\log\left(1+\tfrac{3}{2}\cos i\right)\cos i, \tag{4}$$

where we have used a limb darkening coefficient of 0.6. Equation (4) fits well the model calculations of Mayo, Wickramasinghe & Whelan (1980). It gives $\Delta M_V(56\overset{\circ}{.}7)=0$ and $\overline{\Delta M_V}=-0.367$ (averaged over all inclinations) $=\Delta M_V(44°)$.

To apply equation (4) an estimate of i is required, which is variously obtained from observed eclipses, amplitude of radial velocities or orbital modulation of brightness. The correction factor $\Delta M_V(i)$ is an important factor in determining the true absolute magnitudes of disc-dominated systems; the apparent magnitude of a system viewed at 0° inclination is 3½ magnitudes brighter than the same system seen at $i=85°$.

If we want the brightness of the disc alone then at minimum light we may need to subtract the contribution of the secondary, white dwarf and/or the bright spot. Where the contribution of the secondary is not directly measurable (e.g. from its presence in the spectrum) an estimate may be formed of how important it might be from use of

$$M_V(2)=22.0-17.46 \log P(\mathrm{hr}) \tag{5}$$

(Patterson 1984), which gives the absolute magnitude of the secondary for $10 \geqslant P \geqslant 4$ hr (and which agrees well with a similar equation given by Warner 1976) and, for the disc,

$$M_V=\bar{M}_V+\Delta M_V(i) \tag{6}$$

where $\bar{M}_V$ is the mean absolute magnitude for the CV subclass. Anticipating the results found later, equations (5) and (6) imply that the secondary will be at least one magnitude fainter than the disc if

$\log P(\mathrm{hr}) \leqslant 0.95-0.057\,\Delta M_V(i)$ for CN remnants, nova-like variables and for DN at maximum

and

$\log P(\mathrm{hr}) \leqslant 0.68-0.057\,\Delta M_V(i)$ for DN at minimum.

3 Absolute magnitudes from surface intensities

Before applying the above methods to individual CVs we explore the possibility of employing the surface intensity approach of Wesselink (1969) to CV discs. For stellar atmospheres Wesselink gave the relationship [analogous to equation (1)]

$$M_V=S_V+15.15-5 \log R/R_\odot, \tag{7}$$

where S_V is the surface brightness in the V-band. From Wesselink's calibration data for S_V, Warner (1972) found

$$S_V=3.65\,(B-V)_0-12.56 \qquad \text{for } -0.1<(B-V)_0<1.9. \tag{8}$$

In an ideal world it would be possible to recalibrate the relationships expressed in equations (7) and (8) by appeal to CV discs of known radius and over a range of $(B-V)_0$, but in the absence of reliable data* we adopt the stellar atmospheres results expecting that some systematic errors may emerge.

Assuming that equation (7) applies to an optically thick disc we note that as a similar inclination correction is to be made to each side [$\Delta M_V(i)$ to M_V and $\cos i$ to the R^2 factor] it is insensitive to i. The disc radius R_d is calculated from $R_\mathrm{d}=0.70\ R_\mathrm{L}$ (Sulkanen, Brasure & Patterson 1981), where R_L is the mean radius of the Roche lobe of the primary. This result appears to be widely applicable to the CVs; in general there are no large changes in R_d during outbursts. For example, the disc radii measured at quiescence and outburst in Z Cha and OY Car agree closely with equation (10) below (Cook & Warner 1984; Cook 1985a, b; O'Donoghue 1986); however, although in U Gem (Smak 1984) the disc radius at quiescence agrees with equation (10), it is ~35 per cent larger at maximum of outburst and almost completely fills the Roche lobe of the primary. If this is a common occurrence among the DN with longer orbital periods then our combination of equations (7) and $R_\mathrm{d}=0.70\ R_\mathrm{L}$ will underestimate their brightness at maximum light.

For mathematical convenience we adopt the approximate expression for R_L (Warner 1976):

$$\frac{R_\mathrm{L}}{a}=0.46\,(1+q)^{-1/3} \tag{9}$$

*Wade's (1984) model discs show a tight relationship between S_V and colour, as required by equations (7) and (8) but cannot be used for purposes of calibration as his disc flux distributions do not match the observed values of $B-V$.

Table 1. Absolute magnitudes of dwarf novae.

Star	Type	P(h)	d(pc)	m_V(max)	m_V(min)	i°	M_V(i)	A_V	M'_V(max)	M_V(max)	Δ	M_V(min)	m_V(mean)	$M_V{}^+$(mean)
T Leo	SU	1.41	>110	10:	15.5	<50	−0.6:	(0)	<4.8:	<5.4:	0.2	<11.1:		
OY Car	SU	1.51	100	11.9	15.6	80	1.65	(0)	6.9	5.3	0.2	9.1	14.5	8.7
EX Hya	SU?	1.64	105	11.7	13.6	75	1.11	0	6.6	5.5	?	>>7.4		
IR Gem	SU	1.70	>250:	11.7	15.5	50	−0.25	(0)	<4.7	<5.0	0	<8.8		
Z Cha	SU	1.79	130	12.5	16.0	82	1.94	0	6.9	4.9	0.3	8.8	15.9	8.5
SU UMa	SU	1.83	280	12.2	14.8	44	−0.43	(0.1)	4.9	5.3	0	7.9	13.6	6.7
YZ Cnc	SU	2.10	290	11.9	14.5			0	4.6				13.3	
TU Men	SU	2.82	270	12.5	16.6	65	0.40	0.24	5.1	4.7*	0	8.8	15.2:	7.4:
IP Peg	UG	3.80	124	12.3	15.8	85:	2.5:	(0)	6.8	4.3:	0	7.8:		
X Leo	UG	3.94	>345	12.1	15.6	45	−0.41	(0.2)	<4.2	<4.6	0	<8.1		
U Gem	UG	4.17	81	9.4	14.6	67	0.52	0	4.9	4.3	0.1	9.6	13.2	8.1
CW Mon	UG	4.23	290	12.5	16.0	65	0.40	(0.2)	5.0	4.6	0	8.1	14.5:	6.6:
SS Aur	UG	4.38	200	10.5	14.7	32:	−0.7:	0.1	4.0:	4.7*	0	8.9	13.2	7.4
TW Vir	UG	4.38	455	12.1	15.5	43	−0.46	0	3.8	4.3	0	7.7	14.1	6.3
RX And	ZC	5.08	135	10.9	13.6	65:	0.4:	0.2	5.0	4.6	0	7.3	11.8	5.5
BX Pup	ZC	(5.9)	750	13.8	15.7			0.12	4.3*					
AH Her	ZC	6.19	250	11.3	14.3	46	−0.38	0.09	4.3	4.5	0.2	7.6	12.3	5.6
TZ Per	ZC	(6.5)	275	12.5	14.1			0.72	4.6		(0.2)		13.2	4.7++
UZ Ser	UG	(6.6)	300	12.1:	15.6	50:	−0.2:	0.96	3.8:	4.0*:	(0.2)	7.7		
SS Cyg	UG	6.63	76	8.2	11.7	30	−0.75	(0.2)	3.6	4.3	0.5	8.4	10.4	6.5
Z Cam	ZC	6.96	173	10.4	13.6	60	0.14	0.06	4.1	4.0	0.5	7.7	11.7	5.3

EM Cyg	ZC	7.00	350	12.0	14.2	63	0.29	0	4.3	4.0	1.0:	7.2:	12.9	4.9
KT Per	ZC	(7.1)	300	11.7	14.8	65:	0.4:	0.45	3.9	3.5:	(0.3)	6.9:	13.2	5.0:
RU Peg	UG	7.79	174	9.0	12.7	32	-0.71	0.15	2.6	3.4*	0.7	7.4	12.2	6.6
SY Cnc	ZC	9.1:	450:	11.1	13.7	50:	-0.25:	0	2.8	3.1:*	0.7	6.4:	12.2	4.2:

m_V(max) are for ordinary (not super) maxima of the SU UMa stars. Uncertain data are indicated by colons. Estimated values appear in brackets.

*Distance not derived from IR photometry of secondary.

+For the ZC stars m_V(mean) and M_V(mean) are for standstill.

++Derived assuming validity of equation (13).

Notes:

T Leo — *d* and m_V (min) from Shafter & Szkody (1984), who also give 28°<*i*<65° and state that the lower end of the range is the most probable.
OY Car — *d* from Sherrington *et al.* (1982); *i* from Berriman (1984).
EX Hya — *d* from *K* of Berriman *et al.* (1985) and equation (3); *i* from Ritter (1984). EX Hya is an intermediate polar (Warner 1983) in which a substantial fraction of the light at minimum is contributed by an accretion column.
IR Gem — *d* from *K* of Szkody & Mateo (1986) and equation (3); m_V(min) and *i* from Szkody, Shafter & Cowley (1984).
Z Cha — *d* from *K* of Bailey (1981) and equation (3); *i* from Cook & Warner (1984). m_V(min) excludes the optical companion (Wood *et al.* 1986).
SU UMa — *d* from *K* of Berriman *et al.* (1985) and equation (3); *i* from K_1=58 km s^{-1} (Thorstensen, Wade & Oke 1987). m_V(min) from Oke & Wade (1982).
YZ Cnc — *d* from *K* of Berriman *et al.* (1985) and equation (3); A_V from Szkody (1981). Magnitudes from Patterson (1981) – those listed by Bruch (1984) disagree with other observations.
TU Men — *d* and *i* from Stolz & Schoembs (1984) from fit of Balmer line profiles during outburst, m_V(min) from appearance on finding chart (Vogt & Bateson 1982).
IP Peg — *d* from *K* of Szkody & Mateo (1986) and equation (3); *i* from Wood & Crawford (1986).
X Leo — *d* from *K* of Szkody & Mateo (1986) and equation (3); *P* and *i* from Shafter (1986, private communication).
U Gem — *d* from *K* of Bailey (1981) and equation (3); *i* from Smak (1976).
CW Mon — *d* from *K* of Szkody & Mateo (1986) and equation (3); *i* from the same authors.
SS Aur — *d* from Hyades Moving Group parallax (Eggen 1968), which is consistent with *d*>152 pc from the *K*-magnitude (Szkody & Mateo 1986); *i* from Ritter (1984).
TW Vir — *d* from *K*-magnitude of Berriman *et al.* (1985) and equation (3); *i* from Shafter (1983a); A_V from Hassall (1985).
RX And — *d* from *K* of Berriman *et al.* (1985) and equation (3); *i* from Clarke & Bowyer (1984).

Table 1–*continued*

BX Pup	d from membership of NGC 2482 (Moffat & Vogt 1975). P from Vogt (1981).
AH Her	d from K of Berriman *et al.* (1985) and equation (3); m_V(max) from average of Bruch (1984) and Mattei (1986, private communication); i from Horne, Wade & Szkody (1986).
TZ Per	d and P from Sherrington & Jameson (1983); A_V from Hassall (1985); m_V(standstill) from Matei (1986, private communication); m_V(min) from Mumford (1966).
UZ Ser	d from location in dark cloud and deduced reddening parallax (Schmidt-Kaler 1962); i and A_V from Hassall (1985); P from Vogt (1981).
SS Cyg	d from K of Berriman *et al.* (1985) and equation (3); i and Δ from Kiplinger (1979).
Z Cam	d from K of Berriman *et al.* (1985) and equation (3); i from Kiplinger (1980). Δ from Szkody (1981).
EM Cyg	d from Bailey (1981); i from Stover, Robinson & Nather (1981); A_V and Δ from Szkody (1981).
KT Per	d and P from Sherrington & Jameson (1983); m_V(max) from Mattei (1986, private communication); A_V from Hassall (1985).
RU Peg	d from cpm companion (Eggen 1968); i from similarity of P and velocity amplitude (Stover 1981) to SY Cnc (Shafter 1983b); Δ from Stover (1981).
SY Cnc	The K-magnitude of the secondary is poorly determined as it contributes only a very small fraction of the flux (Berriman *et al.* 1985). Our value of d is based on the observation of Szkody (1981) and the calibration of M_V of the secondary as a function of P (Patterson 1984). A_V and Δ are from Szkody (1981); i is determined from consideration of the radial velocity amplitude (Shafter 1983b) and the presence of orbital modulation in the photometry (Patterson 1981).

where $q=M_2/M_1$ and a is the separation of the stars. From Kepler's Third Law we have

$$R_d=0.7R_L=1.14\times10^{10}\,(M_1/M_\odot)^{1/3}P(\mathrm{hr})^{2/3}\quad \mathrm{cm}. \tag{10}$$

From equations (7), (8) and (10) we have

$$M_V=3.65\,(B-V)_0+6.53-\frac{5}{3}\log\left(\frac{M_1}{M_\odot}\right)-\frac{10}{3}\log P(\mathrm{hr}). \tag{11}$$

An application of this equation to dwarf novae is given in the next section.

4 Application to dwarf novae

4.1 DWARF NOVAE WITH DISTANCE DETERMINATIONS

The data collected in Table 1 represent the best available body of observations from which to calculate absolute magnitudes. Most of the distances are based on IR photometry of the secondaries, but we have available a few distances found by other means.

Magnitudes uncorrected for disc inclination are calculated from

$$M'_V(\max)=m_V(\max)+5-5\log d-A_V. \tag{12}$$

Corrected absolute magnitudes are $M_V(\max)=M'_V(\max)-\Delta M_V(i)$, and at minimum light $M_V(\min)=M_V(\max)+m_V(\min)-m_V(\max)+\Delta$, where Δ is the correction in magnitudes required to remove the contribution of the secondary and the bright spot. That is, $M_V(\min)$ refers here to the *disc luminosity*. The contribution of the bright spot is estimated from the amplitude of the orbital brightness modulation; it is not required if $M_V(\min)$ is obtained from detailed light curves where the 'hump' caused by the bright spot may be avoided, and it is assumed to be unimportant for $i\leqslant70°$.

The most striking aspect of Table 1 is the systematic increase of brightness of $M_V(\max)$ with increasing orbital period: at the shortest periods ($P\sim1\frac{1}{2}$ hr) $M_V(\max)\sim5.3$ and at $P\sim7$ hr $M_V(\max)\sim4.0$. From a much smaller sample of stars, Vogt (1981) suspected that all DN have the same absolute magnitude at maximum and gave $M_V(\max)=4.70\pm0.14$, which is near the centre of gravity of our distribution of $M_V(\max)$.

The variation of $M_V(\max)$ with P is illustrated in Fig. 1. It may be seen that the $M_V(\max)$ derived from non-IR methods agree in size and trend with the K-magnitude distances. This provides us with confidence that the contributions of the secondaries and the accretion discs have been separated with considerable success and that effects of underestimation of distance (Berriman *et al.* 1985) are not serious.

A linear least squares fit to the $M_V(\max)$ of Table 1 gives

$$M_V(\max)=\underset{\pm0.13}{5.64}-\underset{\pm0.024}{0.259}\,P(\mathrm{hr}) \tag{13}$$

and the rms scatter about that relationship is ±0.23 mag.

Before applying this relationship to other DN we investigate the possibility that it arises from selection effects. Could it be the case, for example, that we are merely detecting the *faintest* accretion discs and that in reality there is an upward spread in luminosity in Fig. 1, but the brighter discs are not represented because they prevent detection of the secondary in the IR? Against this, it should be noted that most of the easily observable (apparently bright) DN with $4\leqslant P\leqslant7$ hr are present in Fig. 1 and these do not show a large range of $M_V(\max)$. Even at short periods, where it might be expected that the systems would have to be of very high inclination to allow the intrinsically fainter secondaries to be detected at K, there is no evidence for strong selection: in

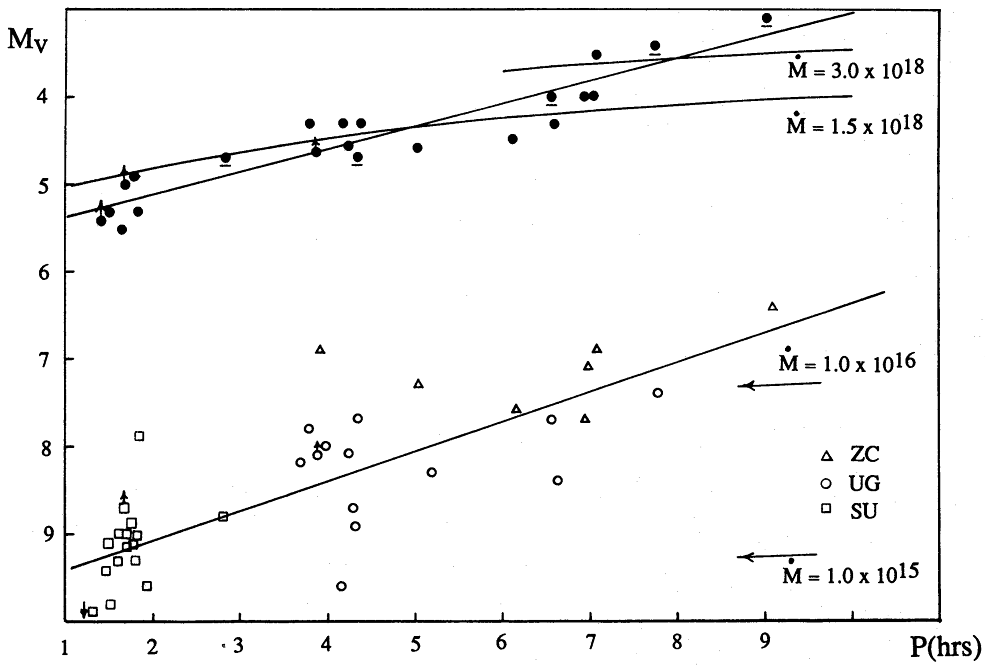

Figure 1. Absolute magnitudes of the accretion discs of dwarf novae at maximum of outburst and at minimum light as a function of orbital period. The symbols as defined here for Z Cam, U Gem and SU UMa stars are used in Figs 2–5. Underlined solid circles for M_V (max) indicate that distances were not obtained from the K-magnitude method. Lines of constant rate of mass transfer through the disc $\dot{M}$ are indicated. The linear fits to the points are those of equations (13) and (18).

both Z Cha and OY Car the secondary completely dominates in the K-band (Bailey 1981; Sherrington *et al.* 1982) and the discs could be up to two magnitudes brighter (as is the case in SU UMa: Table 1) without preventing detection of the secondary.

