Predicting the Future of Superhumps in Classical Nova Systems

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Abstract

Oscillations observed in the light curve of Nova V1974 Cygni 1992 since summer 1994 have been interpreted as permanent superhumps. From simple calculations based on the Tidal-Disk Instability model of Osaki, and assuming that the accretion disc is the dominant optical source in the binary system, we predict that the nova will evolve to become an SU UMa system as its brightness declines from its present luminosity by another 2-3 magnitudes. Linear extrapolation of its current rate of fading (in magnitude units) puts the time of this phase transition within the next 2-4 years. Alternatively, the brightness decline will stop before the nova reaches that level, and the system will continue to show permanent superhumps in its light curve. It will then be similar to two other old novae, V603 Aql and CP Pup, that still display the permanent superhumps phenomenon 79 and 55 years, respectively, after their eruptions. We suggest that non-magnetic novae with short orbital periods could be progenitors of permanent superhump systems.

Key words: novae - stars: individuals: V1974 Cyg - stars: individuals: V603 Aql - stars: individuals: CP Pup - stars: evolution - stars: white dwarfs - stars: oscillations - accretion discs

1 INTRODUCTION

1.1 The (permanent) superhump phenomenon

Regular superhumps are quasi-periodic oscillations that appear in the light curve (LC) of the SU UMa subclass of dwarf novae, superimposed on the superoutburst LC of these systems. The superhump period is a few percent longer than the orbital period of the system in which it is observed (laDous 1993). Permanent superhumps (PSH), on the other hand, appear permanently or most of the time in systems where they prevail, and do not demand a superoutburst for their emergence. Superhumps are detected in the LC of cataclysmic variables (CVs) with short orbital periods (\(P_{\text{orbital}}\approx 17-200\) min. - Ritter & Kolb 1998). Stolz & Schoembs (1984) found a linear relation between the relative excess of the superhump period over the orbital one, and the orbital period.

The Tidal-Disc Instability model (for a review see Osaki 1996) is the commonly accepted explanation of the phenomenon. The superhump periodicity is the beat of the orbital period of the binary system with the period of the precession of the accretion disc around the white dwarf (WD) in the binary co-rotating frame. The difference between regular superhumps and PSH is understood as a result of the much larger mass transfer rate in the system showing PSH than in SU UMa systems. In fact, Osaki’s schematic diagram (Fig. 1) states that the values of only two parameters, the orbital period and the mass transfer rate, determine the basic differences among the four major classes of CVs, namely, U Gem, SU UMa, PSH and Nova-like variables.

1.2 Superhumps in Classical Nova Systems

Photometric observations of V1974 Cyg (N. Cyg 1992) revealed two periodic oscillations in the LC of the star (Retter, Ofek & Leibowitz 1995). While there is an overall agreement that the shorter is the orbital period of the binary system, two interpretations for the nature of the second period, which is about 5% larger than the orbital one, have been suggested. Semeniuk et al. (1995) and Olech et al. (1996), argued that it is the spin period of a rotating WD. Retter, Leibowitz & Ofek (1997) and Skillman et al. (1997) proposed, on the other hand, that the longer period is that of PSH oscillations. We think that the increase of this period

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relation of Stolz & Schoembs (1984) between orbital and superhumps periods in SU UMa systems. In addition, the spin periods in all but one intermediate polars are shorter than their orbital periods (Patterson 1994). Even in the one exceptional case (RX J19402-1025), the period excess is very minute - \( \left( P_{\text{spin}} - P_{\text{orbital}} \right) / P_{\text{orbital}} \approx 0.3\% \) (Patterson et al. 1995), much smaller than in a typical superhump system. We believe that the observed photometric features of CP Pup favour the superhump interpretation for this system and we adopt it in this work.

