A&A 394, 231–239 (2002)
DOI: 10.1051/0004-6361:20021136
© ESO 2002

Astronomy & Astrophysics

VY Sculptoris stars as magnetic cataclysmic variables

J.-M. Hameury[1] and J.-P. Lasota[2]

[1] UMR 7550 du CNRS, Observatoire de Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France
e-mail: hameury@astro.u-strasbg.fr
[2] UMR 7095 du CNRS, Institut d'Astrophysique de Paris, 98bis boulevard Arago, 75014 Paris, France
e-mail: lasota@iap.fr

Received 14 May 2002 / Accepted 30 July 2002

Abstract. We show that the absence of outbursts during low states of VY Scl stars is easily explained if white dwarfs in these systems are weakly magnetized ($\mu \gtrsim 5 \times 10^{30}$ G cm^3). However, some of the VY Scl stars are observed to have very slow declines to minimum and similarly slow rises to maximum. The absence of outbursts during such *intermediate* (as opposed to *low*) states, which last much longer than typical disc viscous times, can be explained only if accretion discs are absent when their temperatures would correspond to an unstable state. This requires magnetic fields stronger than those explaining outburst absence during low states, since white dwarfs in this sub-class of VY Scl stars should have magnetic moments $\mu \gtrsim 1.5 \times 10^{33}$ G cm^3 i.e. similar to those of Intermediate Polars. Since at maximum brightness several VY Scl stars are SW Sex stars, this conclusion is in agreement with recent claims about the magnetic nature of these systems.

Key words. accretion, accretion discs – instabilities – stars: novae, cataclysmic variables – stars: binaries: close

1. Introduction

Cataclysmic variables (CVs) are close binary systems in which a white dwarf primary star accretes matter lost from a Roche-lobe filling, low-mass secondary companion. In most CVs, matter transferred from the secondary forms an accretion disc around the white dwarf. Orbital periods of CVs extend from a sharp minimum at ~80 min to ~10 hrs (a few systems with giant or sub-giant secondaries have longer periods), with a prominent deficit of systems between ~2 and ~3 hours (the "period gap"). CVs are divided into different types according to their observed properties. Some of these properties reflect the way the systems are seen (e.g. their inclination) but most are a reflection of the physical parameters of the system. Here we will be mainly interested in two broad types of CVs which are classified according to the value of the rate at which matter is transferred from the secondary. These are the Dwarf Novae (DNs) and Nova-Like (NLs) variables – a nomenclature reflecting misunderstandings of historical interest only (see Warner 1995 for details). DNs show 2–5 mag (up to 8 mag in some cases) outbursts lasting from a couple of days up to more than a month. Outbursts are separated by quiescent intervals lasting from ~10 d to tens of years. It is believed that DN outbursts are due to a thermal-viscous accretion-disc instability occurring at temperatures where hydrogen recombines. According to the disc instability model (DIM) which is currently used to describe DN outburst cycle (see Lasota 2001 for a review), the condition for the instability to occur can be expressed in terms of a critical rate at which matter is fed to the outer disc's regions. Above this critical rate (whose value strongly increases with the disc's radius) accretion discs are hot and stable. CVs with such discs belong to the class of Nova-Like variable, which are defined as "non-eruptive" CVs. There exists also a second critical accretion rate below which a CV disc is cold and stable. The two critical rates have the same radial dependence.

The membership of a class is not permanent but depends on the actual mass-transfer rate. It seems, for example, that a NL should become a DN if a fluctuation brings the mass-transfer rate below the critical value for instability (the opposite fluctuation would transform a DN into a NL). The behaviour of VY Scl stars contradicts, however, this apparently reasonable conclusion. These are very bright NLs which occasionally undergo a fall in brightness by more than one magnitude. Although such drops in luminosity bring them into the DN instability strip, they show no outbursts. In fact, during their low states, which may last weeks or several years, VY Scl stars may spectroscopically appear like quiescent DNs but they *do not* become "regular" DNs (see Warner 1995 and references therein). At best they show once or twice a DN-type outburst but not an outburst cycle one could expect from systems at mass-transfer rates lower than the critical one for the disc instability to occur.

It would be tempting to say that VY Scl stars during low states are stable with respect to the DN-type instability, i.e. the effective temperature of their disc is below the instability strip. Since they are also stable in their high states, they would

Send offprint requests to: J.-M. Hameury,
e-mail: hameury@astro.u-strasbg.fr

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20021136

just oscillate between two stable steady-state configurations, explaining the general absence of outbursts. However, this simple explanation cannot be correct because during the transition from one stable state to the other, the disc configuration (its accretion rate) must cross the dwarf-nova instability strip and therefore show outbursts.

1.1. Mass transfer fluctuations

Before trying to explain this strange behaviour, one should determine the cause of brightness fluctuations in these systems. They seem to be due to mass-transfer rate fluctuations. Indeed, there is compelling evidence for mass-transfer fluctuations of various amplitudes occurring on various time-scales. Of course, in systems with an accretion disc, it might be difficult to make the difference between variations in the *accretion* and the *mass-transfer* rates, unless one can observe the mass-transfer-stream impact region in the outer disc (the so called "bright" or "hot" spot) whose changes of brightness would reflect mass-transfer variations. However, in polars (AM Her stars), a class of strongly magnetized CVs, no accretion disc is present so that observed changes in brightness by 1.5 do 4.5 mag must result directly from mass-transfer variations (see Hessman et al. 2000 and Buat-Ménard et al. 2001b for an evaluation of the effect in DNs of mass transfer variations similar to those observed in AM Her systems). Also in VY Scl stars it is obvious that the mass-transfer rate fluctuates between a very high value (comparable or higher than the *accretion rate* at DN's maximum; Warner 1995) and a value so low that the mass-transfer rate can be considered to have stopped.

Let us first consider what is happening when the mass-transfer rate is rapidly switched off. In such a case, as nicely explained by Leach et al. (1999, hereafter L99), the moment the mass-transfer rate drops below the (upper) critical value the outer disc becomes unstable and a cooling front propagates inwards, bringing the whole disc into a cold state. This state, however, is *non-stationary* as the accretion rate in the disc is not constant but increases with radius (see e.g. Figs. 10 and 17 in Lasota 2001). Since in such a disc most of the mass is in its outer regions, matter will diffuse inwards and inevitably cross the critical line as in Figs. 10 and 17 of Lasota (2001) and the system will go into outburst.