That we should look closely for selection effects is shown by the following equation, obtained from combining equation (3a) with the equation defining absolute magnitude:

$$M'_V(\mathrm{max})=m_V(\mathrm{max})-K(\mathrm{secondary})+9.65-5.36\log P(\mathrm{hr}). \qquad (14)$$

This shows that if $M_V(\mathrm{max})-K$ were for any observational reason restricted to a small range, then $M'_V(\mathrm{max})$ would inevitably show a trend with P. Evaluation of $m_V(\mathrm{max})-K$ from the data of Table 1 and of Berriman *et al.* (1985) shows that it ranges from ~0.5 to −6 and, although there is a correlation such that the most negative values of $m_V(\mathrm{max})-K$ occur at the shortest orbital periods, there is a spread ~2 mag at any given P. It is this spread that is greatly reduced by applying the corrections A_V, $\Delta M_V(i)$ and Δ to give the final $M_V(\mathrm{max})$. This observational spread shows that it is unlikely that the tight correlation between $M_V(\mathrm{max})$ and P seen in Fig. 1 arises from difficulties of detecting the secondary in the presence of the disc [which would limit values of $m_V(\mathrm{min})-K$ and thereby cause some restriction on values of $m_V(\mathrm{max})-K$].

It should be noted en passant that equation (14) shows that for those CVs without known orbital periods, an accurate guess of P is required before the K-magnitude method may be used: a 20 per cent uncertainty in P transforms into an uncertainty of ±0.23 mag in $M'_V(\mathrm{max})$.

A completely independent method of estimating $M_V(\mathrm{max})$ is provided by the surface brightness technique. Vogt (1981) found a strong correlation between dereddened UBV colours of DN at outburst and their orbital period:

$$(B-V)_0=\underset{\pm 0.0056}{0.0293}\,P(\mathrm{hr})-\underset{\pm 0.030}{0.130} \qquad 1\tfrac{1}{2}<P<9\ \mathrm{hr}. \qquad (15)$$

Although from model discs $(B-V)_0$ must be a function of i (Mayo *et al.* 1980), equation (15) should represent an average over i, probably weighted towards lower inclinations which, from equation (4), produce brighter systems at maximum light than highly inclined systems.

Equations (11) and (12) give

$$M_V(\max)=0.107\ P(\mathrm{hr})-\frac{10}{3}\log P(\mathrm{hr})-\frac{5}{3}\log\left(\frac{M_1}{M_\odot}\right)+6.06. \quad (16)$$

Adopting $M_1=0.9\ M_\odot$ (Ritter & Burkett 1986) we have the following $M_V(\max)$:

P (hr)	2	3	4	5	6	7	8	9	10
$M_V(\max)$	5.35	4.87	4.56	4.34	4.18	4.07	3.98	3.92	3.87

Over most of the range of P these are close to what is obtained from Fig. 1 or equation (13). The reasonable accord of the surface brightness method with the independently determined $M_V(\max)$ suggests that the calibration effects that we ignored in deriving equation (11) (e.g. the non-uniform distribution of temperature over the disc and the different averaging processes over a disc and a sphere) have largely compensated each other.

According to Vogt (1981), equation (15) applies equally well to DN at maximum and Z Cam (ZC) stars at standstill. Although many of the $(B-V)_0$ may not have been observed exactly at maximum, and are therefore representative of slightly fainter magnitudes, there is on average ± 1.0 mag difference between maximum and standstill magnitudes (Table 1). Equation (16) appears therefore to give magnitudes which are too bright for the ZC stars in standstill. In reality, however, the radii of DN accretion discs at maximum may be larger than at standstill (our earlier discussion of U Gem suggests this); then through equation (7) M_V(standstill) will be fainter than $M_V(\max)$ even for identical $(B-V)_0$. The basic problem is that we do not yet have sufficient observational data to determine the $R_d(P)$ relationship separately for maximum, standstill and quiescence; equation (10) is an average over these states. In consequence, application of equation (11) is not able to distinguish between different outburst states of CV accretion discs.

4.2 DWARF NOVAE WITHOUT DISTANCE DETERMINATIONS

The correlation between $M_V(\max)$ and P for DN can be used to give $M_V(\min)$ for any DN with known orbital period. We make use of the fact that

$$M_V(\min)=M_V(\max)-m_V(\max)+m_V(\min)+\Delta \quad (17)$$

independent of A_V and $\Delta M_V(i)$. The correction Δ, however, must be applied when required. If, in addition, we have some estimate of i and A_V then a distance can also be derived.

Table 2 gives information for DN with orbital periods from Patterson (1984) and Ritter (1984) and other data from sources listed in the supplementary notes. With the exception of WW Cet*, the $M_V(\min)$ derived from assuming that equation (13) applies to all DN are also plotted in Fig. 1.

*The classification of WW Cet is problematical. It is listed as nova-like (ZC?) by Patterson (1984), as DN (ZC) by Ritter (1984) and as an SU UMa star by Bateson (1979). Ritter gives $m_V(\min)=15.0$–15.7, $m_V(\mathrm{standstill})=13.9$ and $m_V(\max)=9.3$. As is seen from Table 2, adopting this interpretation of the magnitudes leads to $M_V(\min)$ and M_V(standstill) that are too faint relative to other ZC stars. If instead we reassign the $m_V=13.9$ level to $m_V(\min)$ then we have $M_V(\min)=9.2$, which is a more acceptable result. This reinterpretation of the light curve of WW Cet implies that the star is a DN with quiescent magnitude 13.9, outbursts to magnitude 9.3 and occasional low states of 15.0–15.7. As such it could represent an important link between the normal DN, none of which is known to have a low state, and the subclass of nova-like variables known as MV Lyrae stars.

Table 2. Absolute magnitudes and distances of additional dwarf novae.

Star	Type	P(h)	m_v(max)	m_v(min)	i°	ΔM_v(i)	A_v	$M_v{}^*$(max)	M_v(min)	d(pc)	m_v(mean)	M_v(mean)
SW UMa	SU	1.36	10.8	16.5	50	-0.25	(0)	5.3	11.0	140	16.0	10.5
V436 Cen	SU	1.50	11.9	16.0	45:	-0.4:	0.42	5.3	9.4	210	15.1	8.5
EK TrA	SU	1.53	12.0	16.6:				5.2	9.8:			
RZ Sge	SU	1.64	12.8	16.9				5.2	9.3		16.6	9.0
AY Lyr	SU	1.75	13.2	17.0				5.2	9.0		15.9	7.9
HT Cas	SU	1.77	12.6	16.5	76	1.20	(0.1)	5.2	9.1	165	16.1	8.7
VW Hyi	SU	1.78	9.4	13.3	60	0.14	(0)	5.2	9.1	65	12.7	8.5
WX Hyi	SU	1.79	11.8	14.7	<40	-0.7	(0.2)	5.2	8.1	265	13.7	7.1
CU Vel	SU	1.85	11.4	15.5				5.2	9.3		15.2	9.0
TY Psc	SU	1.85	12.2	16.0:				5.2	9.0:			
TY PsA	SU	1.97	12:	16.5	65	0.40	(0.2)	5.1	9.6:	190:		
WW Cet	ZC?	3.83	9.3	15.7	40	-0.54	0.19	4.6	11.0^+	100	13.9	9.2
CN Ori	ZC	3.91	11.9	14.2	50:	-0.25	(0.2)	4.6	6.9	295	12.8	5.5
CZ Ori	UG	(4.0)	12.1	15.5				4.6	8.0		14.3	6.8
BD Pav	UG	4.30	12.4	16.6				4.5	8.7		15.8	7.9
HL CMa	UG	5.20	10.5	14.5	45	-0.41	(0)	4.3	8.3	210		

*Assumed. ⁺Not plotted in Figure 1: see text.

4.3 M_V(MIN) FOR DWARF NOVAE

The least squares linear fit to the 33 stars with M_V(min) listed in Tables 1 and 2 is

$$M_V(\text{min}) = \underset{\pm 0.25}{9.72} - \underset{\pm 0.056}{0.337}\, P(\text{hr}) \tag{18}$$

and the rms scatter about this relationship is ±0.70 mag.

Current ideas on the evolution of CVs (e.g. Verbunt & Zwaan 1981; Patterson 1984) suggest that below the period gap ($2.2<P<2.8$ hr) CVs have low mass transfer rates because they are driven by loss of angular momentum via gravitational radiation, whereas above the gap magnetic braking provides the loss and much higher rates of mass transfer occur. In this case, in producing equation (18) we may suspect that we are merely connecting a group of points with large M_V(min) below the gap to a spread of points with smaller M_V(min) above the gap and there may not be the smooth relationship implied by equation (18).

In order to test this point we considered only those DN with $P>2.8$ hr and found the following least squares linear fit to the data:

$$M_V(\text{min}) = \underset{\pm 0.54}{9.48} - \underset{\pm 0.095}{0.30}\, P.$$

As only 19 stars are used this relationship is not well determined but its extrapolation to shorter periods passes close to the centre of the cluster of points with $P<2$ hr in Fig. 1.

From the M_V(min) listed in Tables 1 and 2 we find that the average $\bar{M}_V(\text{min}) = 8.4 \pm 1.0$, which is close to the result $\bar{M}_V(\text{min}) = \bar{M}'_V(\text{min}) - \overline{\Delta M_V(i)} = 8.2 \pm 0.7$ obtained by Kraft & Luyten (1965). It is now evident that the large spread in M'_V(min), already remarked upon by Kraft & Luyten in 1965, is caused by the systematic variation of M_V(min) with orbital period, the range of M_V(min) at a given P, and the need to apply the correction ΔM_V(min).

In Fig. 1 it can be seen that M_V(min) for the ZC stars is systematically brighter than the U Gem (UG) stars. The difference, $\bar{M}_V(\text{UG, min}) - \bar{M}_V(\text{ZC, min}) \simeq 0.6$ mag.

4.4 MASS TRANSFER IN DWARF NOVAE

The accretion discs of dwarf novae at their maximum luminosity during outburst are optically thick and may approximate models of steady-state discs. This provides us with an opportunity to

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Notes to Table 2:

SW UMa i from Shafter (1983c).
V436 Cen i from Gilliland (1982a).
EK TrA m_V(max) from Bateson (1976).
AY Lyr m_V(max) from Danskin & Mattei (1978); m_v(min) from GCVS (Kholopov 1985).
HT Cas i from Young, Schneider & Schectman (1981a).
VW Hyi i from Ritter (1984); magnitudes from Bateson (1973).
WX Hyi i from absence of orbital brightness modulation (Bailey 1979; Warner, unpublished).
CU Vel m_V(max) from Bateson (1977).
TY Psc m_V(min) is very uncertain.
TY PsA i from shallow eclipses observed at end of outburst (Barwig *et al.* 1982; Warner & O'Donoghue, unpublished).
WW Cet i from Thorstensen & Freed (1985).
CN Ori i from orbital modulation but absence of eclipses (Schoembs 1982).
CZ Ori P from Szkody & Mattei (1984).
HL CMa i from Hutchings, Crampton & Cowley (1981).

calibrate the absolute magnitudes in Table 1 as a function of $\dot{M}_d$, the rate of mass transfer through the disc.

The absolute visual magnitude M_V of a model disc is a function of many variables (e.g. Lynden-Bell & Pringle 1974):

$$M_V = M_V(\dot{M}_d, M_1, R_1, R_d). \quad (19)$$

Adopting an M_1–R_1 relationship for white dwarfs, choosing $M_1 = 1M_\odot$, for which most published computations of discs have been performed, and using equation (10) we have

$$M_V = M_V(\dot{M}_d, P) \quad (20)$$

which we can invert in order to find $\dot{M}_d = M(M_V, P)$, i.e. $\dot{M}_d$ as a function of position in the observational diagram, Fig. 1.

Computations of discs have been made for a variety of purposes. The only ones usable here are those which provide $M_V(\dot{M}_d, R_d)$ directly (Tylenda 1981) or with a small amount of additional calculation (Wade 1984). For our purposes we have had to extrapolate these computations to larger values of $\dot{M}_d$. In addition, as the grids of models do not cover sufficient values of both $\dot{M}_d$ and R_d, we have assumed $M_V(\dot{M}_d, R_d) = M_V(\dot{M}_d) + F(R_d)$, where $F(R_d)$ is determined from the models made for a specified $\dot{M}_d$ and assumed to apply to other, not greatly differing, values of $\dot{M}_d$.

We have used an extrapolation of the $M_V(\dot{M}_d)$ relationship given by Tylenda and obtained the function $F(R_d)$ from Wade's (Kurucz) models to derive $M_V(\dot{M}_d, R_d)$ and hence $M_V(\dot{M}_d, P)$. In Fig. 1 the line $M_V(P)$ obtained for $\dot{M}_d = 1.5 \times 10^{18}$ g s^{-1} $= 2.4 \times 10^{-8}$ $M_\odot$ yr^{-1} is seen to represent the observed M_V(max) quite well for $P < 7$ hr. The slope of the theoretical line is a result of the variation of M_V with R_d which, from Wade's most luminous models, is $M_V \simeq \text{const} - \log R_d^2$ and hence most of the increase in M_V from $P = 9$ to $P = 1\frac{1}{2}$ hr is accounted for by this effect alone. It should be noted, however, that we have used $M_1 = M_\odot$ throughout. If the shortest period DN have systematically smaller primary masses (e.g. Ritter & Burkett 1986) then this would increase M_V for this group relative to longer periods and it is possible that $\dot{M}_d = \text{const}$ will describe M_V(max) very well.

This suggests that mass stored in the disc [in the disc instability model of Osaki (1974) and Hoshi (1979)] or in the secondary star [in the modulated mass transfer model of Bath (1969)] in the intervals between outbursts, may be transferred through the disc during outburst at a rate which has a previously unsuspected upper limit.

At minimum light the large spread of M_V(min) precludes an exact description of the variation of $\dot{M}_d$ with P. However, conversion of equation (18) gives

$$\log \dot{M}_d(\text{min}) \simeq 14.9 + 0.15\, P(\text{hr}) \quad (21)$$

for $M_1 = M_\odot$, which shows that above the period gap mass transfer rates average about 10 times those below.

The conversion from M_V to $\dot{M}_d$ would be made more secure if further models were available, thus eliminating the extrapolations and interpolations found necessary here.

4.5 STABILITY OF ACCRETION DISCS

In the disc instability model of dwarf novae, material is stored in the disc between outbursts; therefore at quiescence $\dot{M}_d \neq -\dot{M}_2$. The model does, however, show that the mass loss rate from the secondary can be obtained from $-\dot{M}_2 \sim \dot{M}_d(\text{quiesc}) \times Q$, where Q is the correction factor which results from including $\dot{M}_d$(outburst) averaged over time. Patterson (1984) has given Q-values for a number of systems [note that his Qs are not always calculated with respect to m_V(min)], obtained from averaging their light curves over a number of outbursts. As defined here, the Q-values are to be applied to M_V(min), i.e. with the contributions Δ of the secondary and bright spot removed. Where the latter are significant contributors, and Q-values are measured relative to the observed m_V(min) of the system, then $Q=Q(\text{system})\times 10^{-0.4\Delta}$.

For the SU UMa stars, where we will require M_V(mean) for the light curves averaged only over the ordinary outbursts (i.e. without inclusion of supermaxima), we modify Patterson's Q-values according to the prescription given in Section 4.6.

For Z Cam stars there is evidence (Zuckerman 1954; Warner 1976) that the time-averaged flux for periods when normal outbursts are occurring is close to the flux at standstill. For these stars we adopt Q(standstill)=1, or $-\dot{M}_2=\dot{M}_\text{d}$(standstill).

In the context of our present investigation it may be noted that the Q-values are in principle purely observational quantities, not dependent on models. Although not directly observable in other than Z Cam stars, the time-averaged magnitude $m_V(\text{mean})=m_V(\text{min})-2.5\log Q$ [$=m_V$ (standstill) for ZC stars] is an observational quantity open to theoretical evaluation. Estimates of m_V(mean) are included, where available, in Tables 1 and 2, together with the deduced M_V(mean). The latter are plotted in Fig. 2.

Unlike the small scatter in M_V(max), the M_V(mean) in Fig. 2 show a large range at any P, with a trend towards higher luminosity at longer orbital periods that is steeper than that for M_V(min) in Fig. 1. This steepening arises from the tendency for the systems with longer orbital periods to have large Q-values, as can be seen from inspection of the values of $m_V(\text{min})-m_V(\text{mean})$ in Tables 1 and 2.