There are a few more reports on short periods in other novae. RW UMi 1956, with a possible orbital period of \( \sim 2 \) hr (Szkody et al. 1989), is a natural permanent superhump candidate, but intensive continuous photometry of the nova during 25 nights in 1995 and 1997, carried out at the Wise Obs., suggests that the variation is irregular. Two periods of \( \sim 3.3 \) hr, which differ from each other by less than 2%, were found in V1500 Cyg 1975. These periods, however, don't obey the Stolz & Schoembs relation. The variation in the polarization, found in this system, is also a very strong evidence for the magnetic nature of the WD. (Stockman, Schmidt & Lamb 1988). There are also some evidence that the 85-m period found in GQ Mus 1983 is caused by the rotation of the magnetic pole of the primary (Diaz & Steiner 1996), showing the location on the (Orbital Period, \( \dot{P} \)) plane of four major groups of CVs: UG=Geminorum, SU UMa, PSH=permanent superhumps and NL=nova like variables. The two dashed vertical lines represent the two ends of the well known period gap in the period distribution of CVs. Systems on the right hand side, the UG and NL groups, have accretion discs that are tidally stable. Systems on the left, PSH and SU UMa, are tidally unstable. Systems above the dotted tilted line, PSH and NL, have thermally stable discs. Systems below that line, UG and SU UMa, have thermally unstable discs. The upper dot represents the present location of V1974 Cyg in this plane. The arrow indicates the expected decrease in the \( M \) value in the future. The lower point is the location of value of \( M \), corresponding to the pre-nova magnitude according to Skiff (1997). If the fading of the nova, in magnitude units, continues linearly, the arrow will intersect the tilted line around the year 2000.

Figure 1. A schematic theoretical diagram based on Osaki (1996), showing the location on the (Orbital Period, \( M \)) plane of four major groups of CVs: UG=Geminorum, SU UMa, PSH=permanent superhumps and NL=nova like variables. The two dashed vertical lines represent the two ends of the well known period gap in the period distribution of CVs. Systems on the right hand side, the UG and NL groups, have accretion discs that are tidally stable. Systems on the left, PSH and SU UMa, are tidally unstable. Systems above the dotted tilted line, PSH and NL, have thermally stable discs. Systems below that line, UG and SU UMa, have thermally unstable discs. The upper dot represents the present location of V1974 Cyg in this plane. The arrow indicates the expected decrease in the \( M \) value in the future. The lower point is the location of value of \( M \), corresponding to the pre-nova magnitude according to Skiff (1997). If the fading of the nova, in magnitude units, continues linearly, the arrow will intersect the tilted line around the year 2000.

2 CALCULATIONS

2.1 Deriving the Equations

For each system, with a given orbital period, \( P_{\text{orb}} \), in hours, the critical mass transfer rate, that separates between the thermally stable and unstable discs is given by Osaki (1996): \( M_{\text{crit}} \approx 2.7 \times 10^{17} \left( \frac{P_{\text{orb}}}{4 \text{hour}} \right)^{1.7} \frac{g}{\text{sec}} \).

The bolometric brightness of the disc is (Patterson 1994):

\[
L_{\text{bol}} = \frac{GM_{\text{wd}} M}{2R_{\text{wd}}} \tag{2}
\]

where \( G \) is the gravitational constant; \( M_{\text{wd}} \) and \( R_{\text{wd}} \) are the mass and radius of the WD and \( M \) is the mass transfer rate. For a 1.05 \( \odot \) primary we take \( R_{\text{wd}} \approx 5,500 \) km, and \( R_{\text{wd}} \sim M_{\text{wd}}^{1/3} \) (Carol & Ostlie 1996). We also use the basic equation (Allen 1976):

\[
M_{\text{bol}} = 4.75 - 2.5\log(L_{\text{bol}}/L_{\odot}) \tag{3}
\]

where \( M_{\text{bol}} \) is the bolometric magnitude of the disc. From equations 1, 2 & 3 we obtain the following relation:

\[
M_{\text{bol}} \approx 5.02 - 4.25\log(P_{\text{orb}}) - 3.33\log(M_{\text{wd}}) \tag{4}
\]

where \( M_{\text{wd}} \) is the mass of the primary in solar units, and we used the mass-radius relation mentioned above for eliminating the radius. For a given WD mass, \( M_{\text{wd}} \), equation 4 gives the bolometric magnitude of a disc-dominated system crossing the tilted border line in Fig. 1, as a function of the orbital period.