L99 suggested that in VY Scl irradiation by white dwarfs heated by accretion to very high temperatures ($\gtrsim$40 000 K) during high states, stabilizes the inner disc thus preventing outbursts. Indeed, as noticed by Lasota et al. (1995) a cold, dwarf-nova-type accretion disc (i.e. a disc whose structure results from the passage of a cooling front) can be stable if its inner part is removed. In L99 it is assumed that the inner disc is kept hot by white-dwarf irradiation which, as far as the cooling-front propagation is concerned, has the same effect a disc truncation: the cooling front has to stop at the transition radius between the cold and the hot part of the disc. The transition radius has to be large enough to allow the cold disc to settle to a quasi-stationary stable configuration (see L99 for details). As we will see in Sect. 2 the L99 model cannot work for white-dwarf masses larger than $\sim$0.4 $M_\odot$, which makes its application to *all* VY Scl stars rather questionable. In Sect. 3 we will show, however, that inner disc truncation by magnetic fields of not extravagantly large values (magnetic moments $\mu \gtrsim 5 \times 10^{30}$ G cm^3, i.e. magnetic fields $\gtrsim$40 kG for a $\sim$0.7 $M_\odot$ white dwarf) also suppress outbursts in VY Scl low states and does not require unrealistic parameters. The proposal that VY Scl systems may contain magnetized white dwarfs is not new: using arguments based on the observed spectral or timing properties of these systems, Jameson et al. (1982), and Hollander & van Paradijs (1992) proposed that TT Ari might be magnetized, while Voikhanskaia (1988) suggested that accretion in MV Lyr occurs on a magnetic pole during its low states.

In Sect. 4 we point out that although such a truncation suppresses outbursts during the minimum light, it cannot explain the absence of outbursts during the very slow decays from maximum to minimum light and very slow rises back to maximum. For example, Honeycutt et al. (1993) observed a $\sim$500 day, 4 mag rise of DW UMa, which is very long compared to the disc viscous time expected to be rather 10–20 days. It is instructive to have a closer look at Fig. 4 of L99. It shows part of the MV Lyr light-curve and the light-curve calculated by L99. Their model nicely fits the first rapid drop in luminosity but fails to reproduce the following slow rise and had these authors continued their calculation it would miserably fail to account for next, very slow (50 days) decay (see our Fig. 3), contrary to their expectations.

The reason is simple: when the mass-transfer rate remains in the instability strip longer than the viscous time, the system must produce a series of outbursts. We will show that in order to suppress outbursts during very slow rises and decays one has to suppress the disc as soon as the mass-transfer rate enters the instability range. This, as we argue, requires magnetic moments similar to those of Intermediate Polars,

In Sect. 5 we recall the independent evidence for the magnetic nature of VY Scl stars. In Sect. 4.2, after discussing the possibility that in some VY Scl stars the magnetized white dwarf could be in the propeller regime (we modify the standard inner boundary condition of the model in order to account for a source of angular momentum and matter ejection), we decide this would not change our main conclusion about the magnetic moment required to stabilize intermediate luminosity states. In Sect. 6 we discuss the relation between VY Scl stars and other types of CVs. Section 7 summarizes our results.

2. Irradiation by a hot white dwarf

As mentioned above, L99 proposed that in the low-state, the inner disc of VY Scl stars is kept in a hot and stable state by white-dwarf irradiation as in King (1997). Because most of the time they accrete matter at very high rates, white dwarfs in VY Scl stars are hotter than in most dwarf novae ($T_{\rm eff} \sim$ 35 000−65 000 K) so the L99 proposal seems to be reasonable. As described by these authors, the cooling front, which propagates inward when the mass-transfer rate falls below the critical value for instability, will reach only the boundary with the hot region. If this region is large enough the disc left behind the cooling wave will be cold and stable. The condition for this to happen can be written as:

$$r_{\rm tr} > r_{\rm crit} \approx 6 \times 10^9 \left(\frac{\dot{M}}{10^{15}\ {\rm g\ s^{-1}}}\right)^{0.375} M_1^{0.333}\ {\rm cm}, \quad (1)$$

where $r_{\rm tr}$ is the transition radius and M_1 is the white-dwarf mass in solar unit (see e.g. Lasota 2001; Lasota et al. 1999). The quiescent disc would thus have two components: very hot ($T_{\rm eff} > 7000$ K) for $r < r_{\rm tr}$; very cold ($T_{\rm eff} < 3000$ K) for $r > r_{\rm tr}$.

We repeated L99 calculations using Hameury et al. (1998) code as modified by Buat-Ménard et al. (2001a – we have corrected Eq. (1) of this paper, in which the heating rate was overestimated by a factor ∼2), treating disc irradiation by the white dwarf as in Hameury et al. (1999, see also Dubus et al. 1999). The main difference between our code and the one used by L99 is that in their case the outer radius is kept fixed and heating by tidal torques and stream-heating are neglected, while in our case the outer radius is allowed to vary (in agreement with both angular momentum conservation and observations) and we include in our calculation external heating of the outer disc. The difference in the heating term is not very important in this context. We considered first the case of a 0.4 $M_\odot$ white dwarf and the same disc parameters as in L99. The high-state mass-transfer rate is $\dot{M}_{\rm tr} = -2 \times 10^{17}$ g s^{-1}, lower than the value used in L99, since heating of the outer disc by the tidal torques and the stream impact lowers the critical mass transfer rate above which the disc is stable. To trigger a low state the mass-transfer is switched off. We considered the same two white-dwarf temperatures as L99: 20 000 and 40 000 K. The results, very similar to those of L99 are shown in Fig. 1. Irradiation by a 40 000 K white dwarf suppresses dwarf-nova type outbursts, although some residual mini-outbursts (or rather micro-outbursts) are still present. Their amplitudes are too small to be of observational importance. They are of physical, not numerical origin. As explained in Hameury et al. (1999), the intermediate region (at $r = r_{\rm tr}$), where the temperature ranges from 3000 to 7000 K, is violently unstable and generates a series of "mini-outbursts". When $r_{\rm tr} < r_{\rm crit}$ these "mini-outbursts" can be quite prominent (Hameury et al. 1999, 2000), but here they are rather inconspicuous.

L99 used only one value of the white dwarf mass, $M_1 \approx 0.41$ – the (apparently well determined) mass of the primary in LX Ser – an eclipsing system. This value, however, is crucial for the effect to work because the larger the white dwarf, the larger the inner-disc hot region. As shown in Fig. 1, for a typical NL mass of 0.7 $M_\odot$, even a 40 000 K white dwarf cannot prevent a series of prominent outbursts. We checked numerically how the outburst amplitude decreases with increasing white dwarf temperature; for 50 000 K, we get 0.6 mag outbursts, and for 60 000 K, the amplitude is only 0.25 mag.