The ZC stars in Fig. 2 form what could be construed as an upper envelope to the M_V(mean) for $P>3$ hr. It has long been hypothesized (see Warner 1976) that Z Cam stars at standstill are DN stuck temporarily in an outburst condition. In the disc instability model of DN outbursts there is a critical $\dot{M}_\text{d}$ for a given size of disc, above which stable rather than intermittent mass transfer occurs (e.g. Smak 1982). The conclusion is that whereas the UG subset of the DN have $|\dot{M}_2|$ too small to satisfy the condition, in ZC stars the situation $-\dot{M}_2\sim\dot{M}_\text{d}$(crit) obtains, which enables them occasionally to remain just in the stable state. Supporting evidence for this is given by

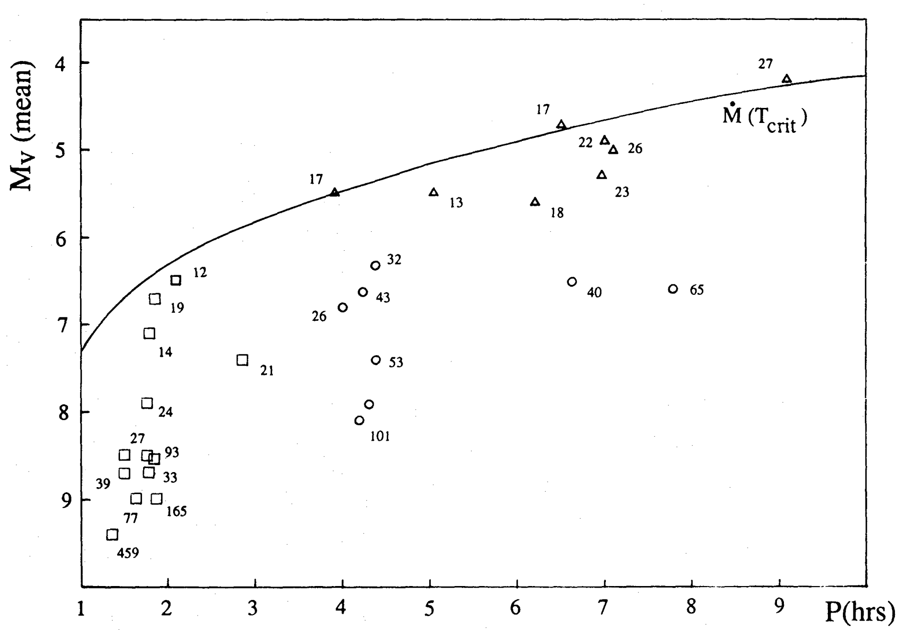

Figure 2. Absolute magnitudes of dwarf novae at mean light as a function of orbital period. The points are labelled with the recurrence times T_n of the dwarf novae normal outbursts (see Section 4.6). The curve is the theoretical relationship for stable mass transfer in an accretion disc.

Szkody & Mattei (1984) who find an increase in frequency of outbursts and a rise in brightness of the quiescent state preceding standstills of RX And and Z Cam. Although this has now been seen in other ZC stars (Mattei 1986, private communication), it does not happen before all standstills, but it is what would be expected if there were a gradual rather than a relatively fast increase in $|\dot{M}_2|$. For the short time before standstills in which these effects are seen, M_V(mean) will brighten both because of the decrease in M_V(min) and the increase in Q; the combined effect could take the star across the M_V(crit) boundary required for stable mass transfer through the disc.

Smak (1982) has shown from a comparison of two ZC and three UG stars that $-\dot{M}_2$ is indeed close to $\dot{M}_d$(crit) in the ZC stars but not in the UGs. With our more extensive data set it is worthwhile examining the situation further.

Following Smak (1982) we use the relationship describing the temperature distribution in a steady-state accretion disc (Lynden-Bell & Pringle 1974):

$$\dot{M}_d = \frac{8\pi}{3} \sigma T(r)^4 \frac{r^3}{GM_1} \left[1 - \left(\frac{R_1}{r}\right)^{1/2}\right]^{-1} \tag{22}$$

where r is the radial distance in the disc. If T_{crit} is the temperature of the disc above which stable transfer takes place then we require $T(r) > T_{crit}$ everywhere, which requires only that $T(R_d) > T_{crit}$. As $R_d \gg R_1$, equation (22) becomes

$$\dot{M}_d > \frac{8\pi}{3} \sigma T_{crit}^4 \frac{R_d^3}{GM_1} \tag{23}$$

for stability.

For T_{crit} we adopt the expression given by Meyer & Meyer-Hofmeister (1983) (see also Ritter & Burkert 1986)

$$\log T_{crit} = 3.81 - 7.67 \times 10^{-2} \log R_d/R_\odot. \tag{24}$$

Other theories of disc instability lead to very similar values of $\dot{M}_d$(crit) (Shafter, Wheeler & Cannizo 1986).

Together with equations (10) and (22), equation (24) gives

$$\dot{M}_d(\mathrm{crit}) = 1.60 \times 10^{16} \left(\frac{M_1}{M_\odot}\right)^{-0.10} P(\mathrm{hr})^{1.80} \ \mathrm{g\ s^{-1}}. \tag{25}$$

Equation (25), transformed through equation (20), gives the function $M_V(T_{crit}, P)$ which is drawn in the observational diagram Fig. 2. As can be seen, the theoretical line passes close to the region of the ZC stars and is compatible, within the uncertainties of the theory and the transformation from $\dot{M}_d$ to M_V, with the hypothesis that ZC stars have $-\dot{M}_2 \sim \dot{M}_d$(crit).

4.6 CORRELATIONS WITH OUTBURST TIME-SCALES

The large spread in M_V(min) or M_V(mean) at a given orbital period (Figs 1 and 2), which implies a wide range of $\dot{M}_d$ and $\dot{M}_2$, requires further attention to check on the possibility that the scatter originates in observational error. Fortunately there is a property of the DN, the mean time between their outbursts, which is an observational quantity unrelated to, or influenced by, any of the observational parameters that we have used thus far.

Among the SU UMa stars (Warner 1985a) two outburst time-scales are known: the mean time T_n between normal outbursts and T_s between super outbursts. Evidence is accumulating that during a supermaximum the rate of mass transfer from the secondary is greatly increased, probably through heating of the secondary (Vogt 1982; Osaki 1985). The visual flux radiated during a supermaximum is therefore not characteristic of the average behaviour of the system; the greater luminosity near the beginning of a supermaximum arises probably from an enhanced bright spot and the additional duration of maximum results from the period of increased mass transfer. In our analysis of the systematics of ordinary outbursts we therefore require Q-values which omit the effects of supermaxima (other than counting a supermaximum as an ordinary maximum because the former appears to be triggered by the latter). If the durations of the two types of maxima are ΔT_s and ΔT_n respectively, then a Q which includes averaging over supermaxima can be converted into a Q' which does not by the formula

$$Q' \simeq \left(1+\frac{T_n}{T_s}\right)\left(1+\frac{\Delta T_s}{\Delta T_n}\times\frac{T_n}{T_s}\right)^{-1} Q. \tag{26}$$

From the estimates of widths of outbursts in SU UMa stars (Szkody & Mattei 1984; van Paradijs 1983) we find $\Delta T_s/\Delta T_n \simeq 5$ for all stars.

For the ordinary U Gem (UG) DN and the ZC stars all outbursts are considered normal.

In Table 3 we collect together information on the outburst properties of those DN for which we can provide M_V(min) from Tables 1 and 2. The apparent magnitudes at superoutburst for the SU UMa stars are obtained mostly from Ritter's (1984) compilation. The values of T_n and T_s come

Table 3. (a) Outburst properties of SU UMa stars.

Star	P(h)	m_V(super)	A_s	A_n	T_s(d)	T_n(d)	M_V(min)	M_V(mean)
SW UMa	1.36			5.7	459		11.0	9.4
T Leo	1.41			5.7:	420		<11.1:	
V436 Cen	1.50	11.3	4.7	4.1	335	<164	9.4	8.5
OY Car	1.51	11.4	4.4	3.9	318	39	9.1	8.7
EK TrA	1.53	12.0	4.6:	4.4:	487	231	9.8:	
RZ Sge	1.64			4.1	266	77	9.3	9.0
IR Gem	1.70	11.2	4.3	3.8	174	26	9.0*	
AY Lyr	1.75	12.3	4.7	3.8	205	24	9.0	7.9
HT Cas	1.77	10.8	5.8	3.9	500:	33	9.1	8.7
VW Hyi	1.78	8.5	4.8	3.9	179	27	9.1	8.5
Z Cha	1.79	11.9	4.4	3.8	287	93	8.8	8.5
WX Hyi	1.79	11.4	3.3	2.9	140	14	8.1	7.1
SU UMa	1.83	11.2	3.2	2.5	200	19	7.9	6.7
CU Vel	1.85	11.0:	4.5:	4.1	386	165	9.3	9.0
TY Psc	1.85	11.7	4.3:	3.8:	333	39	9.0:	
TY PsA	1.94	12.0	5:				9.6:	
YZ Cnc	2.10	10.5	4.0	2.6	134	12	7.7*	6.5*
TU Men	2.82	11.6	5.0	4.1	157	21	8.8	7.4:

*Deduced from application of equation (13).

partly from Ritter (1984), supplemented with improved estimates from Szkody & Mattei (1984), Bateson (1979) and Mattei (1986, private communication).

The amplitudes of outburst are for the disc. As the secondary and bright spot do not contribute significantly at maximum light, these are

$$\left.\begin{array}{ll}\text{Mean amplitude of normal outbursts} & A_n = m_V(\text{min}) - m_V(\text{max}) + \Delta \\ \text{Mean amplitude of superoutbursts} & A_s = m_V(\text{min}) - m_V(\text{super}) + \Delta\end{array}\right\} \quad (27)$$

The correlation between M_V(min) and T_n, seen in Fig. 3(a), shows considerable scatter and gives the impression that the SU UMa stars follow a different relationship than the other DN. However, the departure from the linear relationship defined by the SU UMa stars is highly correlated with orbital period – Fig. 4(a). A similar result is found for the relationship between M_V(mean) and T_n: Figs 3(b) and 4(b). Clearly neither M_V(min) nor M_V(mean) alone is the sole factor governing the recurrence time T_n.

Before pursuing this further, we note that the use of the independent parameter T_n has demonstrated that the spread in M_V(min) in Fig. 1 and the spread in M_V(mean) in Fig. 2 is largely

Table 3. (b) Outburst properties of dwarf novae.

Star	Type	P(h)	A_n	T_n(d)	M_V(min)	M_V(mean)
CN Ori	ZC	3.91	2.3	17	6.9	5.5
X Leo	UG	3.94	3.5	22	8.1*	
CZ Ori	UG	(4.0)	3.4	26	8.0	6.8
U Gem	UG	4.17	5.3	101	9.6	8.1
CW Mon	UG	4.23	3.5	43	8.1	6.6:
BD Pav	UG	4.30	4.2		8.7	7.9
SS Aur	UG	4.38	4.2	43	8.9	7.4
TW Vir	UG	4.38	3.4	32	7.7	6.3
RX And	ZC	5.08	2.7	13	7.3	5.5
HL CMa	UG	5.20	4.0	15	8.3	
AH Her	ZC	6.19	3.1	18	7.6	5.6
TZ Per	ZC	(6.5)	1.8	17	6.2*	4.7*
UZ Ser	UG	(6.6)	3.7	21	7.7	
SS Cyg	UG	6.63	4.0	40	8.4	6.5
Z Cam	ZC	6.96	3.7	23	7.7	5.3
EM Cyg	ZC	7.00	3.2:	22	7.2:	4.9:
KT Per	ZC	(7.1)	3.4	26	6.9:	5.0:
RU Peg	UG	7.79	4.4	65	7.4	6.6
SY Cnc	ZC	9.1:	3.3	27	6.4:	4.2:

*Deduced from application of equation (13).

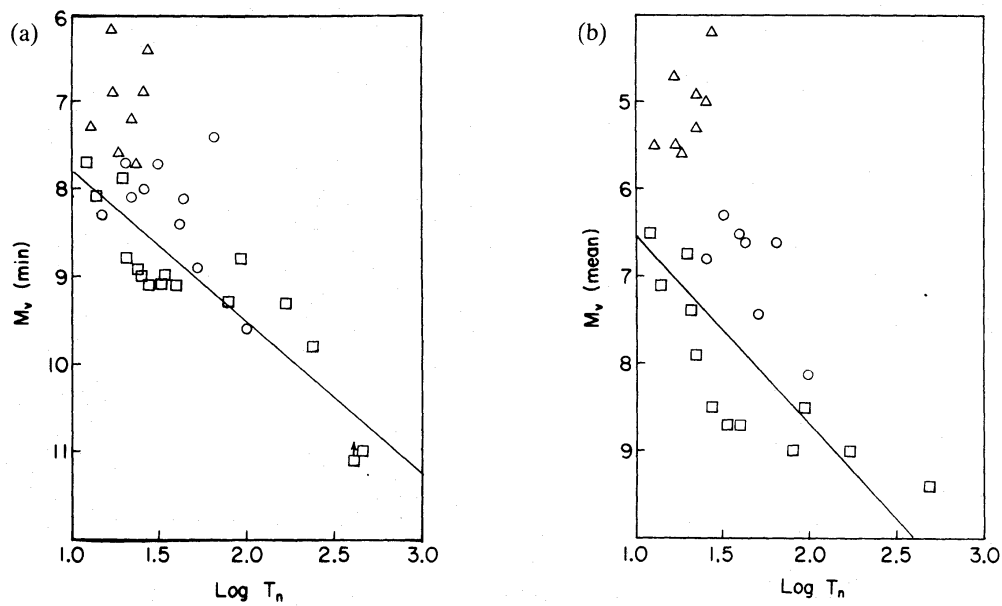

Figure 3. Correlations of recurrence time-scale T_n for dwarf novae with (a) absolute magnitude at minimum light and (b) absolute magnitude at mean light. The linear fits are to the SU UMa stars only.

intrinsic and does not originate in observational error. For the SU UMa stars (which have a small range of *P*) in Fig. 3(a) the rms scatter about the linear fit is ±0.39 mag. As there are some residual uncertainties in the values of T_n (partly an interpretive problem as the DN do not outburst regularly, so T_n can depend on the completeness or length of observational coverage), this result suggests that the error in determination of M_V(min) in Tables 1 and 2 is probably not greater than ~0.3 mag.

There are therefore two parameters that influence M_V(min). One of these is the orbital period *P*; the other is as yet undetermined but it is the controlling factor in the recurrence cycle (it can be seen from inspection of Table 3(a) and (b) that *P* does not influence T_n).

The slightly poorer correlation between M_V(mean) and *P* [Fig. 3(b)] than between M_V(min) and *P* [Fig. 3(a)] could arise in part through the additional uncertainties of the *Q*-values.

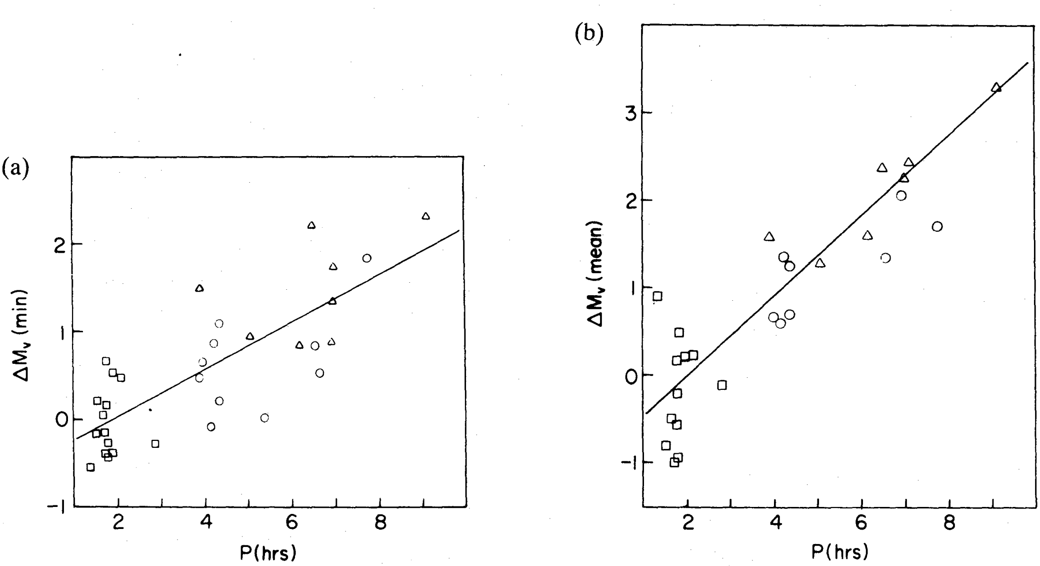

Figure 4. Correlation between orbital period and the deviations ΔM_V in (a) Fig. 3(a), and (b) Fig. 3(b).

From the correlations seen in Figs 3(a) and 4(a) we derive the relationship

$$M_V(\text{min})=7.11+1.64\ \log\ T_n\ (\text{day})-0.264\ P(\text{hr}). \qquad (28)$$
$$\pm0.44 \quad \pm0.24 \qquad\qquad \pm0.037$$

The rms scatter of the 33 DN with M_V(min) in Tables 1 and 2 is ±0.49 mag when compared with equation (28). Again part of this scatter must be attributed to uncertainties in T_n. Equation (28) is a generalization of equation (18).

Another way of viewing the correlation for M_V(min) is to note that, as we may represent the line of $M_V(T_{\text{crit}})$ in Fig. 2 by the approximate relationship

$$M_V(T_{\text{crit}})\simeq6.5-0.26\ P(\text{hr}),$$

then, from equation (28),

$$M_V(\text{min})-M_V(T_{\text{crit}})=0.6+1.64\ \log\ T_n \qquad (42)$$

independent of orbital period. That is, the time between normal outbursts is a function only of the factor by which the luminosity (or mass transfer rate) of the quiescent disc falls short of the minimum needed to produce a steady state disc. This is a new observational result which requires explaining by models of the dwarf nova outburst.

A similar analysis can be made for M_V(mean), but we postpone discussion of this to the following section. The existence of a correlation between M_V(mean), T_n and P is clearly seen in Fig. 2, where we have labelled the points in the M_V(mean) – P diagram with their corresponding T_n. In case it be thought that the correlation has been introduced through the Q corrections, described in Section 4.5, which could reduce the M_V(mean) of systems with small T_n relative to those with large T_n, inspection of M_V(min) – M_V(mean) in Tables 1 and 2 will show that no such strong correlation exists: a correlation with P is, however, present. The correlation between M_V(mean), T_n and P is merely a modification of the correlation that exists between M_V(min), T_n and P. The latter is seen in Figs 3(a) and 4(a).

4.7 THE KUKARKIN–PARENAGO RELATIONSHIP FOR DWARF NOVAE

The data contained in Tables 1 and 2 constitute the most homogeneous observations with which to examine the correlation between amplitude and outburst time-scale, i.e. the Kukarkin–Parenago (KP) relationship (Kukarkin & Parenago 1934). In particular, the amplitudes of outburst, freed from distortion by contributions from the secondaries and bright spots, and the latest determined T_n are available. These should provide a better test for the existence of a KP relationship than does the use of the heterogeneous data contained in the GCVS (e.g. van Paradijs 1985).