The bolometric magnitude is hard to assess observationally, because observations at all wavelengths are needed. The ratio between the visual luminosity of the accretion disc to its bolometric brightness may, however, be estimated during 1995 and 1996, as well as other features of the optical LC of the nova discussed in Retter et al. (1997), argue against the magnetic interpretation for the longer period, and for the PSH one, which we adopt in this letter.

Two other novae, V603 Aql 1918 (Patterson & Richman 1991; Patterson et al. 1993; Thomas 1993 and Patterson et al. 1997) and CP Pup 1991; Patterson et al. 1993; Thomas 1993), also show PSH in their LCs. While the presence of PSH in the LC of V603 Aql is rather well established, there is still some controversy in the case of CP Pup. White et al. (1993) and Balman, Orio & Ogelman (1995) proposed a WD spin interpretation for the second periodicity in the LC of this nova, which was initially thought to be 11% longer than the orbital period. However, an extensive photometric study by Thomas (1993) revealed that the period excess is only about 2%, and that the two periods obey the well-known...
from theoretical models of stable accretion discs. LaDous (1989) calculated such a model for a $1 M_\odot$ primary with $M \approx 1 \times 10^{-9} M_\odot$/yr. From this model we find:

$$\frac{L_V}{L_{bol}} \sim 0.14.$$  

We note here that the main point presented in this letter is not very sensitive to the exact value of this ratio. It does not change by much even if there is an error of a factor two in its value. We can now use the distance modulus equation (Allen 1976):

$$m_V = M_V - 5 + 5 \log(d) + A_V$$  \hspace{1cm} (6)

where $m_V$ is the apparent visual magnitude of the disc; $d$ is the distance to the object in parsec and $A_V$ is the interstellar extinction in the V band. The final relation between the critical $m_V$ and the parameters of the binary system is therefore:

$$(m_V)_{crit} = 2.16 - 4.25 \log(P_{orb}) - 3.33 \log(M_1) + 5 \log(d) + A_V$$  \hspace{1cm} (7)

We can also use the above equations in a different order and write down an expression for the mass transfer rate as a function of the apparent visual magnitude of the nova:

$$M_{17} = \left(\frac{10^{(m_V - A_V - 0.69)}}{M_1}\right) \frac{d^2}{M_1^3}$$  \hspace{1cm} (8)

where $M_{17} = \dot{M}/(10^{17} \text{gr/sec})$. Deriving the former two equations, we assumed that the visual brightness of the nova system emanates solely from the accretion disc. This obviously neglects the light of the secondary star in the system. Other light sources, such as the nebula and the WD, probably contribute to the brightness of the system as well. These contributions, however, diminish in time, as the system decays after the nova event. We may also relax somewhat our assumption of the exclusiveness of the accretion disc as a light source, without changing considerably our final conclusion, except for shortening the time required for the system to cross the critical $\dot{M}$ line.

2.2 V1974 Cyg

Table 1 presents values of the input parameters to the equations of the previous section for the three PSH classical novae. The ranges of possible values given in the table are intervals between two estimates of the corresponding parameter that were made in the cited literature. For V1974 Cyg there are also a few estimates that are outside the intervals given in the table. We shall discuss them in Section 3.5.

For Nova Cygni, with $P_{orb} \approx 1.95$ hr, equation 1 yields: $\dot{M}_{crit} \approx 8 \times 10^{16}$ gr/sec, and the range of visual magnitudes that we extract from equation 7 is: $m_V = 17.9 - 18.5$. These numbers are much smaller than the pre-nova magnitude of the system, which is either $m_V = 19.5$ (Annum, Kolka & Leedljav 1993) or $m_2 = 21 \pm 1$ (Skiff 1997). It is, on the other hand, still larger than the magnitude of V1974 Cyg in 1997 May - $m_V \approx 15.85$.