This is can be also seen without using numerical codes. The white-dwarf irradiation temperature is given by (e.g. Smak 1989)

$$T_{\rm irr}^4 = (1-\beta) T_*^4 \frac{1}{\pi} [\arcsin \rho - \rho (1-\rho^2)^{1/2}] \quad (2)$$

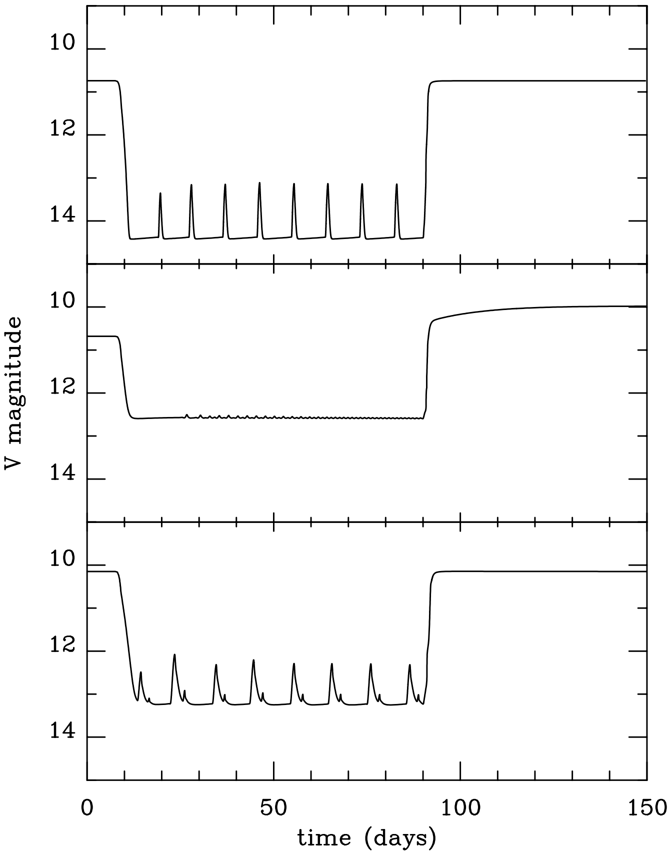

Fig. 1. Visual light curves of a binary system in which the mass transfer from the secondary stars is switched off for 80 days and then brought back to its previous value $\dot{M}_{\rm tr} = -2{\times}10^{17}$ g s^{-1}. The upper and intermediate panels correspond to the cases calculated by L99, i.e. to 0.4 $M_\odot$ white dwarf heated to $T_* = 20\,000$ and 40 000 K respectively. The lower panel corresponds to a 40 000 K, 0.7 $M_\odot$ white dwarf.

where $\rho = R_*/r$, R_* and T_* are the white dwarf radius and temperature. $1-\beta$ is the fraction of the incident flux which is absorbed in optically thick regions, thermalized and re-emitted as photospheric radiation. Therefore one can estimate the transition radius as

$$r_{\rm tr} \approx 6.7\, T_{*,40}^{4/3} \left(\frac{T_{\rm crit}}{6500\ {\rm K}}\right)^{-4/3} R_*\,, \quad (3)$$

where we put $\beta = 0$ (no albedo, which obviously maximizes the transition radius) and assumed for simplicity that a disc is thermally stable if its photospheric temperature is larger than $T_{\rm crit} \simeq 6500$ K. ($T_{*,40} = T_*/40\,000$ K). A comparison with Eq. (1) shows immediately the advantage of using a 0.4 $M_\odot$ white dwarf, for which $R_* = 1.07 \times 10^9$ cm. A 0.7 $M_\odot$ would stabilize the disc only if heated to more than 50 000 K. So unless *all* VY Scl have very low-mass and/or very hot white dwarfs the L99 model cannot explain the lack of outbursts during the low states of these binary systems.

It is unlikely that the VY Scl phenomenon occurs only in systems with very low-mass primaries. White dwarf masses are notoriously difficult to measure (see e.g. the discussion by Shafter 1983), and some care must be taken when considering each mass determination individually, but it would be very surprising that all mass measurements would be in error when exceeding 0.4 $M_\odot$. For example, another eclipsing VY Scl star, BH Lyn ($P_{\rm orb}$ = 3.74 h) has a primary mass more typical of its class: $M_1 \approx 0.7$ (Hoard & Szkody 1997). Other VY Scl have also higher primary masses: KR Aur – $M_1 \simeq 0.70$ (Shafter 1983),V425 Cas – $M_1 \approx 0.86$; only V442 Oph is reported to have $M_1 \approx 0.34$ (Ritter & Kolb 1998). In any case 0.4 $M_\odot$ is not the value of white-dwarf masses expected in CVs with orbital periods between 3 and 4 hours. It is interesting to note that $M_1 \approx 0.4$ is a value favored by the hypothesis of Greiner et al. (1999) that some (all) VY Scl stars are X-ray supersoft sources, but this hypothesis was rejected by Mauche & Mukai (2002) on the grounds that the X-ray spectra of VY Scl stars are not blackbodies and by Patterson et al. (2001) who argued that very high white dwarfs X-ray luminosities resulting from the blackbody hypothesis should also imply high optical fluxes which are not detected.

One should finally note that not all white dwarfs in VY Scl stars are very hot: Sion (1999) quotes a temperature of 35 000 K for RX And, too low to significantly affect the stability of the disc. Therefore, heating by a hot white dwarf, even if it may affect significantly the stability of the inner disc, cannot be the universal explanation for the VY Scl behaviour.

3. Truncation by a magnetosphere

We conclude that heating of the inner disc by hot white dwarfs is unlikely, at least in general, to prevent outbursts during VY Scl-star low states. There is, however, a different way of removing the inner, unstable part of an accretion disc: disruption by a magnetized white dwarf. We have already calculated dwarf-nova outburst cycles for truncated accretion discs in Hameury et al. (1999) and in Hameury et al. (2000). Here, we apply the same scheme to VY Scl stars.

The inner disc radius is given by the "magnetospheric radius":

$$r_{\rm in} = r_{\rm M} = 9.8 \times 10^8 \, \dot M_{15}^{-2/7} M_1^{-1/7} \mu_{30}^{4/7} \ {\rm cm} \quad (4)$$

where μ_{30} is the magnetic moment in units of 10^{30} G cm^3. As an example we calculated the case of a binary system with $M_1 = 0.7$, $P_{\rm orb} = 3.5$ h, secondary mass $M_2 = 0.3$ for three values of the magnetic moment: with μ_{30}= 1, 2, and 5. The mass transfer rate $\dot M_{\rm tr} = 2 \times 10^{17}$ gs^{-1} was switched off instantaneously on day 8 and switched on back 80 days later. Figure 2 shows that a rather moderate value of the magnetic moment, $\mu = 5 \times 10^{30}$ G cm^3 is sufficient to prevent dwarf-nova-type outbursts. For a 0.7 $M_\odot$ white dwarf, this value of the magnetic moment corresponds to a magnetic field of 40 kG. Thus, even a rather weak magnetic field would explain low-state properties of VY Scl stars.