Fig. 5(a) shows the A_n–T_n relationship for our DN data. A correlation exists, which confirms the conclusion obtained from less homogeneous data (van Paradijs 1985) and convincingly demonstrates the relationship which has previously been questioned (Payne-Gaposchkin 1977). The essence of this correlation is of course already contained in Figs 1 and 4 and equations (13) and (28). From Fig. 5(a) we find

$$A_n=M_V(\text{min})-M_V(\text{max})=1.08+1.67\ \log\ T_n\ (\text{day})-0.005\ P\ (\text{hr}) \qquad (29)$$
$$\pm0.46 \quad \pm0.24 \qquad\qquad \pm0.044$$

which is statistically independent of orbital period. For comparison, van Paradijs (1985) found A_n=1.85 (±0.44)+1.40 (±0.23) log T_n (day) from the GCVS compilation.

One problem that is evident in Fig. 5(a) is the effect that the spread in M_V(min) seen in Fig. 1 has in the KP diagram. It is trivial, once the tight relationship between M_V(max) and P has been

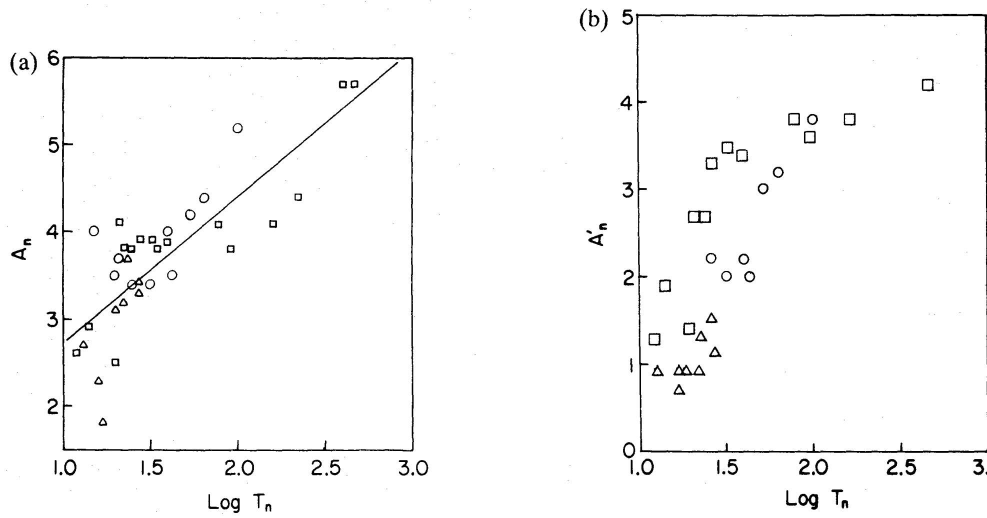

Figure 5. Correlations (Kukarkin–Parenago relationships) of recurrence time-scale T_n with (a) amplitude of dwarf nova outburst measured from minimum luminosity and (b) amplitude measured from mean luminosity.

uncovered, to recognize that stars with exceptionally bright M_V(min) will lie low in the KP diagram. That is, the spread about the M_V(min) – P relationship in Fig. 1 is propagated into the KP diagram [but there is no dependence on P because of the nearly parallel trends of M_V(max) and M_V(min) with P]. It is clear, therefore, that the KP relationship, as usually defined, is inflicted with the same problems as the M_V(min) – P relationship.

We turn to an alternative approach. From Figs 3(b) and 4(b) we see that the use of M_V(mean) in place of M_V(min) also leads to strong correlations. Defining

$$A'_n = M_V(\text{mean}) - M_V(\text{max}) \tag{30}$$

we can plot a modified KP diagram from the data in Table 3(a) and (b), as shown in Fig. 5(b). This shows a good correlation between A'_n and log T_n in which some of the more discrepant points in Fig. 5(a) have become more compatible with the general trend.

In Figs 3, 4 and 5 the ZC stars tend to be systematically displaced from the average trend. For Figs 3(b), 4(b) and 5(b) this could be thought to arise from the different way in which the Q-values were derived in Section 4.5 – for the ZC stars we used the M_V(standstill) as a means of obtaining M_V(mean), whereas for other stars we used averages over the visual light curves. However, in the context of our understanding of the ZC phenomena, it is only the DN with peculiarly bright M_V(mean) that are able to enter into the standstill condition and hence be classified as ZC stars. This is why they occupy such displaced positions in Fig. 3(b) and may also account for their occupying the upper part of the scatter in Fig. 4(b). The similar systematic displacements in Figs 3(a), 4(a) and 5(a) shows that it is not the Q-values that are at fault.

From Figs 4(b) and 5(b) we find the following relationship:

$$\begin{aligned} A'_n = &-0.05 + 2.06 \log T_n\ (\text{day}) - 0.20\ P\ (\text{hr}). \\ &\pm 0.46 \quad \pm 0.29 \qquad\qquad\quad \pm 0.04 \end{aligned} \tag{31}$$

In contrast with the result for A'_n, equation (29), this contains a significant term in P, which accounts for much of the scatter in Fig. 5(b).

4.8 INTERPRETATION OF THE KP RELATIONSHIP

In our continued use of the various M_Vs we have maintained as far as possible the philosophy stated in the Introduction of working with observable quantities. A dwarf nova, of course, is not overly influenced by a human's view of its luminosity: it radiates, erupts and evolves according to the values of $\dot{M}_d$, $\dot{M}_1$ and $\dot{M}_2$. Therefore, in order to gain insight into the mechanisms of DN outbursts we must again transform M_V to $\dot{M}_d$ through equation (20). We are assisted in the present instance in that we require only $\dot{M}_d$ for the various M_V of an individual dwarf nova, i.e. at nearly constant R_d. From the limited range of disc models (Tylenda 1981; Wade 1984), for the range of R_d appropriate to DN, we find

$$M_V \simeq -1.85 \log \dot{M}_d + \text{constant} \quad (R_d \text{ and } M_1 \text{ constant}). \tag{32}$$

From equations (29) and (32) we have

$$\log \dot{M}_d(\text{min}) = \underset{\pm 0.19}{-0.58} - \underset{\pm 0.12}{0.90} \log T_n\,(\text{day}) + \log \dot{M}_d(\text{max}) \tag{33}$$

and from equations (30), (31) and (32) we have

$$\log \dot{M}(\text{mean}) = \underset{\pm 0.25}{0.03} - \underset{\pm 0.16}{1.11} \log T_n\,(\text{day}) + \underset{\pm 0.02}{0.11}\, P\,(\text{hr}) + \log \dot{M}_d(\text{max}). \tag{34}$$

We consider two possible interpretations of DN outbursts, based on equations (33) and (34).

(i) The average amount of mass $\Delta M(\text{min})$ passing through the disc between outbursts is $\dot{M}_d(\text{min})\, T_n$, which, from equation (33) and the approximation $\dot{M}_d(\text{max}) \sim$ constant from Section 4.4, gives

$$\Delta M(\text{min}) \propto T_n\,(\text{day})^{0.10 \pm 0.12}. \tag{35}$$

Neither the exponent of $\dot{M}_d$ in equation (32) nor that of T_n in equation (33) is well enough determined to exclude the possibility that in fact $\Delta M(\text{min})$=constant. Just such a tentative conclusion was reached by van Paradijs (1985), based on the normal KP relationship and Vogt's (1981) result that $M_V(\text{max})$=constant.

Ten years ago (e.g. Warner 1976) the possibility that $\Delta M(\text{min})$=constant would have given support to the hypothesis that DN result from accumulation of hydrogen-rich material on the white dwarf primary, with consequent small-scale thermonuclear runaways. Within the framework of the disc instability and modulated mass transfer models, however, this result does not have any obvious relevance.

(ii) In terms of the disc instability model, the average mass ΔM *accumulated* in the disc between outbursts is

$$\Delta M = [\dot{M}(\text{mean}) - \dot{M}_d(\text{min})]\, T_n. \tag{36}$$

During an outburst a DN must pass this accumulated mass through the disc, and it does so at a rate $\dot{M}_d(\text{max})$. The duration of a normal outburst is therefore

$$\Delta T_n\,(\text{day}) \simeq \frac{[\dot{M}(\text{mean}) - \dot{M}_d(\text{min})]}{\dot{M}_d(\text{max})}\, T_n. \tag{37}$$

We write this as

$$\log \Delta T_n\,(\text{day}) = \log T_n\,(\text{day}) + \log \frac{\dot{M}(\text{mean})}{\dot{M}_d(\text{max})} + \log \left[1 - \frac{\dot{M}_d(\text{min})}{\dot{M}_d(\text{max})}\right]$$

and use equations (29) and (31) to deduce

$$\log \Delta T_n\,(\text{day}) = \underset{\pm 0.25}{0.03} - \underset{\pm 0.16}{0.11} \log T_n\,(\text{day}) + \log [1 - 0.21\, T_n^{0.21}\,(\text{day})] + \underset{\pm 0.02}{0.11}\, P\,(\text{hr}). \tag{38}$$

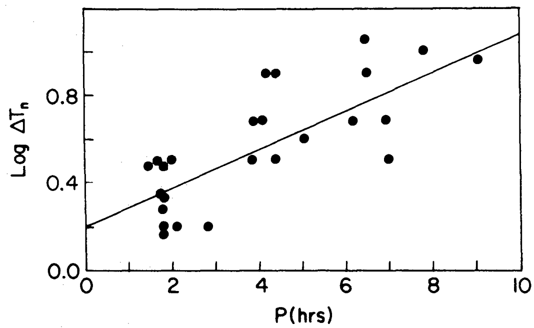

Figure 6. Correlation between outburst duration ΔT_n and orbital period.

The log [ ] factor in equation (38) can be approximated in the range $10<T_n<100$ day by -0.15 log T_n, so we arrive at

$$\log \Delta T_n\ (\text{day})=\underset{\pm 0.25}{0.04}-\underset{\pm 0.16}{0.26}\log T_n\ (\text{day})+\underset{\pm 0.02}{0.11}\ P\ (\text{hr}). \tag{39}$$

Again the coefficient in equation (32) is not well enough known to exclude the possibility that equation (39) is in fact independent of T_n. However, this equation makes the prediction (based on the model for DN outbursts that we are exploring) that the duration of DN outbursts should be a function of P.

From the outburst characteristics of DN listed by Szkody & Mattei (1984) we select the time spent within 0.5 mag of maximum as characterizing our ΔT_n. Their values, supplemented with widths of 'narrow' outbursts (which appear to correspond most closely with the parameter measured by Szkody & Mattei) from the compilation of van Paradijs (1983), give the correlation with P shown in Fig. 6. The linear least squares fit to the points is

$$\log \Delta T_n=\underset{\pm 0.08}{0.00}+\underset{\pm 0.016}{0.087}\ P\ (\text{hr}). \tag{40}$$

A plot of ΔT_n versus T_n for the above stars, supplemented with additional points for the few known stars with $T_n>200$ day, shows that for $\Delta T_n>4$ day there is no correlation between ΔT_n and T_n. Although for $\Delta T_n<4$ day we find T_n only in the range $10<T_n<40$ day, any correlation between ΔT_n and T_n is at most a weak one.

The similarity between equations (39) and (40), which were derived from independent observables, supports the model in which mass is stored in the disc between outbursts.

The vertical scatter in Fig. 5(b) can be greatly reduced by considering the excess visual energy E_v (relative to the mean) radiated during an outburst, instead of the amplitude A_n': log $E_v \simeq \log \Delta T_n + 0.4\ A_n'$ which, from equations (31) and (40), gives

$$\log E_v \simeq \underset{\pm 0.11}{0.82}\log \Delta T_n\ (\text{day})+\underset{\pm 0.016}{0.007}\ P\ (\text{hr}) \tag{41}$$

or $E_v \mathrel{\tilde{\propto}} T_n$ independent of P within observational uncertainty.

4.9 THE SUPEROUTBURSTS

From Table 3(a) we derive the result* (see also Vogt 1981), displayed in Fig. 7, that there is a tight

*HT Cas is omitted from consideration as its supermaximum recurrence time is very uncertain (Wenzel 1985) and it appears to have been for many years in a state where supermaxima did not occur at all (Mattei 1986, private communication).

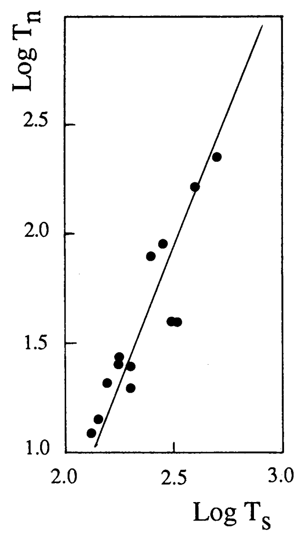

Figure 7. Relationship between supermaximum recurrence time-scale T_s and normal outburst time-scale T_n.

linear correlation between log T_s and log T_n, given by

$$\log T_s = 0.40 \log T_n + 1.73. \quad (43)$$
$$\pm 0.06 \qquad \pm 0.09$$

This shows that $T_s = T_n$ when $\log T_s = 2.88 \pm 0.18$, i.e. at $T_s = T_n = 750 \pm 300$ day, which is compatible with the observed property that for $T_n \geqslant 400$ day there is no distinction between normal and superoutbursts [Table 3(a), supplemented with the known properties of such SU UMa stars as WZ Sge and VY Aqr].

The plot of A_s versus log T_s shows considerable scatter (not illustrated here), probably due partly to uncertainties in A_s because in some stars only a rough estimate is available of m_V(super) rather than the better quality, time averaged m_V(max) available for normal outbursts. If the A_n and T_n of stars longward of the orbital period gap are included in the same diagram, the SU UMa stars form a separate group, which does not support the suggestion of van Paradijs (1983) that the superoutbursts of SU UMa stars and the normal outbursts of the UG and ZC stars are of the same kind.

5 Classical novae

5.1 ABSOLUTE MAGNITUDES OF CLASSICAL NOVAE

The absolute magnitudes of CN during eruption, and particularly at maximum brightness, have long been a subject of special interest in connection with their uses as extragalactic distance indicators. Early studies, using distances derived from interstellar lines, galactic rotation, trigonometric parallaxes and the expansion-parallax method, demonstrated (see reviews by Payne-Gaposchkin & Gaposchkin 1938; Payne-Gaposchkin 1957; McLaughlin 1960) that novae reach at least $M_V = -7$ at maximum brightness. From these data, McLaughlin (1942) noticed that slow novae were on average approximately two magnitudes fainter at maximum than fast novae. A few years later he discovered the M_V(max) – rate of decline relationship (McLaughlin 1945) which has since been a valuable source of estimates of M_V(max).

Until recently the correlation between M_V(max) and t_n (the time in days taken to fall n magnitudes from maximum brightness) has shown a scatter of ± 1 mag about the mean relationship (e.g. fig. 7 of McLaughlin 1960). The discovery and measurement of a number of new nova shells and allowance for systematic errors in the method (arising partly from the asymmetrical expansion of some shells), has significantly improved the relationship (Cohen & Rosenthal 1983; Cohen 1985). The equation given by Cohen (1985):

$$M_V(\text{max}) = -10.70 + 2.41 \log t_2 \qquad (44)$$
$$\qquad \pm 0.30 \quad \pm 0.23$$

can provide M_V(max) for all CN whose rates of decline are known.

The two principal sources of t_n are Payne-Gaposchkin (1957), who lists t_2 for all well-observed novae prior to 1956, and Duerbeck (1981), who lists t_3 for both old and recent novae. A comparison between t_2 and t_3 for those stars in common between the two lists shows that for $t_2 \leq 100$ day, $t_2 \simeq \frac{1}{2} t_3$. With this conversion, we list in Table 4 all the CN for which data are sufficiently complete, or for which further observations have a good expectation, to lead to useful evaluation of the absolute magnitudes at minimum light.

Table 4. Classical novae observed or observable at minimum.

