Thermal stability and nova cycles in permanent superhump systems

A. Retter and T. Naylor

Department of Physics, Keele University, Keele, Staffordshire, ST5 5BG, UK; ar@astro.keele.ac.uk; timn@astro.keele.ac.uk

ABSTRACT

Archival data on permanent superhump systems are compiled to test the thermal stability of their accretion discs. We find that their discs are almost certainly thermally stable as expected. This result confirms Osaki’s suggestion (1996) that permanent superhump systems form a new subclass of cataclysmic variables (CVs), with relatively short orbital periods and high mass transfer rates. We note that if the high accretion rates estimated in permanent superhump systems represent their mean secular values, then their mass transfer rates cannot be explained by gravitational radiation, therefore, either magnetic braking should be extrapolated to systems below the period gap or they must have mass transfer cycles. Alternatively, a new mechanism that removes angular momentum from CVs below the gap should be invoked.

We suggest applying the nova cycle scenarios offered for systems above the period gap to the short orbital period CVs. Permanent superhumps have been observed in the two non-magnetic ex-novae with binary periods below the gap. Their post-nova magnitudes are brighter than their pre-outburst values. In one case (V1974 Cyg) it has been demonstrated that the pre-nova should have been a regular SU UMa system. Thus it is the first nova whose accretion disc was observed to change its thermal stability. If the superhumps in this system indicate persistent high mass transfer rates rather than a temporary change induced by irradiation from the hot post-nova white dwarf, it is the first direct evidence for mass transfer cycles in CVs. The proposed cycles are driven by the nova eruption.

Key words: accretion, accretion discs – novae, cataclysmic variables – stars: evolution – stars:individuals: V1974 Cyg – stars: individuals: CP Pup

1 INTRODUCTION

1.1 Regular superhumps

Superhumps were initially observed in SU UMa systems (Vogt 1974; Warner 1975). This subclass of dwarf novae, shows brighter longer outbursts (so called superoutbursts) in addition to the normal outbursts observed in regular dwarf novae (U Gem systems). A quasi-periodic variation, systematically a few per cent larger than the orbital period, is usually detected during SU UMa superoutbursts, and was nicknamed ‘superhump’ (see la Dous 1993; Warner 1995a for reviews of SU UMa systems and CVs in general). The typical value of the peak-to-trough amplitude of the superhump is about 20-40 per cent. There is a trend of increasing positive period excess (of the superhump period over the orbital one) with the orbital period (Stolz & Schoembs 1984; Patterson 1999).

Vogt (1982) first suggested that the accretion disc around the white dwarf in Z Cha (and other SU UMa systems) develops an elliptical shape during superoutbursts. Osaki (1985) tested the motion of single particles in an eccentric disc, and found a relation between the superhump period excess as a fraction of the binary period and the binary period. Whitehurst (1988) used hydrodynamic simulations to show that the tidal instability explains the formation of the eccentric disc. Osaki (1989) used two instabilities in the accretion disc to create a uniform theory for non-magnetic CVs. According to this model, ‘The Thermal – Tidal Disc Instability Model’, the superhump periodicity is the beat of the orbital period of the binary system with the period of the apsidal precession of the accretion disc. Further hydrodynamical simulations showed that the tidal instability can occur only if the disc radius exceeds a certain value, the 3:1 resonance radius (Whitehurst & King 1991). This requires that superhumps can appear only in binary systems with a small mass ratio q=(M_2/M_1)<0.33, although
observationally the limit is probably bigger (Retter & Hellier 2000; Retter et al. 2000).

During the last decade it has been found that superhump behaviour is common among other classes of binary systems as well as in the SU UMa stars. According to the theory, there are two requirements for the presence of superhumps: an extreme mass ratio and a large accretion disc radius. These two conditions are naturally met in superoutbursts of SU UMa systems, but are satisfied in other systems as well. Thus superhumps have also been detected in the ultra-short orbital period AM CVn systems (Patterson et al. 1993a; Patterson, Halpern & Shambrook 1993; Provençal et al. 1997; Patterson et al. 1997a; Harvey et al. 1998; Solheim et al. 1998; Patterson 1999; Skillman et al. 1999); in SW Sex stars (Patterson & Skillman 1994; Patterson 1999) and during bright outbursts of a few low-mass X-ray transients (White 1989; Charles et al. 1991; Bailyn 1992; Zhang & Chen 1992; Kato, Mineshige & Hirata 1995; O'Donoghue & Charles 1996).