4. Absence of outbursts during intermediate states

4.1. Disrupted discs

As mentioned in the Introduction, the disc truncation sufficient to suppress outbursts in quiescence still allows for their appearance during intermediate states lasting longer than the disc's characteristic viscous time (see Fig. 3). More precisely the condition for the absence of outbursts in the low states is a condition for the absence of *inside-out* outbursts, i.e. outbursts starting in the inner regions of the disc. Inside-out outbursts occur when the viscous-diffusion time is shorter than the accumulation time at the disc's outer rim (see Lasota 2001 for a detailed discussion). When one switches off the mass-transfer rate, the accumulation time is obviously infinite and only inside-out outbursts can occur. That is why inner-disc truncation suppresses outbursts in this case. However, if the mass-transfer rate is lowered slowly from a stable to an unstable range, the disc will enter first the regime of *outside-in* outbursts as such outbursts occur at the highest range of unstable transfer rates, because it is where the accumulation time $\sim 1/\dot M_{\rm tr}$ is the shortest ("outside-in" does not mean necessarily that outbursts start exactly at the outer edge – see e.g. Buat-Ménard et al. 2001a). During this phase, the disc slowly builds up; its mass increases significantly above the minimum values reached after the end of the stable hot phase, and outbursts appear in the outer disc regions, even for values of the magnetic field for which the disc was found to be stable when the mass transfer rate was very rapidly shut off.

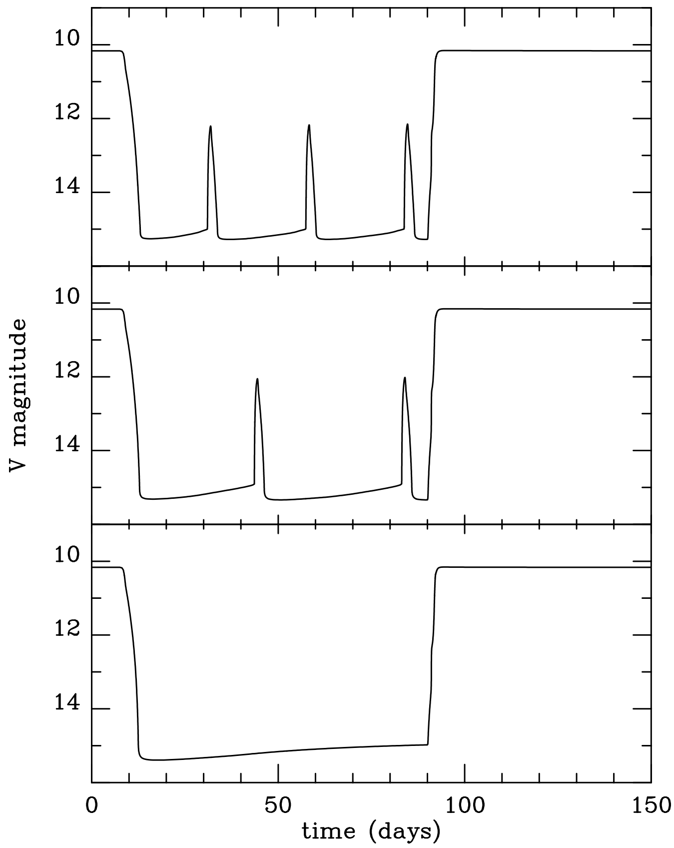

Fig. 2. Visual light curves of a binary system in which the mass-transfer rate is switched off for 80 days then switched on back to its previous value. The accretion disc is disrupted by the magnetic field of a 0.7 $M_\odot$ white dwarf. Three values of the magnetic moment were used: μ_{30} = 1 (top panel), 2 (intermediate panel), and 5 (bottom panel).

As an example, we show in Fig. 3 what is happening in a system with the same parameters as those assumed for Fig. 2 but with a slow (300 days) drop (and rise) of the mass-transfer rate. A series of outbursts appear before the system settles to the low state in which, as before, outbursts are absent; outbursts also reappear on the way back to maximum brightness. (In this case the low state was found to be stable only for magnetic moments $\mu_{30} = 10$ because of a different disc evolution prior to the low state).

If the VY Scl phenomenon were to be explained by irradiation of the disc, this would require illumination to be large enough for the outer edge of the disc to be brought to a temperature larger than about 6500 K, i.e. $r_{\rm tr} > r_{\rm out}$. This condition is much more stringent than the conditions for having no outburst in quiescence which implies a much smaller $r_{\rm tr}$. For typical disc radii of order of 2–2.5$\times 10^{10}$ cm, this would require white dwarf temperatures in excess of 100 000 K, which have never been reported. Moreover, at such large temperatures, the luminosity would be dominated by the intrinsic and reprocessed white dwarf luminosity, the accretion luminosity would be comparatively small, and low states very shallow.

Therefore, irradiation can perhaps explain the nature of systems with low mass white dwarfs, and in which sharp transitions are observed between low and high states; it cannot possibly explain the systems which show slow variations between outburst and quiescence. As long as there is a full-fledged disc there will be outbursts. Therefore the only remedy against outbursts is the suppression of the disc as soon as the mass-transfer rate from the secondary enters the unstable range, $\dot M_{\rm tr} \leq \dot M^{\rm h}_{\rm crit}$, where $\dot M^{\rm h}_{\rm crit}$ is the minimum accretion rate for stable, hot equilibria.

Observations tend to support this conclusion: Gänsicke et al. (1999) found that the spectra of TT Ari during a low state shows virtually no sign of an accretion disc. The UV and IR continuum emission was clearly dominated by the two stellar components, very weak lines were visible in the continuum, which lead these authors to conclude that there was no optically thick disk up to at least 12 white dwarf radii. Similarly, Knigge et al. (2000) found that they were able to see the hot, bare white dwarf during quiescence, which was hidden by the disc during high states.

The only possibility we can think of for suppressing the disc is the existence of a relatively large magnetic field; the precise form of the required "no-disc" condition then depends essentially on the inner disc boundary condition.

In general this condition states that the magnetospheric radius must be larger than some characteristic disc radius, i.e.

$$r_{\rm M} > fa \qquad (5)$$

where the "characteristic radius" is a fraction f of the orbital separation

$$a = 3.53 \times 10^{10} (M_1 + M_2)^{1/3} P_{\rm h}^{2/3} \ {\rm cm} \qquad (6)$$

$P_{\rm h}$ being the orbital period in hours. The critical accretion rates is (see e.g. Lasota 2001)

$$\dot M^{\rm hot}_{\rm crit} = 9.5 \times 10^{15} \, \alpha^{0.01} M_1^{-0.89} \left(\frac{r}{10^{10} {\rm cm}} \right)^{2.68} \ {\rm g\ s^{-1}}. \qquad (7)$$

As a "no-disc" condition we can require, for example, that when the mass transfer rate from the secondary drops below the critical value corresponding to the end of hot branch at the outer disc's edge, $\dot M_{\rm crit}(r_{\rm out})$ ($r_{\rm out}$ being the outer disc radius), the magnetospheric radius becomes larger than the circularization radius. From Eqs. (4)–(7) one obtains the following general "no-disc" condition in terms of the required magnetic moment:

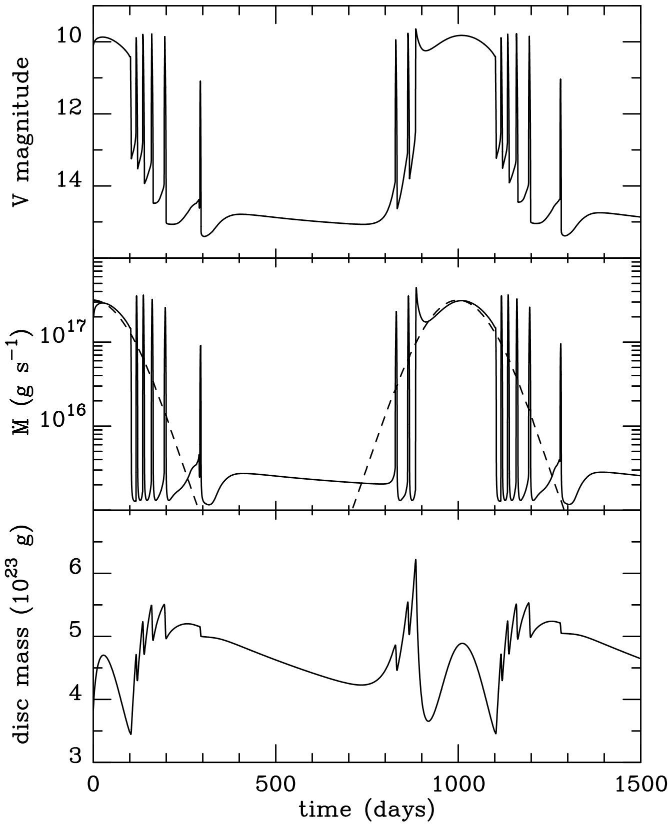

Fig. 3. Top panel: visual light curve of a binary system in which the mass-transfer rate slowly varies. The accretion disc is disrupted by the magnetic field of a 0.7 $M_\odot$ white dwarf with $\mu_{30} = 10$. Intermediate panel: mass accretion rate onto the white dwarf (solid line), and mass transfer rate (dashed line). Bottom panel: disc mass.

$$\mu \gtrsim 1.5 \times 10^{33} f_{0.12}^{1.75} P_4^{2.06} (3 r_{\rm out}/a)^{1.34} M_1^{1.4} \ {\rm G\ cm^3} \qquad (8)$$

where we assumed a mass ratio $M_2/M_1 = 0.43$, used the value $f = 0.12$ corresponding to the circularization radius, measured the orbital periods in units of 4 hours, and normalized $r_{\rm out}$ by its "typical" value $a/3$.

Numerical simulations show that this is an overestimate, the critical magnetic moment being about half the value deduced from Eq. (8). This is due to the fact that heating by the tidal torque and stream impact has a stabilizing effect in the outer disc regions, so that Eq. (7) gives an overestimate of $\dot M^{\rm hot}_{\rm crit}$. Also $r_{\rm out}$ decreases significantly when the inner disc radius approaches $r_{\rm circ}$. So for a 0.7 $M_\odot$ white dwarf in a 4 hours binary the required magnetic field would be $B \gtrsim 6$ MG.

The values of magnetic moments required to prevent outbursts during intermediate states of VY Scl stars are in the range between DQ Her and Intermediate Polars (see e.g. Warner 1995). We should therefore consider what might be happening if a VY Scl star were in the propeller regime which apparently characterizes the DQ Her star AE Aqr (Wynn et al. 1997).

4.2. Dwarf-nova outbursts in the magnetic propeller regime

In deriving condition Eq. (4) we have assumed that the inner edge of the accretion disc corresponds to the (variable) magnetospheric radius. In the numerical calculation the inner boundary condition was the usual "no–stress" condition which in practice corresponds to the condition $\nu\Sigma|_{\rm in} = 0$. Of course this condition is not the right one in the propeller regime and in general when there is an angular momentum source at the inner disc edge. Livio & Pringle (1992) modified the surface-density diffusion equation to include the existence of a torque due to the interaction of the white dwarf magnetic field with the accretion disc, keeping the inner disc radius equal to that of the white dwarf. Duschl & Tscharnuter (1991) on the other hand considered the case of an extended boundary layer, which also changed the $\nu\Sigma = 0$ inner boundary condition, with a disc inner radius larger than the white dwarf radius. Here we find a boundary condition which is appropriate for the magnetic propeller regime.

The magnetic torque T exerted on a small portion Δr of the disc can be written as (Livio & Pringle 1992):

$$T = \frac{B_z^2}{4\pi}\frac{\Omega_{\rm in} - \Omega_*}{\Omega_{\rm in}} 4\pi r_{\rm in}^2 \Delta r \tag{9}$$

where $r_{\rm in}$ is the inner disc radius, B_z the vertical component of the magnetic field, which can be assumed to vary as r^{-3}, and $\Omega_{\rm in}$ and Ω_* are the Keplerian and stellar angular velocities respectively. The inner radius should be equal to the magnetospheric radius, defined by:

$$\frac{B_z^2(r_{\rm in})}{8\pi} = \frac{\dot{M}}{4\pi r_{\rm in}^2}\Omega_{\rm in} r_{\rm in} \tag{10}$$

which gives:

$$T = 2\dot{M} j \frac{\Omega_{\rm in} - \Omega_*}{\Omega_{\rm in}} \tag{11}$$

for $\Delta r \sim r$, j being the Keplerian specific angular momentum. This torque has to be balanced by the viscous torque at the inner disc edge, $T_{\rm visc} = 3\pi\nu\Sigma j$, leading to the new boundary condition at $r = r_{\rm in}$:

$$\nu\Sigma = \frac{\dot{M}}{3\pi} f \left| \frac{\Omega_{\rm in} - \Omega_*}{\Omega_{\rm in}} \right| \tag{12}$$

which is similar to that obtained by Duschl & Tscharnuter (1991) in a slightly different context; $f \leq 1$ here accounts for the fact that matter will be ejected from the system, carrying a fraction of the flow of angular momentum deposited in the disc.

The steady state solution is now:

$$\nu\Sigma = \frac{\dot{M}}{3\pi}\left[1 + \left(\frac{f|\Omega_{\rm in} - \Omega_*|}{\Omega_{\rm in}} - 1\right)\left(\frac{r_{\rm in}}{r}\right)^{1/2}\right]. \tag{13}$$

Because $r_{\rm in}$ need not be much smaller than the outer disc radius, the whole disc could be affected by this new boundary condition when $\Omega_{\rm in} \ll \Omega_*$, i.e. when the propeller effect is efficient. The surface density is increased as compared to the standard case; the increase in luminosity (the dissipation, proportional to $\nu\Sigma$, is due to the work done by the torque, the energy source being the rotation of the white dwarf which is partly redistributed over the whole disc).

The local thermal equilibrium equations are unchanged, so that the S-curves are unaffected by the propeller effect, which therefore lowers the minimum mass transfer for the disc to remain on the hot branch, and thus has a stabilizing effect. The change in the critical $\dot{M}$, however, remains moderate: for $r_{\rm out}/r_{\rm in} = 6$ and $\Omega_*/\Omega_{\rm in} = 5$, Eq. (13) predicts a change by a factor 3.7 in $\dot{M}$, which would in principle lower the critical magnetic moment for which the disc would disappear before becoming unstable (see Sect. 4). However, the "no-disc" criterion is also changed; a disc can still exist even for a circularization radius larger than the inner radius, because of the torque exerted by the magnetosphere. Both effects compensate; numerical calculations showed that Eq. (8) is still a reasonably good approximation of the critical magnetic moment.