Star	Date	t_2	M_V(max)	m(max)	m(min)	A_V	A_{CN}	M_V'(min)	Refs
CI Aql	1917	-		11:p	15.5p		4.5:		
DO Aql	1925	450:	-4.3:	8.6p	17.8p		9.2	4.9	
EL Aql	1927	12	-8.1	6.4p	19.0p		12.6	4.5	
EY Aql	1926	20	-7.6	10.5:p	>20		>9.5	>1.9	3
V356 Aql	1936	150	-5.4	7.0p	16.5p	2.04	9.5	4.1	
V368 Aql	1936	15	-7.9	5.0p	17.5:p		12.5:	4.6:	
V500 Aql	1943	15	-7.9	6.1:p	17.8:p		11.7:	3.8:	
V528 Aql	1945	17	-7.7	7.4	18.1p	2.6	10.7	3.0	
V603 Aql	1918	3.5	-9.4	-1.4v	11.6	0.5	13.0	3.6	
V604 Aql	1905	12	-8.1	7.6:p	18p		10.4:	2.3	
V606 Aql	1899	17	-7.7	5.5:p	17.3:p		11.8:	4.1:	
V1229 Aql	1970	25	-7.3	6.7B	17.6	1.6	10.9	3.6	9
V1301 Aql	1975	21	-7.5	10.3v	20.5p		10.2	2.7	10,11
V1370 Aql	1982	12	-8.1	7.5p	20.0:p		12.5:	4.4:	
OY Ara	1910	44	-6.7	6.2p	17.5p		11.3	4.6	
T Aur	1891	80	-6.1	4.1B	14.9B	1.25	10.8	4.7	
QZ Aur	1964	<17	<-7.7	6.0p	18.0p		12.0	<4.3	
RS Car	1895	-		5.0:	14.3?		9.3?		18
IV Cep	1971	16	-7.8	7.0B	19.3B	1.65	12.3	4.5	
RR Cha	1953	25:	-7.3:	7.1p	>15p		>7.9		
X Cir	1926	3.3	-9.5	6.5p	>16.5p		>10.0	>0.5	
AR Cir	1906	208	-5.1	10.3p	15.0p		4.7	-0.4*	7
V394 CrA	1949	10:	-8.3:	7.5p	>13.5p		>6		
V655 CrA	1967	-		8.0:p	17:p		9.0:		

Table 4 – *continued*

Star	Date	t_2	M_V(max)	m(max)	m(min)	A_V	A_{CN}	M_V'(min)	Refs
V693 CrA	1981	6	-8.8	6.5v	>19v	0.45	>12.5	>3.7	5,6
V450 Cyg	1942	110	-5.8	7.0p	16.5	1.4	9.5	3.7	
V465 Cyg	1948	200:	-5.2:	7.3:p	17.5:p		10.2:	5.0:	
V476 Cyg	1920	6	-8.8	2.0v	16.2	0.85	14.2	5.4	
V1330 Cyg	1970	12	-8.1	7.5B	18.1B		10.6	2.5	9
V1500 Cyg	1975	2	-10.0	2.0B	16.3B	1.25	14.3	4.3	8
V1668 Cyg	1978	12	-8.1	6.0v	20:	1.10	14.:	5.9:	1,12
Q Cyg	1876	11	-8.2	3.0v	14.9	1.4	11.9	3.7	
HR Del	1967	152	-5.4	3.3v	12.1v	0.56	8.8	3.4	
DM Gem	1903	11	-8.2	4.8v	16.5v		11.7	3.5	
DN Gem	1912	17	-7.7	3.6B	15.8B	0.27	12.2	4.5	2
DQ Her	1934	67	-6.3	1.3v	14.7v	0.16	13.4	7.1	
V360 Her	1892	-		6.3p	>16p		>9.7		
V446 Her	1960	5	-9.0	2.8p	15.8p	1.7	13.0	4.0	
V533 Her	1963	26	-7.3	3.0p	14.4p	0.25	11.4	4.1	
CP Lac	1936	5	-9.0	2.1p	15.6p	1.5	13.5	4.5	
DI Lac	1910	20	-7.6	4.3B	14.5B	1.3	10.2	2.6	
DK Lac	1950	19	-7.6	5.0:p	15.5p	1.2	10.5:	2.9:	
RZ Leo	1918	-		10.5p	17.5p		7.0		18
HR Lyr	1919	45	-6.7	6.5B	15.8B	0.45	9.3	2.6	
BT Mon	1939	140	-5.5	4.0:p	15.8p	0.63	11.8	6.3	
GI Mon	1918	13	-8.0	5.2:p	15.1p		9.9:	1.8:	
KT Mon	1942	20	-7.6	9.8p	15.5p		5.7	-1.8*	
IL Nor	1893	54	-6.5	4.8v	>16.3p		>11.5	>5.0	
IM Nor	1920	>30	>-7.1	9.0B	>20:p		>11:	>4	
V840 Oph	1917	20:	-7.6:	6.5:p	17.0p	0.72	10.5:	2.9:	
V841 Oph	1848	56	-6.5	4:v	13.3v	1.25	9.3:	2.8:	
V849 Oph	1919	88	-6.0	7.2:p	>17.5		>10.3	>4.3	
V972 Oph	1957	50?	-8.3:	8.0p	>16.5p		>8.5	>0.2	
V2024 Oph	1967	15	-7.9	9.5:v	>18		>8.5	>0.6	
V2104 Oph	1976	15:	-7.9:	8.8v	>20		>11.2	>3.3:	
GR Ori	1916	-		11.5p	>20		>8.5		
GK Per	1901	6	-8.8	0.2v	13.0v	0.7	12.8	4.0	
V400 Per	1974	22	-7.5	8.0p	19.5p		11.5	4.0	
RR Pic	1925	80	-6.1	1.2v	12.3v	0.04	11.1	5.0	
CP Pup	1942	5	-9.0	0.2v	15.0v	0.8	14.8	5.8	

Table 4 – *continued*

Star	Date	t_2	M_V(max)	m(max)	m(min)	A_V	A_{CN}	M_V'(min)	Refs
DY Pup	1902	118	-5.7	7.0p	16.0p		9.0	3.3	
HS Pup	1963	33	-7.0	8.0p	>20p		>12	>5	
HZ Pup	1963	35	-7.0	7.7p	18.5p		10.8	3.8	
WY Sge	1783	-		6.0v	19.5v		13.5		
HS Sge	1977	10:	-8.3:	7.2p					
AT Sgr	1900	18:	-7.7:	8.7:p	>16.5p		>7.8:	>0.1:	
FL Sgr	1924	16	-7.8	8.3p	>13p		>5		
FM Sgr	1926	15	-7.9	8.6p	16.5p		7.9	0.0*	
GR Sgr	1924	120?		11.4?p	16.6p		5.2?	*	
HS Sgr	1901	120:	-5.7:	11.6?p	16.5p		4.9	-0.8:*	
KY Sgr	1926	-		7.2:p	>16.5p		>9.3		
V363 Sgr	1927	40	-6.8	7.9:p	>16p		>8.1:	>1.3:	
V441 Sgr	1930	75:	-6.2:	8.0:p	16.0p		8.0	1.8:	
V630 Sgr	1936	4	-9.2	4.0v	14.4v	1.6	10.4	1.2*	
V726 Sgr	1936	45	-6.7	9.0:p	>16.5p		>7.5	>0.8	
V732 Sgr	1936	32	-7.1	6.5p	>16.0p		>9.5	>2.4	
V787 Sgr	1937	23	-7.4	9.4p	>16.5p		>7.1	>-0.3	
V909 Sgr	1941	3.8	-9.3	6.8p	>16.0p		>9.2	>-0.1	
V927 Sgr	1944	-		7.3:p	>16.5p		>9.2		
V999 Sgr	1910	220	-5.0	8.0p	16.5p		8.5	3.5	
V1012 Sgr	1914	-		8.0p	>17p		>9		
V1015 Sgr	1905	17	-7.8	6.5:p	>12p				
V1016 Sgr	1899	12	-8.1	6.9:p	14.9p		8.0:	-0.1:*	
V1059 Sgr	1898	10	-8.3	2.0:v	16.5p		14.5	6.2	
V1175 Sgr	1952	15:	-7.9:	7.0p	>12				
V1275 Sgr	1954	15	-7.9	7.8p	>13	1.0			
V1583 Sgr	1928	20	-7.6	8.9p	>16.5		>7.6	>0.0	
V1944 Sgr	1960	-		7.0p	13p		6	*	
V2572 Sgr	1969	20	-7.6	6.3p	14.8p		8.5	0.9*	
V3645 Sgr	1969	-		8.0:p	18p		10.0:		
V3888 Sgr	1974	-		7.0:p	>13p				
V3889 Sgr	1975	5	-9.0	8.4p	20:p		11.6:	2.6	
V3890 Sgr	1962	-		-	17.2p				
V3964 Sgr	1975	-		6.5:p					
V4021 Sgr	1977	50	-6.6	8.8p					
V4065 Sgr	1980	6:	-8.8:	8.6p					

Table 4 – *continued*

Star	Date	t_2	M_V(max)	m(max)	m(min)	A_V	A_{CN}	M_V'(min)	Refs
V4077 Sgr	1982	20:	-7.6:	8.0p	>20p		>12:	>4.4:	
T Sco	1860	11	-8.2	6.7p					
KP Sco	1928	21	-7.5	9.4p	>16.5p		>7.1	>-0.4	
V696 Sco	1944	-		7.5p	>16.5p		>9		
V720 Sco	1950	9	-8.4	7.8p	>18.0p		>10.2	>1.8	
V721 Sco	1950	120	-5.7	9.5p	>18.0p		>8.5	>2.8	
V723 Sco	1952	11:	-8.2:	9.8p	22p		12.2	4.0:	
EU Sct	1949	14	-7.9	7.6p	17.0p	2.6	9.4	1.5	
FS Sct	1952	14	-7.9	10.1p	16.6p		6.5	-0.3*	
FV Sct	1960	-		7.0p	21p		14		
V368 Sct	1970	16	-7.8	6.9p	19.3p	1.6	12.4	4.6	9
V373 Sct	1975	43	-6.8	7.3p	18.5p	1.0:	11.2	4.4	13,14
X Ser	1903	400:	-4.4:	8.9p	18.3p		9.4	5.0:	
CT Ser	1948	100:	-5.9:	5.0:p	>16p		>11:	>5:	
DZ Ser	1960	-		8.0:p	16.9		8.9:		
FH Ser	1970	40	-6.8	4.4v	16.1v	2.3	11.7	4.9	15,16
LW Ser	1978	25	-7.3	8.0p					
MU Ser	1983	5	-9.0	7.7p	>20p		>12.3	>4.3	
XX Tau	1927	24	-7.4	6.0p	16.5p		10.5	3.1	
RR Tel	1949	670	-3.9	6.9p	16.5p		9.7	5.8	
CN Vel	1905	400	-4.4	10.2p	>16.5p		>6.3	>1.9	
LU Vul	1968	19	-7.6	9.2p	>21p		>11.8	>4.2	
LV Vul	1968	21	-7.5	4.5v	16.9p	1.7	12.4	4.9	17
NQ Vul	1976	43	-6.8	6.5p	17.6p	2.5	11.1	4.3	
PW Vul	1984	-		6.4v	17:v	1.4	10.6:		4

References

1. Di Paolantonio, Patriaria & Tempesti (1981); 2. Duerbeck, Lemke & Willerding (1979); 3. Duerbeck (1983); 4. Duerbeck, Geffert & Nelles (1984); 5. Caldwell (1982); 6. Brosch (1981); 7. McLaughlin (1939); 8. Kruszewski, Semeniuk & Duerbeck (1983); 9. Ciatti & Rosino (1974); 10. Chiasson (1977); 11. Vrba, Schmidt & Burke (1977); 12. Deurbeck, Rindermann & Seiter (1980); 13. van den Bergh (1976); 14. van Genderen (1979); 15. Burkhead & Seeds (1970); 16. Borra & Anderson (1970); 17. Tempesti (1972); 18. Cecchini & Gratton (1942).

In contrast with the situation of DN, in the CN we cannot deduce M_V(min) simply by adding the range to M_V(max). At maximum light of a CN we have

$$m_V(\text{max}) = M_V(\text{max}) - 5 + 5 \log d + A_V$$

where, as a result of the approximate sphericity of the expanding nova shell, the correction $\Delta M_V(i)$ is not required. At minimum light

$$m_V(\text{min}) = M_V(\text{min}) - 5 + 5 \log d + A_V + \Delta - \Delta M_V(i)$$

and hence

$$M_V(\text{min}) = M_V(\text{max}) + \text{Range} + \Delta - \Delta M_V(i). \quad (45)$$

As shown in Section 2, $\Delta = 0$ except for the longest period systems (no significant contribution to Δ is made by the bright spots in CN). We can therefore deduce M_V(min) for individual CN only for those systems where i is known. However, for statistical purposes we can use $M'_V(\text{min}) = M_V(\text{max}) + m_V(\text{min}) - m_V(\text{max})$ knowing that it will be independent of the often heavy interstellar extinction that affects CN.

There is considerable inhomogeneity in the data given in Table 4: not only is there an unavoidable mixture of m_V and m_{pg}, there will also be systematic differences (but probably not of great importance here) between t_n found from visual and from photographic light curves. Fortunately, the unreddened colours of CN at maximum and at minimum light are not greatly different from zero, so any method which derives M_V(min) by an extinction-independent method is insensitive to the choice of m_V or m_{pg}, provided the same system is used for both m(max) and m(min). The direct application of the expansion-parallax method, or any of the techniques other than the M_V(max)–t_n relationship, requires a measurement of A_V; we will therefore concentrate here on application of equation (44).

5.2 COMPARISON OF DIFFERENT METHODS

We have found only four CN for which distances are available both from the K-magnitudes of the secondaries and from a reliable independent method. These are listed in Table 5.

The comparison, although very limited, gives similar values of M'_V(min) by the various methods. In particular, the sample contains CN ranging from very fast to very slow yet produces the same ordering among the M'_V(min) by the K-magnitude method and the alternatives. The absence of any very large differences, despite the range of a factor of 25 in t_2 and the spread of 3 mag in M'_V(min), is encouraging.

A comparison with M_V(min) derived from the surface brightness method, which requires i to be known, is given in Section 5.4.

5.3 ACCRETION DISC INCLINATIONS

Direct determinations of orbital inclinations are available for a few eclipsing CN. Although it is fortunate that the eclipsing systems afford the best opportunity of finding i for the high inclination

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Notes to Table 4:

m(max) are mostly from Evans & Bode (1987) and include extrapolated values.
m(min) are from the GCVS, with improvements where possible.
A_V are mostly from Duerbeck (1981).
t_2 are from Warner (1986b) and Duerbeck (1981) – see Section 5.1.
*See Section 5.6 and Table 8.

Table 5. Comparison of absolute magnitudes.

Star	P(h)	m_V^*(max)	m_V(min)	A_V	t_2	M_V^{**}(max)	d(pc)	M_V'(min)$^+$	M_V'(min)$^{++}$
DQ Her	4.65	1.3	14.7	0.16	67	-6.3	327±84	7.1	7.0±0.5
HR Del	5.14	3.3	12.1	0.56	152	-5.4	285	3.4	4.2
V841 Oph	(7.0)	2:	13.3	1.25	56	-6.5	255	4.8:	5.0
GK Per	47.9	0.2	13.0	0.7	2	-8.8	337	4.0	4.7

* From Evans & Bode (1986).
**From equation 44.
$^+$ From $M_V'(\mathrm{min}) = M_V(\mathrm{max}) + m_V(\mathrm{min}) - m_V(\mathrm{max})$
$^{++}$From $M_V'(\mathrm{min}) = m_V(\mathrm{min}) + 5 - 5 \log d - A_V$

Notes:

DQ Her — m_V(min) from Patterson (1979a); A_V (for all stars in Table 5) from Duerbeck (1981); d from Young & Schneider (1981) – from red spectrum of secondary and assumption that it is a normal main-sequence star, which it is according to Patterson (1984).

HR Del — d from K of Berriman *et al.* (1985) and equation (3).

V841 Oph — d from K of Berriman *et al.* (1985) and equation (3).

GK Per — Sherrington & Jameson (1983) gave d=726 pc from *JHK* photometry and the spectral type K2IV of the secondary. From their $V-K$ colour (assumed to be entirely from the secondary) corrected for reddening, we find S_K=3.77. The other quantity needed in equation (1), namely $R_2/R_\odot$, is found from Patterson's (1984) equation (11) and M_2=0.2 $M_\odot$. The long period of GK Per excludes use of equation (3). Use of the Sherrington & Jameson distance would give M_V'(min)=3.0. Note that in Tables 4 and 5 no correction for the contribution of the secondary has been made.

systems where $\Delta M_V(i)$ [equation (4)] is most sensitive to i, for our present needs we would like to keep errors in $\Delta M_V(i)$ to $\leqslant$0.2 mag, which requires i to be known to $\leqslant$10° at intermediate inclinations and ~20° for small inclinations. There are very few CN of intermediate inclination that can meet these strictures.

Eclipses are observed in T Aur (Walker 1963; Bianchini 1980), BT Mon (Robinson, Nather & Kepler 1982), RR Pic (Haefner & Metz 1982; Warner 1986a) and WY Sge (Shara & Moffat 1983; Shara *et al.* 1984), all of which furnish reliable orbital inclinations. The case of DQ Her illustrates a rarely occurring but important point: interpretation of the eclipse profile leads to $68° \leqslant i \leqslant 85°$ (Warner 1976; Young & Schneider 1981) but modelling of the phase variation during eclipse of the 71-s oscillations (Petterson 1980; O'Donoghue 1985) requires i=89°. As the accretion disc subtends an unknown half-angle Δi at the primary, these latter studies actually measure $i+\Delta i$ which would be used in place of i in equation (4). However, the intensity distribution of the reprocessed beam from the white dwarf probably does not appear at all like the limb-darkened distribution of the underlying disc, so the i=89° from the phase shift arises from a different weighting over the surface of the disc and is not necessarily the precise value to be used in equation (4). There is no doubt, however, that in DQ Her $i+\Delta i$ is close to 90° where the correction $\Delta M_V(i)$ is both sensitive to i and uncertain.

The systems of very low inclination can usually be recognized by their narrow emission-line widths (e.g. V841 Oph and DI Lac: Kraft 1964) or small K_1. The later is not an unimpeachable diagnostic: in the eclipsing CN WY Sge, K_1 is only ~50 km s^{-1} (Shara *et al.* 1984).

In Table 6 and its supplementary notes, CN with inclinations previously measured or estimated by the above methods are listed. From these data it emerges that, with the caveat that the number of objects is small, there is a good correlation between inclination and the equivalent width of the emission lines, particularly with Hα which shows a wide range in the CN: Fig. 8. This relationship presumably arises because the emission lines are produced in a volume that is optically thin and not totally obscured by the disc at high inclinations. It provides us with a means of extending our estimates of i to several more systems; these also are listed in Table 6. Only those CN are included for which the orbital period is known or has been estimated from a colour–period relationship (Vogt 1981).

5.4 CLASSICAL NOVAE WITH KNOWN ORBITAL INCLINATIONS

The CN listed in Table 6 are the only ones that we can place in the M_V(min)–P diagram. As previously pointed out (Warner 1985b), studies of CN at minimum have been neglected relative to those of the DN and as a result few orbital periods are known. Fig. 9 confirms the conclusion, based on a similar data set, that M_V(min) for CN show a quite small spread about an average $\bar{M}_V$(min)=4.3. However, the inclusion in Fig. 9 of the mean relationship found in Section 4.1 for DN at maximum of outburst now suggests an alternative interpretation, namely that within observational uncertainty [which for the CN, including the errors in t_2 and the coefficients of equation (44) and the additional problems of determining m_V(max), m_V(min) and $\Delta M_V\,(i)$, certainly amounts to ± 0.5 mag], the quiescent CN discs and the DN at maxima follow the same relationship. Because of the absence of CN with $P{\sim}1\frac{1}{2}$ hr [the spectroscopic and photometric modulations at 95 min in CP Pup (Warner 1985c) have yet to be proved an orbital rather than a rotational period], the baseline in P is too small, given the relatively large errors and the uncertainty in P for many systems, to detect a definite trend with P, but the brighter magnitude of DI Lac is suggestive. At P=2 day, GK Per (Table 5) with $i{\sim}75°$ (Warner 1986b) and half of the V-flux contributed by the secondary, has M_V(min)~3.6, but such a long-period system has an evolved secondary which may be transferring mass at a rate determined by nuclear evolution rather than magnetic braking.