1.2 Permanent superhumps

In many systems, which do not show eruptions, superhumps are observed. An outburst is thus not a necessary condition for this phenomenon. Patterson & Richman (1991) termed this behaviour as ‘permanent superhump’. During the last few years permanent superhumps have been found in almost twenty CVs (see Patterson 1999 for an observational review on permanent superhump systems). Typical full amplitudes of permanent superhumps are about 5-15 per cent, but they are highly variable, and sometimes even disappear from the light curve (Patterson, personal communication). Their name is thus somewhat misleading.

In several systems, a quasi-stable periodicity, a few per cent shorter than the orbital period has been observed. These variations are called ‘negative superhumps’. In a few systems they appear simultaneously with the positive superhumps (Patterson et al. 1997b; Arenas et al. 2000; Retter & Hellier 2000; Retter et al. 2000), but in other cases they are the only kind of superhump observed. An alternation between the positive and negative superhumps has been observed in a few objects (e.g. Skillman et al. 1998). The negative superhump deficit over the orbital period seems to be correlated with the orbital period in a manner similar to the Stolz & Schoembs (1984) relation, however with a shallower trend. It has been suggested that negative superhumps are formed by the precession of the accretion disc in the azimuthal axis (Patterson et al. 1993c; Patterson 1999), but there are some theoretical difficulties with this idea (Murray & Armitage 1998; Wood, Montgomery & Simpson 2000).

Osaki (1996) further proposed that only the values of the orbital period and the mass transfer rate determine the basic differences among the four major subclasses of non-magnetic CVs (U Gem systems, SU UMa stars, permanent superhumpers and nova-likes). Fig. 1 is taken from his paper. The permanent superhump systems are thought to be in a state of higher accretion rate (implying large accretion disc radii) than in regular SU UMa systems. Osaki’s model describes pretty well most superhump observations, although his suggestion that the period gap separates between systems with tidally unstable accretion discs and tidally stable objects is violated by the presence of many permanent superhump systems above the gap (Patterson 1999; Retter & Hellier 2000; Retter et al. 2000; see also Table 1 and Fig. 2).

1.3 Superhumps in classical nova systems

The permanent superhump model has been invoked so far for three classical novae: V603 Aql (Patterson & Richman 1991; Patterson et al. 1993c; Patterson et al. 1997b), CP Pup (White & Honeycutt 1992; White, Honeycutt & Horne 1993; Thomas 1993; Patterson & Warner 1998) and V1974 Cyg (Retter, Leibowitz & Ofek 1997; Skillman et al. 1997). In all cases an alternative magnetic explanation has been proposed as well (Haefner & Metz 1985; White et al. 1993; Balman, Orio & Ogelman 1995; Semeniuk et al. 1995; Olech et al. 1996), however the arguments for the superhump explanation seem much stronger. The periods of the three novae fit well in the Stolz & Schoembs (1984) diagram, and in two cases negative superhumps have been observed in addition to the presence of positive superhumps (Patterson et al. 1997b; Patterson 1999). Nova V4633 Sgr 1998 is another permanent superhump candidate (Lipkin, personal communication; see also Lipkin & Leibowitz 2000).

Retter & Leibowitz (1998) introduced a simple way of testing the thermal stability state of accretion discs in CVs. Employing this method on the three permanent superhump novae they found that these systems are indeed thermally stable, while the progenitor of V1974 Cygni was located below the critical line for stability. This result led Retter & Leibowitz to suggest that if the decline from outburst in V1974 Cyg towards the pre-nova magnitude continues, the post-nova should evolve into a regular SU UMa system with superhumps appearing only during superoutbursts. Alternatively, its disc might stay optically thick, keeping above the thermal stability limit, and continue to show superhumps.
permanently in its light curve. Retter & Leibowitz thus proposed that non-magnetic classical novae can be progenitors of permanent superhump systems. Retter, Naylor & Leibowitz (1999) and Retter & Naylor (2000) developed this proposal. In this work we elaborate and extend these ideas.

1.4 Existing nova cycle models for CVs

The different subclasses of CVs share a similar configuration, namely a binary system with a primary white dwarf and a Roche-lobe filling secondary red dwarf. Spectra of old novae usually show strong continua and emission lines, very similar to nova-like systems (Bode & Evans 1989; Warner 1995a). A few observations further support a possible connection between classical novae and dwarf novae. Two old novae experience regular dwarf nova outbursts a few decades after their eruption – the peculiar nova, GK Per 1901 (Sabbadin & Bianchini 1983), and V446 Her 1960 (Honeycutt, Robertson & Turner 1995; Honeycutt et al. 1998). Dwarf nova outbursts a few decades before the nova eruption of V446 Her have probably been observed as well. Livio (1989) and Warner (1995a) listed a few other cases, however, the evidence for such a transition in these systems is rather poor.