Finally, it should be noted that, even in the propeller regime, pulsations at the white dwarf spin period are expected. AE Aqr for example clearly show these pulsations which can be due either to residual accretion or to magnetic dissipation at the poles (Wynn et al. 1997).

5. VY Scl stars as intermediate polars?

Equation (8) states that (at least some) VY Scl stars have magnetic fields close to those of intermediate polars (IPs). This conclusion follows solely from photometric properties of VY Scl stars during their intermediate states as confronted with requirements of the disc instability model. Obviously, to be treated seriously, it better be supported by some direct evidence such as circular polarization and/or pulsations reflecting the presence of a spinning magnetized white dwarf. No such evidence has been found yet.

However, three (LX Ser, BH Lyn and DW UMa) VY Scl stars (see e.g. Hellier 2000) are classified at high state as SW Sex stars (to which one could add PG And, a SW Sex not classified as VY by Hellier 2000, but which has occasional low states, Thorstensen et al. 1991). These are nova-like CVs showing anomalous phenomena in their emission lines, where "anomalous" means different from the simple binary model of CVs (see e.g. Warner 1995). Also their continua show unusual temperature profiles (see however Smak 1994 for a discussion of the bias introduced by the high inclination on the determination of the temperature profile). These anomalies are detected in systems with high inclinations, but seem in fact to be shared by most CVs at high accretion rates (Horne 1999).

In two SW Sex stars, LS Peg (Rodríguez-Gil et al. 2001) and V795 Her (Rodríguez-Gil et al. 2002), variable circular polarization has been discovered. The authors of these observations deduce magnetic fields of 5–15 MG (LS Peg) and 2–7 MG (V795 Her). It is interesting to notice that V795 Her has been an IP candidate for a long time (it is listed as an "DQ Her" star in the Downes et al. 2001 catalogue and atlas of cataclysmic variables). The circular polarization in LS Peg and V795 Her is modulated with periods of ~20–30 min, typical of IPs and fitting the $P_{\rm spin}/P_{\rm orb} \sim 0.1$ relation (see e.g. King & Lasota 1991). These observations provide indirect support to our conclusion about the magnetic nature of VY Scl stars.

Groot et al. (2001) having observed SW Sex itself – in an "excited, low state", which probably means fainter than maximum by less than about 1 mag, but no value of m_V is given in their paper – find a disc structure which could be compatible with a IP-like white dwarf. These authors however were sceptical about the magnetic nature of SW Sex stars in general because, apparently unaware of the results of Rodríguez-Gil et al. (2001, 2002), they worried about the absence of pulsations and polarization.

Our results could imply that variable circular polarization should be detected, at least in such VY Scl stars as DW UMa or MV Lyr in which long intermediate states are observed. One should keep in mind, however, that circular polarization has been detected only in five IPs out of a total of more than 30, the ones that harbor white dwarfs with highest magnetic fields ~2–8 MG (see Warner 1995). Since VY Scl stars could have fields lower than this value the detection of their circular polarization could be rather difficult. Indeed, Tapia (1981, quoted in Robinson et al. 1981) found the circular polarization of MV Lyr to be less than 0.13% and consistent with zero. This should be compared with the circular polarization of V795 Her – mean level increasing from 0.15% in U to 0.41% in I – and the 0.3% amplitude in LS Peg (Rodríguez-Gil et al. 2001, 2002).

We do not know of VY Scl pulsation periods being reported in the literature, except for a "negative superhump" (i.e. a strong periodic signal displaced from the orbital period by few percent) in V751 Cyg (Patterson et al. 2001), which could reflect the magnetic white-dwarf's rotation. King & Lasota (1991) have also noted that asynchronous systems with AM Her type magnetic field would be very difficult to detect.

6. Mass transfer variations: Relation to other systems

Figure 4 shows the distribution of subclasses of CVs. Here, the data is from the Ritter & Kolb (1998) catalog, except for magnetic systems, which are often detected by their X-ray emission, and whose number has raised significantly in the last few years; these are taken from the online version of the Downes et al. (2001) catalog. We also used the recently found orbital periods of V794 Aql – Honeycutt & Robertson (1998) and V751 Cyg – Patterson et al. (2001) and we do not consider RX And, $P_{\rm orb}$ = 5.04 h, to be a VY Scl star, see below). *All* VY Scl stars have orbital periods between 3.19 and 3.99 h – the strongest correlation observed among CVs (see Warner 2000). It is interesting to compare VY Scl stars with the other class of systems showing large mass-transfer fluctuations: the AM Her stars and IPs.

6.1. Magnetic systems

Only six AM Her stars are known to have periods longer than 4 hours and their long-term light curves do not seem to be known. AM Her, the prototype and best studied polar, has an orbital period of 3.09 h and exhibits high and very low states (see Hessman et al. 2000). Another type of CVs present in the 3–4 hour interval of orbital periods are IPs, already mentioned above. Only two of these systems showed well-documented very low states: V1223 Sgr (which has a light curve similar to that of AM Her; Warner 1995) and AO Psc, with orbital periods of 3.366 h and 3.591 h respectively. On the other hand, FO Aqr has shown no distinct low state since 1923 (Warner 1995) and its orbital period is equal to 4.849 h. It is therefore plausible that the orbital-period interval between 3 and 4 hours is characterized by large amplitude mass-transfer fluctuations. The lower limit of this interval (3 h) marks the upper edge of the famous "period gap" whose lower edge is around 2 hours. One should notice, however, that the mean mass-transfer rate in AM Her stars and IPs is lower than in VY Scl and other NLs of SW Sex, UX UMa and RW Tri type. $\dot M^{\rm IP}_{\rm transf} \lesssim 2\times 10^{17}$ gs^{-1}, while $\dot M^{\rm VY}_{\rm transf} \sim 2 - 8 \times 10^{17}$ gs^{-1}, corresponding to a mean visual magnitude brighter than Z Cam standstills and sometimes even brighter than dwarf-nova maxima.

As seen in Fig. 4 not all systems between 3 and 4 hours are VY Scl stars, IPs or polars. Of course, since low states of VY Scl stars are rather rare, it is still possible that some, or all, nova-like systems are not yet detected as VY Scl stars. This would then indicate that many systems in the 3–4 hr period interval contain a magnetic white dwarf (of order of 10^{30} G), some of them (those showing slow declines/rises) having field strength typical of IPs. Interestingly, quiescent novae also seem to be magnetic when their periods are in this range (Warner 2002). The reason for this is not clear, and could be related to some selection effect. There is nevertheless no reason to assume that the distribution of magnetic fields is the same for isolated white dwarfs and for accreting white dwarfs in a binary.