Fig. 9 illustrates the sensitivity of M_V(min) to the adopted value of i for DQ Her: if we use i=87° or 86° instead of the 89° listed in Table 6, then DQ Her is no longer discrepant. Two equally acceptable values of M_V(min) are available for HR Del from Tables 5 and 6; both are indicated in Fig. 9.

As can be seen in Table 6, the surface brightness method gives surprisingly good M_V(min) for the CN. Only for DI Lac is there serious discord, which could be removed if $i{\sim}50°$ rather than the 30° assumed here.

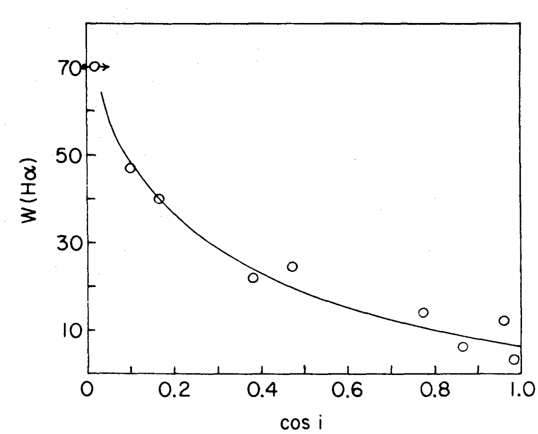

Figure 8. Dependence of Hα equivalent width on orbital inclination for classical nova remnants.

Table 6. Orbital inclinations and absolute magnitudes of classical novae.

Star	P(h)	i°	$\Delta M_v(i)$	M_v'(min)	M_v^*(min)	A_v	$(B-V)_o$	M_v^+(min)	W(Hα)	t_2(d)
V476 Cyg	(3.1)	65:	0.4:	5.4	5.0:	0.85	-0.12	4.5:	20:	6
V603 Aql	3.32	16	-0.93	3.6	4.5	0.5	-0.22	4.0	12	3.5
V1500 Cyg	3.35	55	-0.07	4.3	4.4	1.25				2
RR Pic	3.48	70	0.72	5.0	4.3	0.04	-0.10	4.3	-	80
WY Sge	3.69	80:	1.65:						40:	
Q Cyg	(3.7)	(50)	-0.3:	3.7	4.0	1.4	-0.11	4.2:	14	11
HR Lyr	(4.3)	(30)	-0.8:	2.6	3.4	0.45	-0.01	4.4:	8	45:
DN Gem	(4.4)	(30)	-0.8:	4.5	5.3	0.27	0.12	4.8:	9	17
V841 Oph	(4.6)	0:	-0.99	2.8:	3.8:	1.25	0.00	4.3:	3.3	56
DQ Her	4.65	89:	4.4:	7.1	2.7:	0.16	0.01	4.3	70	67
T Aur	4.91	68	0.58	4.7	4.1	1.25	-0.12	3.8	21	80
HR Del	5.14	40	-0.54	3.4	3.9	0.56	-0.15	3.9	-	152
V533 Her	6.7:	62:	0.2:	4.1	3.9:	0.25	0.10	4.1	22	26
FH Ser	(7.5)	40	-0.54	3.7	4.2	2.3:	0.40:		14	35
BT Mon	8.01	84	2.29	6.3	4.0	0.63			47	140
DI Lac	13.0	30:	-0.75:	2.6	3.4:	1.3	-0.16	2.2	6	20

*From Equation (44).
+From Equation (11).
Estimated orbital periods appear in brackets. Inclinations found from W(Hα) and Figure 8 also are bracketed. $(B-V)_o$ is from Bruch (1984) and A_v from Deurbeck (1981).

The M_V(min) plotted in Fig. 9 include novae with t_2 ranging from 2 to 152 day (Table 6), i.e. from very fast to very slow novae (Payne-Gaposchkin 1957). There is no correlation between t_2 and M_V(min), nor between t_2 and P.

Next we want to consider what may be learned from the M_V'(min) in Table 4, but first we must investigate possible contamination of Table 4 by errors and unrecognized interlopers. For this purpose we turn briefly to examine the recurrent novae.

5.5 ABSOLUTE MAGNITUDES OF RECURRENT NOVAE

The observational data base for recurrent novae (RN) is not very extensive. Definite orbital periods are known only for T CrB (P=228 day) and RS Oph (P=230 day: Garcia 1986). The secondaries in V1017 Sgr and U Sco are G giants, which would give P~day.

Table 7 brings together information from which a comparison may be made between M_V(max) calculated from the rate of decline [equation (44)] and from the independent methods listed in the Notes to Table 7. Within the uncertainties of the methods, the agreement is excellent, which

Notes to Table 6:

V476 Cyg — P from Vogt (1981); W(Hα) an uncertain measurement from Shara (1986, private communication). Our choice of m_v(min) (Table 4) requires an explanation: in the third edition of the GCVS and in Payne-Gaposchkin (1957) it is listed as 16.2 and constant (on average). Bruch (1984) lists 17.1 and gives $B-V$=0.15, so it is irrelevant whether the earlier measurements were m_V or m_{pg}. The flux distribution observed by Shara *et al.* (1987) gives m_V~18.5. There is evidence, therefore, that V476 Cyg, having been constant for many decades, may now be fading rapidly.

V603 Aql — W(Hα) is an average of Williams (1983) and Shara (1986, private communication). An inclination of 16° was found from the shell structure by Mustel & Boyarchuk (1970) and 15° by Warner (1976) from $v \sin i$ and K_1 of the accretion disc.

V1500 Cyg — The pre-nova had m_V(min)>21, but the post-nova has settled down to m_V(min)=16.3. For references and discussion see Warner (1985b, c). i is from Sanyal & Willson (1980).

RR Pic — i is from the presence of shallow eclipses, probably of a bright spot on the rim of the accretion disc (Haefner & Metz 1982; Warner 1986a). Spectra show RR Pic to be hydrogen-poor (Wyckoff & Wehinger 1977) so W(Hα) is not used here.

WY Sge — i from eclipses; W(Hα) estimated from published spectra (Shara & Moffat 1983).

Q Cyg — P from Vogt (1981); W(Hα) from Shara (1986, private communication).

HR Lyr — P from Vogt (1981); W(Hα) from Shara (1986, private communication). t_2 is very uncertain for this star (see light curve Cecchini & Gratton 1942) but t_3=80 day is better defined and suggests t_2=40–50 day.

DN Gem — P from Vogt (1981); W(Hα) from Williams (1983): Shara (1986, private communication) gives W(Hα)<4Å.

V841 Oph — P from Vogt (1981); i from narrowness of emission lines and absence of detectable K_1. W(Hα) is average of Shara (1986, private communication) and Williams (1983).

DQ Her — i from Petterson (1980) and O'Donoghue (1985) – but see discussion in text. W(Hα) from Williams (1983).

T Aur — i from width of eclipse [the value i=57° given by Bianchini (1980) and repeated by Ritter (1984) is only a lower limit]. W(Hα) is the average of Williams (1983) and Shara (1986, private communication).

HR Del — i from Soderblom (1976), Hutchings (1979) and Solf (1983). Hα is contaminated with shell emission and therefore rejected here.

V533 Her — i from absence of eclipses (Robinson & Nather 1983) but large width of emission lines (Williams 1983).

FH Ser — P from Vogt (1981); i from Hutchings (1972).

BT Mon — i from eclipse width and depth (Robinson, Nather & Kepler 1982); W(Hα) from Williams (1983).

DI Lac — i from narrowness of emission lines (Kraft 1964) but existence of measurable K_1 (Ritter 1984). W(Hα) is the average of Williams (1983) and Shara (1986, private communication).

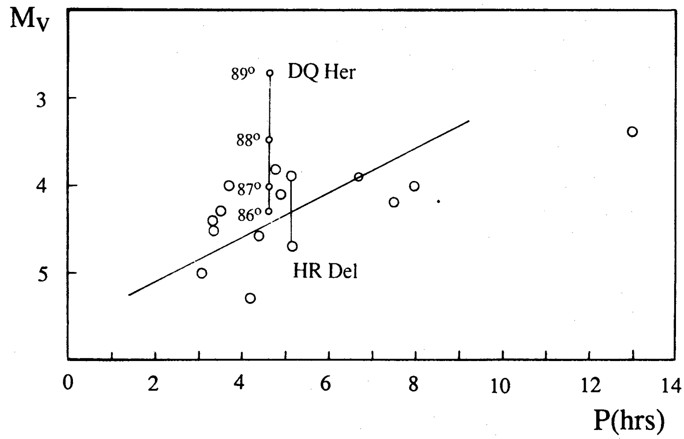

Figure 9. Absolute magnitudes of the accretion discs of classical novae as a function of orbital period. The effect of changes in the assumed inclination of DQ Herculis is shown. Two independent estimates of M_V for HR Del are connected with a vertical line.

establishes empirically that the $M_V(\max)$–T_2 relationship for CN applies to RN. As it has been proposed (Webbink 1976) that the T CrB eruption is an accretion rather than a thermonuclear event, this is not a trivial result.

The values of $M_V'(\min)$ in Table 7 are essentially (except for T Pyx) the luminosities of the secondaries. As pointed out previously (Warner 1976) the true amplitudes of the RN may well be the same as those of the CN. The spectrum of T Pyx at quiescence is dominated by narrow emission lines (Warner 1976) suggesting an accretion disc of small inclination. From Table 7 and equation (4) this gives $M_V(\min)\sim3.0$ for T Pyx, which is in accord with Table 6 if T Pyx has $P\sim1$ day.

5.6 PROBLEM STARS IN TABLE 4

The rather small selection of CN that we have investigated in Table 6 gives the strong impression that $M_V(\min)\gtrsim3.0$ and hence $M_V'(\min)\gtrsim2.0$. There are, however, a few stars in Table 4 which show unusually small ranges with resulting $M_V'(\min)<2$. These 'problem' stars are listed in Table 8.

There are several effects that may cause the range A_{CN} to be too small (but probably none, other than a real fading of the CN itself beyond a normal $M_V(\min)$, that increase the range

Notes to Table 7:

T CrB Distance from Duerbeck (1981), based on expansion-parallax method, and Sherrington & Jameson (1983) from K-magnitude of the secondary.

RS Oph Distance from Davies (1986) based on interstellar lines, H *I* absorption-line profiles and absolute magnitude of the secondary. A_V from Bruch (1984) and Cassatella *et al.* (1985).

T Pyx Distance from Duerbeck (1981) and Bruch, Duerbeck & Seitter (1981). A_V from Bruch (1984).

V1017 Sgr Kraft (1964) gives G5IIIp for the secondary, which dominates the visible spectrum. This agrees, after dereddening, with $V-K=3.07$ found by Feast & Glass (1974). $M_V=0.7$ for G5III (Allen 1973). A_V from Bruch (1984).

U Sco $m_V(\min)$ and A_V from Hanes (1985), who finds a spectral type of GO (±5) and indeterminate luminosity for the secondary. To be in accord with $M_V^*(\min)$ of Table 7 the luminosity class would be II–III (Allen 1973). U Sco would then have an orbital period~few days.

Table 7. Recurrent novae.

Star	Dates of Eruption	T_r(yrs)	m_v(max)	m_v(min)	A_r	t_2(d)	A_v	M_v^*(max)	M_v^+(max)	$M'_v{}^*$(min)	$M'_v{}^+$(min)
T CrB	1866, 1946	80:	2.0	10.0	8.0	3.8	0.26	-9.3	-8.6	-2.6	-2.5
RS Oph	1898, 1933, 1958, 1967, 1985.	22	5.3	11.4	6.1	6.7	2.4	-8.7	-8.8	-1.3	-0.8
T Pyx	1890, 1902, 1920, 1944, 1966.	19	7.0	15.3	8.3	62	1.12	-6.4	-6.5:	1.9	1.8
V1017 Sgr	1901, 1919, 1973.	36:	6.2	13.6	7.4	60	1.38	-6.4	-6.7:	1.0	0.7:
U Sco	1863, 1906, 1936, 1979.	39	8.9	17.8	8.9	2	0.6	-10.0		-1.1	

*Calculated from equation (44).
+From independent distance estimate (see Notes).

Table 8. Classical novae: problem stars.

Star	Date	t_2	M_V(max)	m_V(max)	m_V(min)	Range	M'_V(min)	Notes
AR Cir	1914	208	-5.1	10.3	15.0	4.7	-0.4	1
KT Mon	1942	20	-7.6	9.8	15.5	5.7	-1.8	2
FM Sgr	1926	15	-7.9	8.6	16.5	7.9	0.0	3
GR Sgr	1924	120?		11.4?	16.6	5.2?		4
HS Sgr	1901	120:		11.6?	16.5	4.9?		4
V630 Sgr	1936	4	-9.2	4.0	14.4	10.4	1.2	
V1016 Sgr	1899	12	-8.1	6.9:	14.9	8.0	-0.1	3
V1944 Sgr	1960			7.0	13	6		3
V2572 Sgr	1969	20	-7.6	6.3	14.8	8.5	0.9	
FS Sct	1952	14	-7.9	10.1	16.6	6.5	-0.3	

1. McLaughlin (1939) suspects wrong identification of remnant.
2. Payne-Gaposchkin (1977) says possible RN.
3. Payne-Gaposchkin (1977) says m_V(max) is very uncertain.
4. The true maximum probably was unobserved.

significantly):

(i) Unobserved or poorly observed maxima, leading to M_V(max) too faint. Payne-Gaposchkin (1977) lists FM Sgr, V1016 Sgr and V1944 Sgr in this category. GR Sgr may be similarly afflicted (see light curve in Cecchinio & Gratton 1942).

(ii) Incorrect identification of the nova remnant with a brighter star. McLaughlin (1960) attributes the small range of AR Cir to this cause.

(iii) Unrecognized recurrent novae. Payne-Gaposchkin (1977) considers this to be a distinct possibility for KT Mon.

From Section 5.5 and Table 7 we see that (iii) could be an important contaminant of Table 4. The RN (excluding T Pyx) have $-2.6<M'_V(\text{min})<1.0$, i.e. in the range shown by the problem stars of Table 8. By definition, a RN is classified as a CN until it shows a second eruption. Second eruptions of some of the stars in Table 8 could have been missed or, if there are objects like T CrB with $T_r \sim 80$ yr among the problem stars, they have yet to happen. It is not possible, on the basis of the few known RN, to estimate how many unrecognized RN could be inhabiting Table 4, but from the m_V(max) listed in Table 7 we would expect there to be several RN that reach $8<m_V(\text{max})<11$, only one of which (U Sco) is so far recognized. The completeness of discovery of nova outbursts is poor for $m_V(\text{max})>8$ [even at $m_V(\text{max})\sim 6$ many apparently are missed: Warner 1987c] so the recognition of RN is difficult: from Table 7 we see that no new RN has been found since 1946. One, however, has been lost: VY Aqr, once classified as a RN, is now realized to be a long-period DN of SU UMa type (Richter 1983). This latter is another possible contributing class to Table 8, but probably only for those novae for which spectra were not obtained at maximum light (the DN are distinctive in not showing an expanding shell during eruption).

We conclude that it is not unreasonable to view the stars in Table 8 with suspicion – not merely because they are discrepant compared with those in Table 6, but because we expect there to be a

Table 9. Mean range and mean absolute magnitudes of classical novae.

Speed Class	t_2 (d)	n	M'_V	n	A'_{CN}
VF	0-10	8	4.4	9	13.2
F	11-25	26	3.7	28	11.3
MF	26-80	12	4.4	12	10.9
S	81-150	4	4.1	4	9.6
VS	151-250	3		3	
VVS	>250	3	5.2:	3	9.4:

number of objects in the above categories (i) to (iii) and these will at least contribute to Table 8. Spectra of all of the objects in Table 8 are required to check their nature (none is particularly faint). For the time being we exclude them from further analysis.

5.7 DISTRIBUTIONS OF M'_V(MIN) AND RANGE

Table 9 gives the mean apparent range, $\bar{A}'_{CN}=\bar{m}_V(\min)-\bar{m}_V(\max)$ and $\bar{M}'_V(\min)$ as a function of speed class, based on the data in Table 4. Uncertain data have been given half weight. The rms dispersion on all of the mean values is $\sim\pm1.0$ mag, but this of course results partly from the effects of the $\Delta M_V(i)$ correction and does not represent the actual spread in A_{CN} or $M_V(\min)$. Within the spread in values, all of the $M_V(\min)$ are equal [with the possible exception of the very very slow novae, which have $t_2>250$ day and are consequently dependent on an extrapolation of equation (44) which may not be valid]. Excluding the VVS novae, the others taken all together have $M'_V(\min)=4.0$, which gives $\bar{M}_V(\min)=\bar{M}'_V(\min)-\overline{\Delta M}_V(i)=4.4$, in reasonable agreement with the weighted mean $\bar{M}_V(\min)=4.1\pm0.4$ obtained from Table 6.

The spread of A'_{CN} within a given speed class is similarly affected by the range of inclinations, but here we cannot improve the statistical analysis by taking all CN together. Table 9 shows the well-known correlation between apparent range and speed class (Payne-Gaposchkin 1957). Because of the small numbers of CN involved we do not sample uniformly over inclination, which will significantly distort the derived values $\bar{A}'_{CN}$. The true range, $\bar{A}_{CN}$, for a large sample is $\bar{A}'_{CN}=\bar{A}'_{CN}-\overline{\Delta M}_V(i)$, so the $\bar{A}'_{CN}$ in Table 9 should be increased by 0.4 mag to obtain better estimates of the true mean ranges.

The general correlation between A'_{CN} and t_2 is shown in Fig. 10, where the general effects of inclination of the accretion disc [on the assumption that all discs have $M_V(\min)=4.4$] are also shown. For the stars with known inclination (Table 6) the effect of the correction $\Delta M_V(i)$ is also indicated.