Using equation 8, with this visual magnitude of the nova, we derive a mass transfer rate of $\dot{M} \approx 7 \pm 3 \times 10^{17}$ gr/sec. This value is illustrated in Fig 1. (at the upper left domain), and it is, reasonably, larger than the critical $\dot{M}$.

| Object      | $P_{orb}$ (hr) | $M_{sd}$ ($M_\odot$) | $d$ (kpc) | $A_V$ |
|-------------|----------------|----------------------|-----------|-------|
| V1974 Cyg   | 1.95$^1$       | 0.89-1.07$^{2,3,4}$   | 1.66-1.88$^5$ | 0.96-1.02$^5$ |
| V603 Aql    | 3.32$^6$       | 0.66-0.90$^7$        | 0.33-0.38$^8$ | 0.22-0.5 8.9 |
| CP Pup      | 1.47$^{10}$    | 0.12-0.86$^{10,11}$  | 0.83$^{12}$ | 0.78-0.86$^{9,13}$ |

$^1$ DeYoung & Schmidt 1994.
$^2$ Paresce et al. 1995.
$^3$ Balman, Krautter & Ogelman 1997.
$^4$ Retter et al. 1997.
$^5$ Chochol et al. 1997.
$^6$ Patterson et al. 1993.
$^7$ Friedjung, Selvelli & Cassatella 1997.
$^8$ Krautter et al. 1981.
$^9$ Warner 1995.
$^{10}$ Duerbeck, Seitter & Duenmmler 1987.
$^{11}$ White et al. 1993.
$^{12}$ Bode, Seaquist & Evans 1987.
$^{13}$ Diaz & Bruch 1997.

2.3 V603 Aql and CP Pup

Similar calculations can be made for the two other novae exhibiting PSH in their LCs. The critical visual magnitude values for V603 Aql are in the range $m_V = 12.9 - 14.0$ and for CP Pup it is $m_V = 17.1 - 20.0$. The present visual magnitude of the two systems are - $m_V \approx 12$ and $m_V \approx 15$, respectively (Warner 1995). Both are appreciably brighter than the corresponding critical values.

Using the current magnitudes of these two novae for calculating the present mass transfer rate, we find $\dot{M} \approx 8 \pm 4 \times 10^{17}$ gr/sec for V603 Aql and $\dot{M} \approx 2.8 \pm 2.5 \times 10^{18}$ gr/sec for CP Pup.

3 DISCUSSION

3.1 Consistency

The value of the parameters of the three nova systems that we used in the previous section were derived by various researchers, in general independently of the superhumps phenomenon. Our calculations show that according to Osaki’s theory, the very presence of superhumps in the LCs of these systems is indeed expected from these values.

Further support for the validity of the calculations presented in this work, particularly for the bolometric correction that we used in Section 2.1 (equation 5), comes from the agreement of the mass transfer rate that we obtain for V603 Aql with estimates by other authors using other methods. We derive in Section 2.3 for this parameter the value $8 \pm 4 \times 10^{17}$ gr/sec. It is in good agreement with $4.8 \times 10^{17}$ gr/sec (Krautter et al. 1981), $7.6 \times 10^{17}$ gr/sec (Wade 1988), and $2.6 \times 10^{17}$ gr/sec (Duerbeck 1992).
3.2 The principal light source

Our calculations in Section 2 were made with the assumption that the visual light of all three novae emanates from the accretion discs in these systems. This assumption is supported by the optical spectrum of the three stars. Shai Kaspi kindly took for us two spectrograms of V1974 Cyg with the FOSC camera at the Wise Obs., one in 1995 July and one in 1996 August. The two spectra are dominated by nebular emission lines and by a continuum that seems to be free of stellar absorption features. Similarly, spectra of V603 Aql (Williams 1983) and of CP Pup (O’Donoghue et al. 1989, White et al. 1993), which were taken 69 years after outburst in the V603 Aql case, and 43, 45 and 46 years after outburst in the CP Pup case, do not show any obvious stellar absorption features. Thus, any contribution of the secondary to the light of these systems is indeed negligible.