6.2. Dwarf novae

As for the other systems, Shafter (1992) noticed that there is a dearth of dwarf novae in the orbital period range between ~3 and ~4 h. Indeed, according to latest edition of the CV catalogue (Ritter & Kolb 1998) the shortest orbital period for a bona fide, i.e. U Gem-type dwarf nova is 3.8 hrs. All other confirmed DNs (6 systems) with secure orbital periods are Z Cam stars for shorter periods.

Mass-transfer fluctuations are also observed in DNs, both during outbursts (hot spot brightening, see e.g. Smak 1995) and quiescence ("low" states; see Buat-Ménard et al. 2001b for references). However, Buat-Ménard et al. (2001b) calculated, in the framework of DIM, the impact mass-transfer fluctuation would have on the DN outburst cycle and concluded (contrary to Schreiber et al. 2000) that in these systems their amplitude must be orders of magnitude lower than in polars.

Buat-Ménard et al. (2001b) also showed that the Z Cam "standstill" phenomenon, i.e. the settling of luminosity during decline from outburst at ~0.7 mag lower than the maximum for several months or even years is very well reproduced by allowing the mass-transfer rate to vary by about 30% about the critical value. It could be that many (all?) U Gem stars are as yet unrecognized Z Cam stars (Warner 1995; Buat-Ménard et al. 2001b).

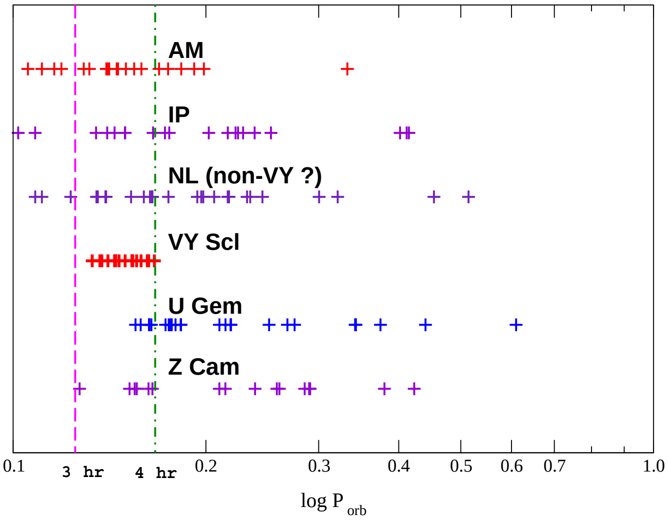

Fig. 4. Orbital period distribution of various classes of CVs between 2.4 and 15 hours.

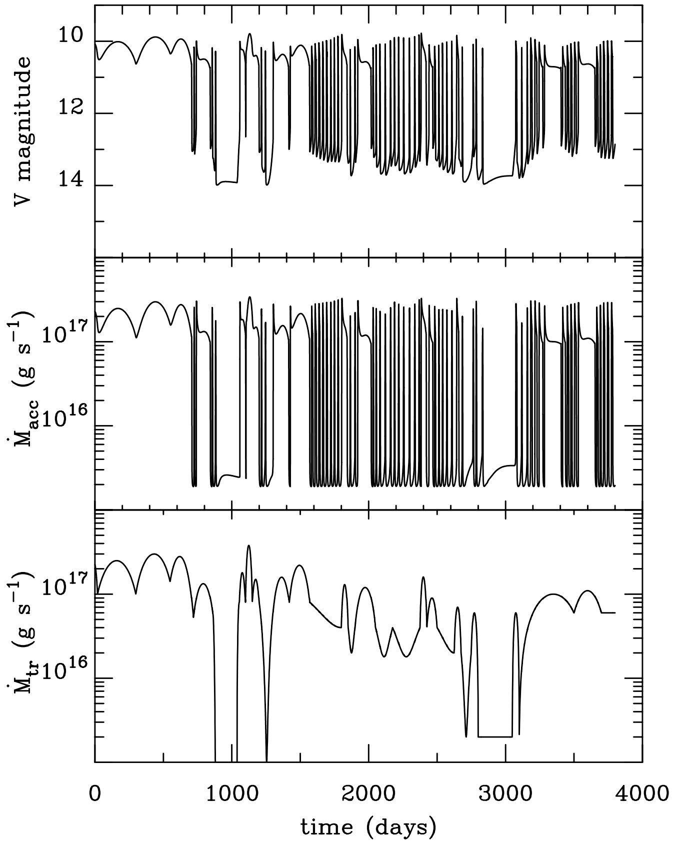

Fig. 5. Variability of a hypothetical system in which the time-dependent mass-transfer rate in AM Her (Hessman et al. 2000) has been multiplied by 10 to bring it into the VY Scl regime. Top panel: visual magnitude; intermediate panel: mass accretion rate; bottom panel: mass transfer rate from the secondary.

6.3. From small to large $\dot{M}$ variations: The case of RX And

A fascinating test case is provided by RX And, the platypus of CVs: half Z Cam, half a VY Scl star (Schreiber et al. 2002). Since it is a dwarf nova during long stretches of its life, the magnetic moment of its white dwarf cannot satisfy Eq. (8) as a disc is needed to produce outbursts. This is confirmed by the absence of long intermediate state with no outbursts: VY Scl-type brightness drops and rises are fast and when the system settles to a long intermediate state below the standstill luminosity it shows an outburst activity. The standstill itself corresponds to a stable mass-transfer rate (Buat-Ménard et al. 2001b). A system exhibiting both dwarf-nova outbursts and long and quiet luminosity descents below the stability limit would contradict our model and presumably the disc instability model in general.

Figure 5 shows a simulation of a system in which the mass transfer rate is 10 times that determined by Hessman et al. (2000) for AM Her; the white dwarf mass is 0.7 $M_{\odot}$, its temperature 40 000 K, and its magnetic moment 2×10^{31} G cm^{-3}. The system changes from a VY Scl type to a Z Cam one; it must however be noted that, contrary to the case of RX And, the standstills are not always 0.5–1 mag fainter than the outburst peak, simply because the mass transfer rate is not close to the stability limit. In addition, one can see relatively large amplitude fluctuations during the standstills, and more generally, one expects these fluctuations during the high state of VY Scl. This probably means that there must be a self-regulating mechanism that maintains the mass transfer rate approximately constant during the high state, possibly as a result of illumination of the secondary. In any case AM Her-type variability cannot be universal, contrary to the assertions of Hessman et al. (2000); in particular, the amplitude of the mass transfer fluctuations in Z Cam systems must be small (Buat-Ménard et al. 2001b) .

It seems therefore that between 4 to 3 hours, dwarf novae – systems with mass-transfer rates in the instability strip – are (gradually?) replaced by systems in which the mass-transfer rates is higher and whose fluctuation have also larger amplitudes. RX And is probably a system undergoing such a transition (Schreiber et al. 2002).In other words, with increasing orbital period both mass-transfer rate and the amplitude of its fluctuations would decrease. Large amplitude fluctuations would die out above the orbital period of 4 hours. The decrease of mass-transfer rate with period is required by the recent work comparing binary evolution with observations (Baraffe & Kolb 2000).