Both $\bar{M}'_V(\min)$ and $\bar{A}'_{CN}$ are disturbed to an unknown extent by an observational bias towards CN of small range – many of those with large range fade beyond detectability and cannot be included in the analysis. However, if $M_V(\min)\simeq$constant then the only effect is to bias the observational sample away from the rare systems with very large inclinations. There does not appear to be any strong selection effect possible in the $M_V(\min)$ derived in Table 6: those stars have $11.6<m_V(\min)<16.3$ and so are readily observable, and we do not know of any CN of high inclination that has faded beyond reach and hence has been excluded from Table 6.

The large apparent ranges A'_{CN} of DQ Her and T Aur were noted by Payne-Gaposchkin (1957) who suspected as a result that these two stars belong to a distinct class which does not follow the usual $M_V(\max)-t_2$ relationship. However, we now see that the small spread in $M_V(\min)$ implies that the true range A_{CN} is determined entirely by $M_V(\max)$, and that the apparent range A'_{CN} is in

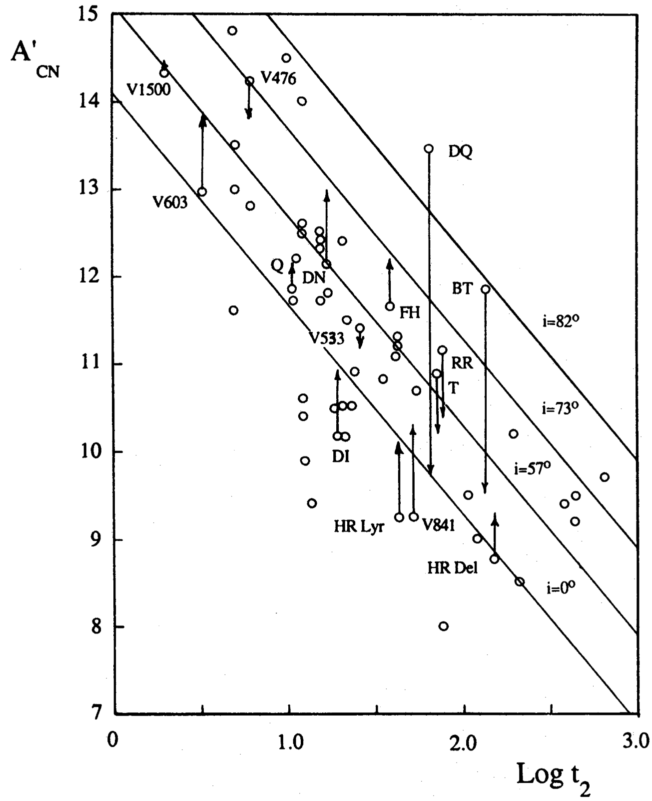

Figure 10. Amplitude–rate of decline relationship for classical novae. The amplitudes A'_{CN} are uncorrected for inclination of the accretion disc. The effects of different inclinations, corresponding to $\Delta M_V(i)=-1, 0, 1$ and 2, are shown by the sloping lines. For stars with known inclinations (Table 6: abbreviated names are given here) the effects of making the corrections $\Delta M_V(i)$ are shown by arrows: the result is a great reduction in dispersion for those stars.

addition influenced by disc inclination. There is therefore no longer a mystery (Payne-Gaposchkin 1977) as to why the range of the $t_2=67$ day nova DQ Her should exceed those of the Very Fast novae V603 Aql and GK Per.

6 Absolute magnitudes of nova-like variables

The nova-like (NL) variables show the spectroscopic and short time-scale photometric behaviour of CVs but have not been observed to erupt (Warner 1976); a few of them (the MV Lyr stars) spend part of their lives in a low state of luminosity. This class of CV is generally considered to include pre-novae, unrecognized post-novae and ZC stars permanently (or at least for long stretches of time in the case of the MV Lyr stars) in standstill. The NL class more generally includes a mixture of other idiosyncratic objects; as more observations of these have been made, common properties have been recognized which have resulted in the definition of further groups such as the polars and intermediate polars. There are still a few stars such as AE Aqr that appear unique.

Among the NL there is a subgroup which has broad absorption lines in the visible spectrum as well as emission lines; these are referred to as UX UMa stars (Warner 1976). Except for AE Aqr we refer to the remainder as RW Tri Stars.

The observational data (Table 10) for the NLs are less extensive and less homogeneous than for the DN and CN. In the absence of outbursts we do not have the special methods of determining distances offered by the latter classes. Only the K-band technique or other uses of the secondaries' fluxes provide distances. Fortunately not only are several of the NLs eclipsing systems, some have low states of mass transfer. In both circumstances the secondaries are more readily observable.

Absolute magnitudes from Table 10 are plotted in Fig. 11. With the exception of AE Aqr [whose unique characteristics are discussed by Chincarini & Walker (1981) and Patterson (1979b)] the NLs are located in the general region of the CN at quiescence. Two stars, CM Del and IX Vel, fall below the luminosity of the ZC stars at standstill and are therefore apparently in the region where DN outbursts should occur. However, these two non-eclipsing stars have not been observed in low states and at normal light the criteria given at the end of Section 2 are not met. We must conclude that their secondaries have not really been detected in the *K*-band and in consequence that their luminosities given in Table 10 are actually lower limits. In order to avoid possible misinterpretation of Fig. 11 we have plotted the M_V of CM Del and IX Vel as upper limits. It may be noted that the bright NLs V3885 Sgr and RW Sex (Table 10), which are similar in most respects to CM Del and IX Vel, have been observed in the *K*-band without certain detection of their secondaries and thus could also have been included in Fig. 11 with upper limits to their M_V.

Another star which falls suspiciously low in Fig. 11 is MV Lyr for which the distance is based on interpretation of red spectra during the low state, rather than the more precise *K*-band photometry. The M_V for MV Lyr and IXVel found from their estimates of distance differ markedly from those found from the surface brightness method ($M_V^\ddagger$ in Table 10). For the other stars in Table 10 there is reasonable accord between the methods.

With more reliable distances for the NL variables it should be possible to distinguish in Fig. 11 between those systems that are ZC stars in extended standstill and those that are more probably pre- or post-novae. With the present data there does not appear to be any systematic difference in luminosity between the UX UMa and RW Tri stars.

7 Miscellaneous other stars

The magnetic CVs (AM Her stars or polars), not possessing accretion discs, cannot be plotted in our M_V, *P* diagrams even when their distances are known. Estimates of their $\dot{M}_2$, however, place them among the DN at minimum light (fig. 7 of Patterson 1984). Of the intermediate polars

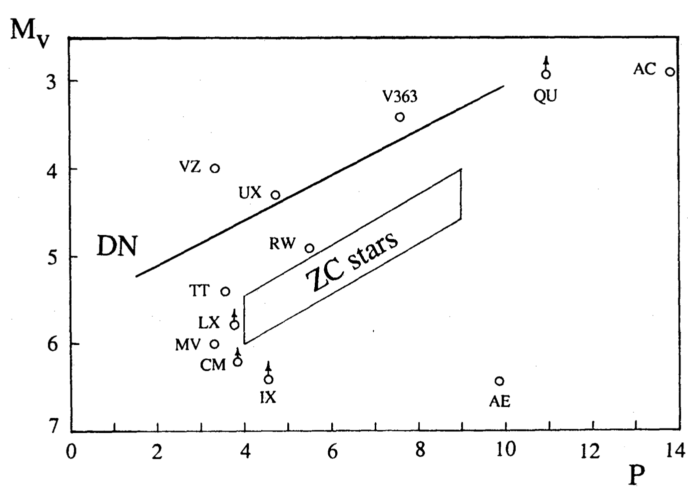

Figure 11. Absolute magnitudes of accretion discs of the nova-like variables as a function of orbital period. The general locations of the dwarf novae at maximum light (Fig. 1) and of the Z Cam stars at standstill (Fig. 2) are shown. Stars are labelled with abbreviated names (see Table 10).

Table 10. Absolute magnitudes of nova-like variables.

Star	P(h)	Type	d(pc)	m_V	i°	$\Delta M_V(i)$	A_V	M_V'	Δ	M_V	B-V	$(B-V)_o$	M_V^+
MV Lyr	3.21	UX	322	12.5	12	-0.96	0	5.0	0	6.0	-0.13	-0.13	4.4
TT Ari	3.30	UX	185	11.1	23	-0.85	0.16	4.5	0	5.4	-0.04	-0.09	4.5
VZ Scl	3.47	RW	530	15.6	85:	2.5:	(0.5)	6.5	0	4.0	0.1	0.00*	4.7
LX Ser	3.80	RW	>300	14.4	75	1.11	(0.2)	<6.9	0	<5.8	0.20	0.13:	5.1:
CM Del	3.89	RW	280	13.4	55:	0:	(0.1)	6.2	0	6.2:			
VY Scl	3.99:	UX		13.2	30:		0.19				-0.05	-0.11	4.1
IX Vel	4.49:	UX	51	9.6	40:	-0.5:	0.10	5.9	0	6.4:	0.00	-0.03	4.2
UX UMa	4.72	UX	300	12.8	72	0.86	0.22	5.2	0	4.3	0.07	0.00	4.3
V3885 Sgr	4.94	UX		10.4	30:		0.16				0.00	-0.05	4.0
RW Tri	5.57	RW	224	13.2	72	0.86	0.75	5.7	0.2	5.0		0.09*	4.4
RW Sex	5.93	UX		10.8	27	-0.80	0.19				-0.02	-0.08	3.7
V363 Aur	7.70	RW	900	14.2	71	0.79	0.9	3.5	0.7	3.4	0.36		
AE Aqr	9.88	--	140	11.5	64	0.36	0	5.7	1.0:	6.4:			
QU Car	10.9	UX	>500	11.4	50	-0.25	0.51	<2.4	0	<2.4	0.02	-0.14	2.6
AC Cnc	13.80	RW	800	13.8	72	0.86	(0.8)	3.5	0.3:	2.9:	0.4	0.14:	3.2:

+From surface brightness method.
*$(B-V)_o$ are from Bruch (1984) except for asterisked values from Vogt (1981).
A_V from Bruch (1984) unless otherwise noted.

(Warner 1983, 1985d), which probably have at least partial discs, only EX Hya (Table 1), V426 Oph (Szkody 1986) and FO Aqr (H2215−086) (Berriman *et al.* 1985) have secondaries detected in the *K*-band. The last two (Table 11) have absolute magnitudes characteristic of DN at minimum light. If plotted in Fig. 2 they would be well below the stability line for steady discs; the fact that they do not possess DN outbursts is presumably connected with the influence of their putative magnetic fields on the inner parts of their discs.

GKPer, although included in Table 5, has not been plotted on any of our diagrams because of its inconveniently long period. However, it can be seen from Table 11 and Fig. 2 that its M_V is sufficiently faint that it almost certainly lies below the $\dot{M}_d$(crit) line, which thus accounts for its DN-like outbursts (Bianchini & Sabadin 1983).

BV Cen has outbursts like a DN but has recently been reclassified as a CN remnant (Menzies, O'Donoghue & Warner 1986). As with GK Per, BV Cen has an M_V faint enough to explain its DN characteristics.

The dwarf nova-like outbursts of GK Per and BV Cen are uncharacteristic in that they have rise times of 30 and 15 day, respectively, as compared with ~1 day for other DN. This may be a result of the larger disc radii implied by the long orbital periods of these two stars. We draw attention here to V446 Her, which had dwarf nova-like outbursts *prior* to its 1960 CN explosion. Robinson (1975) has pointed out that these eruptions had rise times of 10–12 day and as such were uncharacteristic of normal dwarf novae. By analogy with GK Per and BV Cen, it appears likely that V446 Her has a long orbital period.

PG 1012−029 is included in Table 11 in order to illustrate the hazards of using disc models to fit observed flux distributions. Penning *et al.* (1984) found $d \simeq 1200$ pc (with admitted great uncertainty) and hence $M_V \simeq 2.9$ from disc model fitting, but Tables 6 and 10 indicate that at $P = 3.2$ hr,

Notes to Table 10:

MV Lyr — d and i from spectroscopic observations of the secondary while in a low state: Schneider, Young & Schectman (1981), Robinson *et al.* (1981). A_V from Chiapetti *et al.* (1982).

TT Ari — d from K (obtained in low state) of Berriman *et al.* (1985) and equation (3). Vasilevskis *et al.* (1975) give $d > 170$ pc from trigonometric parallax; Wargau *et al.* (1982) give $d \sim 150$ pc from $E(B-V)$. i from Warner (1976).

VZ Scl — d and i from Sherrington *et al.* (1984).

LX Ser — Limit on d from absence of secondary spectrum (Young, Schneider & Schectman 1981b); i from same source.

CM Del — P from Shafter (1985); d from K of Berriman *et al.* (1985) and equation (3); i from K_1 of Shafter (1985). CM Del was classified as a DN but is now considered to be a nova-like (Shafter 1985).

VY Scl — P from Hutchings & Cowley (1984).

IX Vel — (CPD−48° 1577). d from Berriman *et al.* (1985) and equation (3). Eggen & Nienda (1984) give $d = 33$ pc from membership of the Sirius supercluster.

UX UMa — d from K of Berriman *et al.* (1985) and equation (3). i from Petterson (1980).

V3885 Sgr — (CD−42° 14462).

RW Tri — d from K of Berriman *et al.* and equation (3); i from Kaitchuck, Honeycutt & Schlegel (1983); Δ from Oke & Wade (1982).

RW Sex — (BD−7° 3007).

V363 Aur — (Lanning 10). Szkody & Crosa (1981) give $d \sim 900$ pc from the flux distribution of the secondary during eclipse. We use this rather than $d = 600$ pc, obtained from Berriman *et al.* (1985) and equation (3), from observations made out of eclipse. The larger distance is also more compatible with the A_V found by Szkody & Crosa. i from Horne, Lanning & Gomer (1982); Δ from Szkody & Crosa (1981).

AE Aqr — d from Berriman *et al.* (1985) and equation (3); i and Δ from Chincarini & Walker (1981).

QU Car — d from Gilliland & Phillips (1982).

AC Cnc — d from Yamasaki, Okasaki & Kitamura (1983); i from Schlegel, Kaitchuck & Honeycutt (1984).

Table 11. Absolute magnitudes of miscellaneous stars.

Star	P(h)	d(pc)	m_V	i^o	$\Delta M_V(i)$	A_V	M_V'	Δ	M_V
PG1012-029	3.24	1200	15.0	79	1.52	0.2	4.4	0	2.9
FO Aqr	4.03	275	13.5	28	-0.78	0	6.3	0	7.1
V426 Oph	6.0:	100	11.8	60	0.1	0.2	6.6	(0)	6.5
BV Cen	14.6		13.0	62	0.24	1.0	3.8	0.7	4.3
GK Per	47.9		13.0	75:	1.1:	0.7	4.7	1.0:	4.6:

Notes to Table 11

PG1012-029 d and i from Penning et al (1984).

FO Aqr (H2215-086) d from K of Berriman, Szkody & Capps (1985) and equation (3). i from Penning (1985).

V426 Oph d from K of Berriman, Szkody & Capps (1985) and equation (3). i from K_1 of Szkody (1986).

BV Cen M_V' from visual binary companion (Menzies, O'Donoghue & Warner 1986); i and Δ from Vogt & Breysacher (1980) and Gilliland (1982b).

GK Per See notes to Table 5. i from Crampton, Cowley & Fisher (1986).

PG1012−029 is unlikely to have M_V<3.8, whether a NL or an unrecognized CN remnant, in which case D<800 pc.

8 Mass transfer in cataclysmic variables

In Fig. 12 we bring together all of the absolute magnitudes derived in earlier sections that are relevant to the estimation of $\dot{M}_2$: namely, M_V(mean) for the SU and UG stars and M_V(disc) for the ZC, NL and CN classes. We have included the stars from Table 11. Conversion of M_V in Fig. 12 to $\dot{M}$ using the methods of Section 4.4 produces a diagram equivalent to fig. 7 of Patterson (1984) in which a strong increase of $\dot{M}$ with P is apparent: approximately $\dot{M} \mathrel{\tilde{\propto}} P^3$. The fact that one theory of magnetic braking (Rappaport, Verbunt & Joss 1983; Verbunt & Zwaan 1981; Patterson 1984) gives a similar dependence of $\dot{M}$ on P has been cited in its favour (Patterson 1984; Prialnik & Shara 1986); others have considered different braking laws (Verbunt 1984) or have preferred to interpret Patterson's fig. 7 as merely a step function in $\dot{M}$, with higher $\dot{M}$ longward of the period gap and considerable observational or cosmic dispersion at all periods (Shafter *et al.* 1986). With our more detailed investigation we are in a better position to examine these and other possibilities.