Robinson (1975) compared the magnitudes of 18 old novae with the values of their progenitors. He found no significant difference between these numbers, and concluded that all novae return to their pre-outburst luminosities. The observational properties of old novae are very similar to those of nova-likes, which have thermally stable accretion discs (Warner 1995b). Therefore, it seems that the outburst does not alter the thermal stability at all, at least for time scales of the order of a few decades. An exception in Robinson’s sample is V446 Her, mentioned above. It is, however, the only clear case of a regular nova which had dwarf nova outbursts a few decades after (and probably even before) the nova eruption. Recently, it was found that V446 Her has an orbital period near 5 h (Thorstensen & Taylor 2000) – typical for classical novae.

Vogt (1990) investigated a sample of 97 old novae. His results seem to confirm the idea that there is no systematic difference in the brightness of pre-novae and post-novae. He also showed that the brightness of old novae tends to fade slowly in the decades following their outbursts. This finding was confirmed by another study (Duerbeck 1992). A possible interpretation of the decrease in the nova light is a future transition to a different phase (dwarf nova).

Therefore it was suggested that nova outbursts link different CV subclasses. The nova cycle of the subgroups of CVs is, however, still debatable, and several scenarios have been offered for the connections among these subclasses.

The ‘hibernation scenario’ (Shara et al. 1986; Prilukin & Shara 1986; Shara 1989) suggests that dwarf novae → nova-likes → novae → nova-likes → dwarf novae → ‘hibernation’ → dwarf novae etc. However, it was later proposed that the ‘hibernation’ phase (\( M \approx 0 \)) might not exist at all (Livio 1989), thus dwarf novae → nova-likes → novae →

nova-likes → dwarf novae...

The typical time scales for the transitions were estimated as a few centuries – millennia.

An alternative view to the ‘hibernation scenario’ and to the ‘modified / mild / modern hibernation scenario’ was presented by Mukai and Naylor (1995). They suggested that nova-likes and dwarf novae constitute different classes of pre-nova systems. Therefore, there are two possibilities: 1. nova-likes → novae → nova-likes... 2. dwarf novae → novae → dwarf novae...

Nova-likes should have more frequent nova outbursts than dwarf novae because their mass transfer rates are larger than those of dwarf novae. The critical mass for the thermonuclear runaway is thus achieved much faster. Transitions between the two phases are allowed on the long term scale.

It seems that the observations of old novae have not been able to judge between the various models (Naylor et al. 1992). Furthermore, these scenarios were suggested when there were essentially no known non-magnetic novae below the period gap, and before the discovery of the permanent superhump class. In this work we extend the models to the short orbital period CVs and test them by the observations accumulated so far.

2 THE LOCATION OF THE PERMANENT SUPERHUMP SYSTEMS IN THE (\( P_{orb}, M \)) PLANE

To test Osaki’s suggestion (1996), that the accretion discs in permanent superhump systems are thermally stable (unlike the discs of SU UMa systems that are unstable in quiescence, and become quasi-stable only during superoutbursts), we locate these systems in the \( (P_{orb}, M) \) plane. We basically follow the method developed by Retter & Leibowitz (1998). It essentially uses \( M_V \) to estimate \( M \), and assumes that the accretion disc is the dominant light source in the V band. It is also assumed that the disc is not kept at a high temperature due to irradiation by the white dwarf, which is relatively hot in post-novae. A modification that we add to these calculations is the effect of the inclination angle, \( i \), on the visual magnitude, expressed by Warner (1987):

\[
\Delta M_i = -2.5 \log[(1 + 1.5 \cos(i)) \cos(i)]
\]  

where \( \Delta M_i \) is the magnitude change as a function of \( i \). The resulting equations equivalent to equations (7) (for the critical instability value) and (8) (for the calculation of accretion rates) of Retter & Leibowitz (1998) are:

\[
(M_V)_{crit} = 2.16 - 4.25 \log P_{orb} - 3.33 \log M_1 + 5 \log(d/V) - \Delta M_i(2)
\]

\[
M_{17} \equiv \left(10^{\frac{M_V + \Delta M_i - A_V - 0.4}{5 \log(d/V)}} - 1\right)^{\frac{1}{3}} M_1(3)
\]

where our symbols are identical with those of Retter & Leibowitz.