The precursors of VY Scl stars, i.e. systems with orbital periods larger than 4 hours could be IPs or dwarf-novae, or a combination of the two, as TV Col and V1223 Sgr (see Warner 1995 and references therein; the orbital period of the second system is 3.366 h).

The origin of fluctuations and their relation with the vicinity of the period gap has been awaiting explanation since time when Robinson et al. (1981) suggested that low states of MV Lyr could be attempts to enter the period gap and remarked that deep low states appear when the mass-losing star becomes fully convective.

7. Discussion and conclusions

We found that irradiation by a hot white dwarf cannot account for the whole VY Scl syndrome. Even if these systems had the required (low) white dwarf masses and very high white dwarf temperature to prevent dwarf-nova type outbursts during their low states, the absence of outbursts during long intermediate states observed in some VY Scl stars cannot be accounted for by white dwarf irradiation. Therefore in such binaries the white dwarf has to possess a magnetic moment similar to that of IPs. This would also prevent outbursts in the low states. On the other hand in VY Scl systems in which fluctuations of the mass-transfer rate happen on timescales shorter than the disc's viscous time and/or outbursts occur during the long transitions, the stabilizing effect could be produced by a much weaker magnetic field.

Of course we have not *proven* that VY Scl stars must be magnetic. In principle one could imagine an "evaporation mechanism" so tuned that it would get rid of the disc in the right moment. Our model, however, provides the most conservative solution of the VY Sc puzzle. In addition there exist independent indication of the magnetic nature of least some bright nova-like binaries.

Timing and polarization observations of VY Scl stars will provide the ultimate test of our model.

Acknowledgements. This work was supported in part by a grant from the *Programme National de Physique Stellaire* of the CNRS. We are grateful to Guillaume Dubus, Andrew King and Kristen Menou for interesting discussions, suggestions and comments. We thank the anonymous for his careful reading of our paper and comments which helped to improve the clarity of this paper.

References

Baraffe, I., & Kolb, U. 2000, MNRAS, 318, 354
Buat-Ménard, V., Hameury, J.-M., & Lasota, J.-P. 2001a, A&A, 366, 612
Buat-Ménard, V., Hameury, J.-M., & Lasota, J.-P. 2001b, A&A, 369, 925
Downes, R., Webbink, R. F., Shara, M. M., et al. 2001, PASP, 113, 764
Dubus, G., Lasota, J.-P., Hameury, J.-M., & Charles, P. 1999, A&A, 303, 139
Duschl, W. J., & Tscharnuter, W. M. 1991, A&A, 241, 153
Gänsicke, B. T., Sion, E. M., Beuermann, K., et al. 1999, A&A, 347, 178
Greiner, J., Tovmassian, G. H., DiStefano, R., et al. 1999, A&A, 343, 183
Groot, P. J., Rutten, R. G. M., & van Paradijs, J. 2001, A&A, 368, 183
Hameury, J.-M., Menou, K., Dubus, G., Lasota, J.-P., & Huré, J.-M. 1998, MNRAS, 298, 1048
Hameury, J. M., Lasota, J. P., & Dubus, G. 1999, MNRAS, 303, 39
Hameury, J.-M., Lasota, J.-P., & Warner, B. 2000, A&A, 353, 244
Hellier, C. 2000, NewAR, 22, 131
Hessman, F. V., Gänsicke, B. T., & Mattei, J. 2000, A&A, 361, 952
Hoard, D. W., & Szkody, P. 1997, ApJ, 481, 433
Hollander, A., & van Paradijs, J. 1992, A&A, 265, 77
Honeycutt, R. K., & Robertson, J. W. 1998, AJ, 116, 1961
Honeycutt, R. K., Livio, M., & Robertson, J. W. 1993, PASP, 105, 922
Horne, K. 1999, in Magnetic Cataclysmic Variables, ed. K. Mukai, & C. Hellier, ASP Conf. Ser., 157, 349
Jameson, R. F., Sherrington, M. R., King, A. R., & Frank, J. 1982, Nature, 300, 152
King, A. R. 1997, MNRAS, 288, L16
King, A. R., & Lasota, J.-P. 1991, ApJ, 378, 674
Knigge, C., Long, K. S., Hoard, D. W., Szkody, P., & Dihlon, V. S. 2000, ApJ, 539, L49
Lasota, J.-P. 2001, NewAR, 45, 449
Lasota, J.-P., Hameury, J.-M., & Huré, J.-M. 1995, ApJ, 302, L29
Lasota, J. P., Kuulkers, E., & Charles, P. 1999, MNRAS, 305, 473
Leach, R., Hessman, F. V., King, A. R., Stehle, R., & Mattei, J. 1999, MNRAS, 305, 225, (L99)
Livio, M., & Pringle, J. 1992, MNRAS, 259, 23P
Mauche, C. W., & Mukai, K. 2002, ApJ, 566, L33
Patterson, J., Thortensen, J. R., Fried, R., et al. 2001, PASP, 113, 72
Ritter, H., & Kolb, U. 1998, A&AS, 129, 83
Robinson, E. L., Barker, E. S., Cochran, A. L., Cochran, W. D., & Nather, R. E. 1981, ApJ, 251, 611
Rodríguez-Gil, P., Casares, J., Martínez-Pais, I. G., et al. 2001, ApJ, 548, L49
Rodríguez-Gil, P., Casares, J., Martínez-Pais, & I. G., Hakala, P. 2002, in The Physics of Cataclysmic Variables and Related Objects, ed. B. T. Gänsicke, K. Beuermann, & K. Reinch, ASP Conf. Ser., 261, 533
Schreiber, M. R., Gänsicke, B. T., & Hessman, F. V. 2000, A&A, 358, 221
Schreiber, M. R., Gänsicke, B. T., & Mattei, J. A. 2002, A&A, 384, L6
Shafter, A.W. 1983, ApJ, 267, 222
Shafter, A. W. 1992, ApJ, 394, 268
Sion, E. M. 1999, PASP, 111, 532
Smak, J. 1989, Acta Astr., 39, 201
Smak, J. 1994, Acta Astr., 44, 265
Smak, J. 1995, Acta Astr., 45, 355
Thorstensen, J. R., Ringwald, F. A., Wade, R. A., Schmidt, G. D., & Norsworthy, J. E. 1991, AJ, 102, 272
Voikhanskaia, N. F. 1988, A&A, 192, 128
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge University Press, Cambridge)
Warner, B. 2000, NewAR, 44, 3
Warner, B. 2002, Proc. of Classical nova explosions, ed. M. Hernanz, & J. Jordi, AIP Conf. Proc., 637, in press
Wynn, G. A., King, A. R., & Horne, K. 1997, MNRAS, 286, 436