We draw attention first to the obvious impossibility of detecting low $\dot{M}$ systems at long orbital periods. This is illustrated in Fig. 12 by the line for the absolute magnitude of the secondary, $M_V(2)$. This has been obtained from equation (5) of Section 2 and from figs 3 and 4 of Patterson (1984); it is in moderately good agreement with the values of Δ adopted in earlier Sections. From Fig. 12 the fainter accretion discs, if such exist, will not be observable (except if in eruption and of

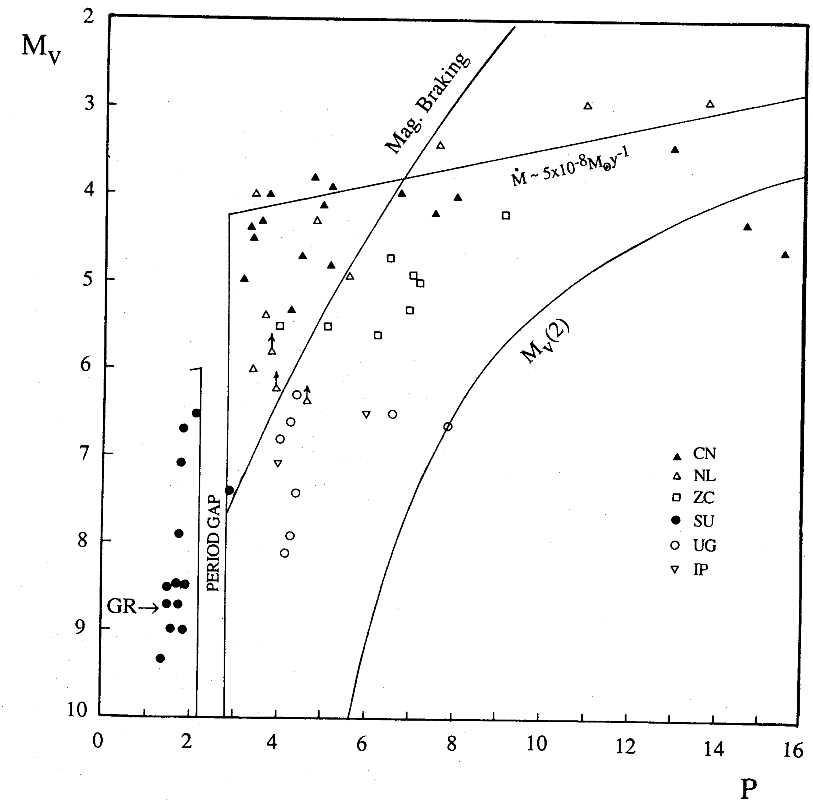

Figure 12. General picture of the absolute magnitudes of accretion discs at mean light, superimposing the results shown in Figs 2, 9 and 11 with additional stars from Table 11. An approximate line of rate of mass transfer $\dot{M}{\sim}5\times10^{-8}\,\dot{M}_{\odot}\,\mathrm{yr}^{-1}$ is shown. The absolute magnitude M_V2 of the secondary is shown as a function of orbital period. A relationship between M_V and P from the theory of magnetic braking is indicated for stars above the period gap. The arrow marked GR shows the visual luminosity expected for mass transfer powered by gravitational radiation.

low inclination) for $P \lesssim 10$ hr. Recalling that a face-on disc is one magnitude brighter than the M_V plotted in Fig. 12, there should be no serious loss of detectable CVs for $P<10$ hr and hence the correlations between M_V and P found for DN do not arise from such a selection effect.

With this restriction taken into consideration, and the fact that CVs with long orbital periods are relatively rare, Fig. 12 is compatible with the hypothesis that there is a wide range of M_V at all P above the period gap. The upper bound to the range is at $M_V{\sim}3.5$, or $M{\sim}5\times10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$. Below the period gap the upper bound is $M_V{\sim}6.5$, or $M{\sim}5\times10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$.

For comparison, the Patterson (1984) $\dot{M}(P)$ law for $M_1=1\,M_{\odot}$ transformed to $M_V(P)$, is shown in Fig. 12. This and the other theoretical $\dot{M}(P)$ laws mentioned above fail to reproduce either the general trend of M_V above the period gap or the upper bound. Below the period gap, gravitational radiation can account for the luminosity of the fainter systems but the predicted $\dot{M}$ (e.g. Patterson 1984) fails by a factor of 10 to account for the brightest systems.

In summary: for observed CVs with $1.5<P<6$ hr many systems have more luminous discs, and hence higher deduced rates of mass transfer, than the theory of magnetic braking allows.

The upper bound on luminosity for the CN and NL systems is close to the relationship found in Section 4.1 for DN during outburst. This could be further evidence for an upper limit on the mass transfer in CV accretion discs. If so, then some of the CN and NL systems may have $-\dot{M}_2>\dot{M}_d$ and will be storing mass in their discs. Other possibilities are discussed later.

9 Secular and cyclical evolution of cataclysmic variables

Although we have found that the theoretical form of mass transfer caused by magnetic braking does not fit the observed trends, the theoretical rate is certainly of the correct order of magnitude to explain the highest observed values of $\dot{M}$. There is, however, no parameter in the theory that will account for the observed range of $\dot{M}_2$ at a given P. Such a parameter, as we have seen in Section 4.6 and later discussions, determines the classification of a CV, i.e. whether it is a UG, ZC or a member of the NL or CN classes – and it determines the recurrence time T_n if it is a member of the first two classes.

Given that the loss of angular momentum which drives mass transfer also causes secular evolution of the system towards shorter orbital periods (we limit discussion to evolution before any period 'bounce': Verbunt 1984), a possible source of $\dot{M}_2$ variation could be age. If CVs are formed over a range of initial orbital periods then there will be a spread of age at any given P. However, if the very low rates of mass transfer implied by the fainter M_V(mean) above the period gap in Fig. 12 are to be characteristic of these systems at all future times, then their rate of evolution is too slow to drive their secondaries out of thermal equilibrium and the currently favoured explanation of the period gap as resulting from shrinkage of the secondary on becoming fully convective (Verbunt 1984) will not work for them. The absence of low or intermediate $\dot{M}$ systems in the period gap argues against such a scenario, in which case the systems above the gap with low $\dot{M}$ must spend at least part of their lives (sufficient to prevent establishment of equilibrium on the Kelvin–Helmholtz time-scale) in a high $\dot{M}$ condition. Unless causes can be found for large variations in effectiveness of magnetic braking on relatively short time-scales we must seek an explanation elsewhere.

The idea that DN and CN are the same objects seen at different stages of evolution has often been suggested, as has the probability that NL systems are pre- or (unrecognized) post-novae. In recent years it has been argued (Vogt 1981, 1987), on the general grounds of similar physical structure of CN and DN, and the fact that the recurrence time T_{CN} for CN is short compared with secular evolutionary time-scales, that there may be cyclical exchange between CN and DN. The same conclusion has been reached from a different approach by Shara *et al.* (1967) and a complete theoretical cycle of CN evolution has been computed by Prialnik & Shara (1987). In order to view the results of our analysis in the context of this evolutionary scheme we describe the mechanisms in more detail.

Shara *et al.* (1987) find that a nova explosion, which ejects a shell of mass $\sim 1-5\times10^{-5}\ M_\odot$, theoretically should result in sufficient loss of angular momentum to increase the separation of the components by a fraction $\sim 10^{-4}-10^{-5}$. The observed increase in orbital period of BT Mon by a fraction 4×10^{-5} after its 1939 eruption is supporting evidence for such an effect (Schaefer & Patterson 1983). The resulting increase in size of the Roche lobe can cause a decrease, even a cessation, of mass transfer from the secondary. However, for 50–200 yr after the nova explosion mass transfer is sustained at a high rate because of heating of the secondary by the now much hotter white dwarf primary. Evidence for a reduction in $-\dot{M}_2$ from the secondary in RR Pic, 50 years after the nova explosion, has recently been found (Warner 1986a). The novae WY Sge (1783) and CK Vul (1670) are the two oldest recovered CN; the former has $M'_V\sim7$ ($M_V\sim5.5$: Table 6) (Shara & Moffat 1983; Shara *et al.* 1984) and shows DN outbursts, the latter has $M_V\sim10.5$ and is probably not transferring mass at all (Shara & Moffat 1982; Shara, Moffat & Webbink 1985).

After termination of mass transfer there can be a period of 'hibernation' during which the CV would not be observable as a UV-rich object. Shara *et al.* (1987) claim that at this time the CV will appear as a normal G, K or M dwarf and therefore be difficult to recognize, requiring detection of the orbital radial velocity variations for identification. However, this overlooks the continued tidal interaction during the phase of detachment, which will keep the secondary rotating synchronously with the orbital revolution. As a result, the secondary will have an equatorial rotational velocity ~130 km s^{-1} (Warner 1976) which will not only be distinctive among the universally slow rotation of lower main-sequence stars but should generate exceptional magnetic and associated activities. For high-inclination systems there will also be photometric variations with the orbital period because of tidal distortion of the secondary. A search for such objects should be made.

Continued magnetic braking, together with the tidal interaction, eventually brings the secondary back into contact with its Roche lobe, with low rates of mass transfer at first, increasing as the Roche surface penetrates deeper into the upper regions of the secondary until the high $\dot{M}$ observed for pre-novae is reached.

V1500 Cyg before its 1975 eruption had $M'_V \gtrsim 10$, rising to $M'_V \sim 7.5$ at least a week before the eruption, but has been steady at $M'_V \sim 5$ for the past few years (Warner 1985c) CP Pup was at $M'_V \gtrsim 7.5$ before its 1942 eruption but has been at $M'_V \sim 5$ for the past 20 years (Warner 1985c).

Although these systems prove that at least some CN can have very low rates of mass transfer prior to, or long after, eruption, which is compatible with the cyclical evolutionary scheme of Shara *et al.*, there is a caveat to be kept in mind. WY Sge and V1500 Cyg have orbital periods of 3.7 and 3.3 hr, respectively and CK Vul has been shown to have $P<3.6$ hr (Shara *et al.* 1985). As such, these systems have orbital periods near the period gap, where other stars (e.g. MV Lyr, TT Ari, VZ Scl) are known to have occasional bouts of low $\dot{M}$. There is no certainty, therefore, that the low states of CK Vul, V1500 Cyg and WY Sge are definitely a result of Roche lobe expansion – it is possible that whatever mechanism causes the MV Lyr systems to descend in luminosity was triggered by the nova explosions in WY Sge and CK Vul.

Robinson (1975) has shown that some pre-novae have gradual rises in brightness for several years before eruption and that V446 Her had dwarf nova-like eruptions for some years prior to the nova explosion (see discussion in Section 7). The latter star has $m_V = 15.8$ as a post-nova (this is the magnitude used in Table 4), which corresponds to $M'_V = 4.0$. The eruptions prior to its becoming a CN took it from 18.0 to 15.0 mag (Robinson 1975), which correspond to $3.2 < M'_V < 6.2$, but the minimum light magnitude may contain a substantial contribution from the secondary if the orbital period is long (Section 7). At the maxima of their DN outbursts, GK Per and BV Cen have $M_V \sim 2.5$ (deduced from their M_V in Table 11 and amplitudes ~2 mag). If V446 Her is similar to these stars, as suggested in Section 7, then its $M'_V \sim 3.2$ at maximum eliminates the possibility of a large inclination (this is also required by $M'_V = 4.0$ for the post-nova). Hence $M_V \sim 6$ when the star was at $m_V = 18.0$ prior to CN explosion, which places it below the region of stable mass transfer in agreement with its pre-nova behaviour.

Of the pre-novae showing systematic rises in brightness before the CN explosion, V533 Her presents an interesting problem. This star had $m_V = 14.2$ as a pre-nova [table I of Robinson (1975): note that his fig. 5 includes the contamination of an optical companion], but rose to $m_V \sim 12.0$ over a 2-yr interval, culminating in the 1963 CN. At its brightest, therefore, $M_V \sim 1.5$ (*cf.* Table 6), which is much brighter than any known pre- or post-nova disc (Fig. 9). Therefore we should either reconsider the rejection of the problem stars of Table 8, or, on the more relevant grounds that no NL has such a bright disc (Table 10, Fig. 11), look for an alternative source for the increased luminosity. Although not popular with contemporary modellers of nova explosions, the suggestion that the white dwarf itself can sometimes increase in luminosity prior to the CN must be reconsidered (see discussion by Robinson 1975). In the context of the cyclical model of CV evolution discussed here, this seems a preferable hypothesis to the alternative that the addition of only a few years' worth of high mass transfer was sufficient to trigger the CN explosions in V533 Her and LV Vul (Robinson 1975) or even a few weeks of high mass transfer in the case of V1500 Cyg (Warner 1985c).

In terms of cyclical evolution we can interpret Fig. 12 in the following way. A CV emerges from hibernation as a low-luminosity DN with large T_n at the bottom of Fig. 12. As $\dot{M}$ increases it moves up the diagram at constant P, remaining as a DN but with increasingly frequent outbursts until it passes across the $\dot{M}(T_{crit})$ line. The mysterious parameter which produces the spread in $\dot{M}$ at a given P is identified as the amount of underfilling of the Roche lobe. This may have a double-valued relationship with the time since the last outburst: a dwarf nova may be a CV on the way down from the last CN explosion or on the way up after hibernation.

The lifetime as a DN cannot in general* be less than ~500 yr otherwise there would be obvious changes in T_n in many of the known DN. Because of the erratic nature of DN outbursts it will be difficult to establish statistical significance of any measured $\dot{T}_n$. For SS Cyg, the first half of the light curve for 1896–1985 (Mattei *et al.* 1986) gives T_n=51.0 day and the second half gives T_n=47.6 day. In U Gem, the first half of the 1855–1955 light curve has T_n=96.5 day and the second half T_n=107.6 day (Mayall 1957); according to Matei (1986, private communication) the mean period for 1937–56 is 111 day and for 1956–77 it is 112 day. If these changes are truly secular then, in terms of the cyclical evolutionary model and equation (34), SSCyg has an increasing $\dot{M}$ and will reach the Z Cam region in ~500 yr, whereas U Gem has a decreasing $\dot{M}$ and may be descending from its last nova outburst.

According to the latest work on CN explosions, which includes the effects of diffusion in the white dwarf during the time of hibernation (Prialnik & Shara 1987) a CV will exist as a NL pre-nova only until it has accumulated $1-5\times10^{-5}$ $\dot{M}_\odot$ on the white dwarf, at which point the next nova explosion occurs. With the high values of $\dot{M}$ implied by Fig. 12 the pre-nova will last only 200–1000 yr. Following the nova explosion the CV will remain as a NL for 200–500 yr until the irradiation-induced high $\dot{M}$ ceases. At this time the star begins to sink in brightness, perhaps lingering long enough to exist temporarily as a DN in the manner of GK Per, BV Cen and WY Sge. Thereafter the CV hibernates as a detached system.

The upper envelope to M_V in Fig. 12 results, in the cyclical evolutionary picture, from the disappearance of CVs from the top part of the diagram, to recycle through the low $\dot{M}$ phase. Even if higher rates of mass transfer could be generated, as for example in a positive feedback mechanism acting through heating of the secondary by the primary, the star is prevented from going to higher luminosities by the intercession of the nova explosion. Note, however, that if there is a maximum developable rate of mass transfer, as hinted at in earlier sections, then the NL pre-nova will store mass in its disc only for the time from when it reaches the limiting mass transfer until the nova explosion disrupts the disc. In the present scenario this could produce disc masses ~few$\times10^{-6}$ $\dot{M}_\odot$ at the time of the explosion. Note also that with such an upper limit on mass transfer there is a natural explanation for the identity of luminosity of the discs in pre- and post-novae: even if the irradiation-induced $-\dot{M}_2$ of the post-nova is greater than in the pre-nova, the disc will be unable to transmit the mass at the higher rate. This process itself would maintain the disc at a high luminosity for some time beyond the point at which mass transfer from the secondary begins to decline.

The lifetime of the hibernation state should be relatively short for systems above the period gap. Conventional theory of magnetic braking requires only ~1000 yr to restore the components to their separation at the previous nova explosion (Shara *et al.* 1987), during which the whole of the hibernation and DN phases must be traversed. Our higher rates of mass transfer, unless generated by a more efficient process than the braking mechanism, imply even shorter recovery times. Thus the recurrence time T_{CN} should be ~2000 yr. A lower limit of $T_{CN}\gtrsim1000$ yr is set by the absence of any known CVs among the Chinese records of the novae of a millennium ago (Shara 1986, private communication).

*That is, for established DN. Some stars may rise so quickly, as appears to have been the case for V1500 Cyg, that they spend no significant time in the DN region.

A value of T_{CN} ~2000 yr based on observed space densities of CN, was obtained by Patterson (1984) and by Duerbeck (1984). With such short CN recurrence times the problem of there being an uncomfortably large number of unrecognized novae between outbursts (Bath & Shaviv 1978) largely disappears.

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Appendix: Cataclysmic variables nearer than 300 pc

The systematics of absolute magnitudes discussed in this paper provide a means of evaluating distances to cataclysmic variables. In order to provide a list of targets for large astrometric reflectors or the HST, we arrange in Table A1 the CVS in order of distance up to 300 pc.

Additional NL variables, for which we have no orbital periods, which may be nearer than 300 pc are CL Sco (m_V=11.2), V592 Cas (12.8), KQ Mon (13.0) and HS Vir (13.0).

Table A1. The nearest cataclysmic variables.

Star	Type	d(pc)	m_V	Star	Type	d(pc)	m_V
VW Hyi	SU	65	13.3	CU Vel	SU	200:	15.5
SS Cyg	UG	75	11.7	V436 Cen	SU	210	16.0
U Gem	UG	81	14.6	HL CMa	UG	210	14.5
OY Car	SU	100	15.6	RW Tri	NL	224	13.2
WW Cet	ZC?	100	15.7	AH Her	ZC	250	14.3
V426 Oph	NL	100	11.8	TY Psc	SU	250:	16.0
EX Hya	SU?	105	13.6	V841 Oph	CN	255	13.3
CY Lyr	SU?	115	17.0	WX Hyi	SU	265	14.7
UV Per	SU?	115	17.5	TU Men	SU	270	16.6
T Leo	SU	120:	15.5	TZ Per	ZC	275	14.1
IP Peg	UG	124	15.8	FO Aqr	NL	275	13.5
Z Cha	SU	130	16.0	SU UMa	SU	280	14.8
RX And	ZC	135	13.6	CM Del	NL	280	13.4
AE Aqr	NL	140	11.5	V3885 Sgr	NL	280:	10.4
SW UMa	SU	140	16.5	HR Del	CN	285	12.1
IX Vel	NL	150	9.6	YZ Cnc	SU	290	14.5
HT Cas	SU	165	16.5	CW Mon	UG	290	16.0
RU Peg	UG	174	12.7	RW Sex	NL	290:	10.8
Z Cam	ZC	175	13.6	CN Ori	ZC	295	14.2
TT Ari	NL	185	11.1	UZ Ser	UG	300	15.6
TY PsA	SU	190:	16.5	KT Per	ZC	300	14.8
SS Aur	UG	200	14.7	CZ Ori	UG	300:	15.5
EK TrA	SU	200:	16.6	UX UMa	NL	300	12.8
				DQ Her	CN	330	14.7