In Table 1, we present values of the relevant parameters of permanent superhump systems compiled from various sources. The list of objects is primarily based on Patterson (1999). Only ‘conventional’ permanent superhump systems (i.e. only positive superhumpers) were chosen. Systems showing only negative superhumps in their light curves were rejected from our sample. Note that evidence for the presence of positive superhumps in TV Col has been presented.

* We exclude GK Per as it is a very atypical nova – its orbital period is very long (~2 d), and its secondary star is believed to be a sub-giant (e.g. Dougherty et al. 1996) unlike red dwarf companions in classical novae.
by Retter & Hellier (2000) and Retter et al. (2000). The permanent superhump AM CVn systems were also excluded. The mass transfer rates were calculated by equation (3) using the values in the table as input parameters.

The results are depicted in Fig. 2. The consistency of the method for estimating the accretion rate was discussed by Retter & Leibowitz (1998). The inclination effect that is added in this study is not severe for the three systems discussed in that work, and the values that we obtain for the accretion rates of the three permanent superhump novae are rather similar to those deduced by Retter & Leibowitz. We thus conclude that the modified version is consistent with other methods of estimating mass transfer rates.

3 DISCUSSION

3.1 Are permanent superhump systems thermally stable?

One of our first aims in this paper was to check whether the accretion discs in permanent superhump systems are indeed thermally stable as was proposed by Osaki (1996). The results found in the previous section, and presented in Fig. 2 seem to support this suggestion. Among the eight objects in our sample with enough data, all have relatively high accretion rates. These values exceed in general the typical mass transfer rates in dwarf nova systems ($10^{15}$–$10^{16}$ gr/sec), and are of the same order of the typical numbers in nova-likes and old novae ($10^{17}$–$10^{18}$ gr/sec – Warner 1995a). Four systems (CP Pup, V1974 Cyg, TT Ari and V603 Aql) are located above the critical line for thermal instability. The permitted ranges of accretion rates of three of the other permanent superhumpers (BK Lyn, AH Men and TV Col) straddle the thermal instability line and are thus consistent with their being stable. Note that the distance estimate for BK Lyn given by Dhillon et al. (2000) is a lower limit thus implying higher values of accretion rates (see the corresponding arrow in Fig. 2). V592 Cas is the only permanent superhump system found below the instability line according to our calculations. Its model-dependent distance estimate (Huber et al. 1998) is very small, and is almost certainly incorrect as its distance to interstellar reddening ratio is about a factor smaller than in the other objects in Table 1. The interstellar reddening thus implies a distance of ~10 times larger, and therefore mass transfer rates ~100 times larger (see the corresponding arrow in Fig. 2).

There are many observational and theoretical uncertainties in calculating these mass transfer rates. In fact even the location of the critical thermal instability line itself is controversial. Warner’s (1995b) border line, for example, is placed about a factor of two below Osaki’s (1996) critical line. We are looking, however, at effects of the order of ~10. We thus conclude that the accretion discs of permanent superhump systems are most likely thermally stable, and that they indeed form a unique subgroup of CVs, with different physical parameters (namely short orbital periods and high mass transfer rates) from other CV subclasses. This finding further supports the suggestion mentioned above that the distance estimate to V592 Cas quoted in Table 1 was underestimated, and a better measurement should raise its location above the critical line. Similarly, the upper limits on the distances of BK Lyn, AH Men and TV Col are preferred to the lower values.

3.2 Angular momentum conservation in permanent superhump systems

Magnetic braking can account for the mean mass transfer rates of systems above the period gap, but is believed to occur only for systems with orbital periods larger than about 2.7 h. Braking by gravitational radiation can explain the typical accretion rates in dwarf novae below the gap, but there seems to be a serious problem for the short period permanent superhump systems (Fig. 2). The mass accretion rates estimated for these systems in Section 2 are ~$10^{18}$ gr/sec, and thus more than two orders-of-magnitude higher than those yielded by gravitational radiation. The presence of permanent superhump systems below the gap is therefore not understood within the current models, if their mass transfer rates represent mean secular values.

One solution to this problem is to invoke an extra source of angular momentum loss below the period gap, the obvious candidate being magnetic braking. It is often stated that the secondary stars in CVs below the gap lack the radiative core required to anchor a magnetic field. In fact, single M stars (which are typical secondary stars in short orbital period

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Figure 2. The location of permanent positive superhump systems in Osaki’s (1996) diagram (Fig. 1). The two vertical dashed lines show the two border lines of the period gap according to Diaz & Bruch (1997). The tilted dotted line separates thermally stable objects (above) and unstable systems (below). The bars correspond to the permitted range of the accretion rates derived by equation (3) with the parameters presented in Table 1. All permanent superhump systems have relatively high mass transfer rates, and are probably located above the thermal instability line, although some doubts exist for four systems. The arrow above the bar corresponding to BK Lyn represents the fact that the distance value given by Dhillon et al. (2000) is a lower limit. The arrow above the permitted range of V592 Cas represents severe doubts on its low distance estimate. The lower tilted dotted-dashed line corresponds to braking by Gravitational Radiation (Warner 1995a). The long-dashed line that starts at P=2.7 h shows the calculation for Magnetic Braking (McDermott & Taam 1989; Warner 1995a) using $M_1=1M_\odot$ and $q=M_2/M_1=0.7$. We note that the three tilted lines are model dependent. See text for more details and discussions.
CVs – Smith & Dhillon (1998), which are fully convective, do show magnetic activity (Fleming, Schmitt & Giampapa 1995). Whilst invoking such braking would preclude certain explanations of the period gap itself, which rely on the cessation of magnetic activity (e.g. Verbunt 1984), it would allow a natural explanation for the presence of high accretion rates in systems with orbital periods below the period gap. Therefore, we suggest that the mere existence of permanent superhump systems below the gap might be an argument that magnetic braking does not cease at the gap.

A different solution to the problem is provided by the possibility of mass transfer cycles. If the permanent superhump phase is very short lived, and systems below the gap spend most of their time as SU UMa systems, perhaps even hibernating for a while, then the mean mass transfer rate might not exceed the Gravitational Radiation values. An argument against such a possibility is that King et al. (1996) could not produce self-sustaining mass transfer cycles in short period systems. However, as we shall show in the next section, there may be emerging observational evidence that nova explosions drive such cycles below the gap.
3.3 Nova cycle scenarios for non-magnetic short orbital period CVs

Post-novae with orbital periods above the gap usually return to their pre-outburst brightness within a few decades (Section 1.4). So far only two non-magnetic novae below the period gap, CP Pup and V1974 Cyg, have been found. Both have permanent superhumps in their light curves suggesting that their discs are thermally stable. Table 2 presents the pre-outburst and post-eruption magnitudes of the two systems. The observations are consistent with the two post-novae being brighter than their progenitors. Moreover, the pre-nova magnitude of V1974 Cyg implies that its disc was thermally unstable and therefore the progenitor of the nova should have been an SU UMa system (Retter & Leibowitz 1998). Thus, it is the first example of a nova that has changed the thermal stability state of its accretion disc. This transition might be explained by a temporary change in the mass transfer rate due to the hot post-nova white dwarf irradiating the secondary star or the disc itself. Alternatively, V1974 Cyg is the first direct evidence for mass transfer cycles, in this case driven by the nova explosion. CP Pup is a candidate for the same behaviour. The nova cycle scenarios proposed for long orbital period CVs (Section 1.4) could thus be applicable to the short period systems, but possibly with some minor modifications.

Table 2. Pre-eruption and post-outburst magnitudes of the two permanent superhump novae below the period gap

| Object   | year of outburst | pre-nova magnitude | post-nova magnitude | difference |
|----------|------------------|--------------------|---------------------|------------|
| CP Pup   | 1942             | $>17^{1}$          | $15.3^{2}$          | $>1.7$     |
| V1974 Cyg| 1992             | $21^{1.4}$         | $16.5^{−0.5}$       | $4.5^{−?}$ |

1 Warner 1995a; 2 Patterson & Warner 1998; 3 Pavelin et al. 1993; 4 Retter & Leibowitz 1998; 5 Goranskiy 2000

4 SUMMARY AND CONCLUSIONS

Our results can be summarized as follows:

1. We established the idea that the accretion discs in permanent superhump systems are thermally stable.
2. If the high values of accretion rates found in the short orbital period permanent superhumpers represent their secular mean values, then there is a problem with the mechanism that removes angular momentum from the systems. It might be solved by extending the magnetic braking mechanism to below the gap, or by invoking another way to lose angular momentum in these CVs. Alternatively, systems below the period gap might have mass transfer cycles, and the permanent superhump stage should be short compared with the full CV cycle.
3. We suggest that nova cycle scenarios similar to those proposed for the long orbital period CVs should be applied to the short period systems. However, they would be slightly modified if the superhumps observed in the post-novae below the gap represent a true long-term change in the mass transfer rate rather than a transient increase in the disc luminosity due to irradiation by the hot white dwarf. The observations of the two non-magnetic novae below the gap seem to support mass transfer cycles driven by the nova outburst.

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