Leibowitz (1993) has drawn attention to the appearance of a kink in the visual LC of many classical novae a few tens of days after maximum light. He suggested that the abrupt change in the slope of the decaying LC signifies a transition of the main light source in the system from the envelope of the contracting nova to the accretion disc in the system. In the two old novae, V603 Aql and CP Pup, the photometry capable of detecting superhumps was performed many years after the outburst, long after the appearance of the kink in their LCs. In V1974 Cyg, the superhumps were also detected only after the kink in the LC of this nova, as shown in Fig. 2. This figure is a comprehensive visual light curve of the nova, from outburst in 1992 February to 1997 May. The data were taken from various amateur groups. The arrow in the figure indicates the time when superhumps were first observed. Since superhumps are a pure disc phenomenon and consistently with Leibowitz’s hypothesis we may conclude that presently in V1974 Cyg, the accretion disc is indeed the major source of the optical continuum.

3.3 The future of the permanent superhumps in the two old novae

We showed in Section 2 that in the three novae discussed in this letter, the present visual magnitude is brighter than the critical value for transition from the PSH to the SU UMa state. The future of the superhumps in their LCs is correlated with the future run of their LCs.

The question of what is the long term behaviour of the LC of classical novae, many years after outburst, is a wide open one. It is difficult to answer it observationally because of the scarcity of these objects on one hand, and the early age, of less than a century of modern observations in novae, on the other. This time duration is probably still shorter than the characteristic time of the returning of classical novae to their real quiescence state.

In two pioneering works, Vogt (1990) and Duerbeck (1992) attempted to systematically investigate the long term photometric behaviour of classical novae. Duerbeck’s sample of 21 old novae includes also the two old novae discussed in this letter. There are large systematic difficulties and uncertainties in the determination of the decline rate of old novae, as underlined by Duerbeck himself. He, nevertheless, suggested for V603 Aql an average decline rate of 10.7 mmag/year, and for CP Pup 36.9 mmag/year (Duerbeck 1992 Table 1).

Taking these numbers at face value and using our results of Section 2.3, we obtain that V603 Aql will cross the critical line in Fig. 1 not before some 75 years in the future from today. CP Pup will undergo this phase transition not before some 55 years from today. In view of the large uncertainties in the value of the critical visual magnitude of these two novae, as well as in their average decline rate, these time intervals are rough lower limits at best.

3.4 The future of the permanent superhumps in Nova Cygni 1992

V1974 Cyg is still in a phase of relatively steep decline from its recent outburst. In its visual LC shown in Fig. 2, three sections of nearly linear decline, at three different slopes, are clearly discernible. The decline rate in the last section, lasting now for more than two years, is about 0.7 mag/year. If the nova keeps this decline rate for another few years, it will reach the critical visual magnitude, indicated by the dot in the figure, sometime around the year 2000. The vertical error bars around the dot denote the formal uncertainty in the critical visual magnitude value (see Section 2.2). The horizontal bars represent the uncertainty in the time of crossing the line of phase transition, due to the uncertainty in the slope of the present average linear decline.
3.5 Sensitivity of the results to the adopted parameters of N. Cygni 1992

Table 1 presents values of system parameters that we used in our calculations. When more than one value is suggested in the literature, the table gives a range of possible values, where the range limits are two particular values that have been suggested for the corresponding parameter. The results of our calculations in Section 2.2 and 2.3 are accordingly given also as interval of possible critical values. For a few parameters of V1974 Cyg, however, there are in the literature more extreme estimates that put the parameter value outside the indicated interval. Here we show that even when using these more extreme values in our calculations, the results do not change very significantly.

Balman et al. (1997) suggested an upper limit of 1.37 $M_\odot$ on the mass of the WD in V1974 Cyg. Paresce et al. (1995) proposed the low value of 0.75 $M_\odot$ for this parameter. The use of these two extreme values in our calculation widens the range of the predicted critical visual magnitude of V1974 Cyg by no more than 0.4 magnitude on each side. Similarly, the upper limit on the distance to this system of 3.2 kpc (Paresce et al. 1995) increases the critical range of magnitudes by about 1.1 mag. It seems, however, that the expansion velocities of the nebulae used by these authors are rather large. All these possible modifications, while changing the calculated time that is required before phase transition occurs, do not alter the qualitative scenario, presented in this work. Nova Cyg '92 is indeed expected to decline further in its optical brightness, as it is presently still nearly four magnitudes brighter than the system pre-nova magnitude $m_V = 19.5$ (upper horizontal line in Fig. 2 - Annuk et al. 1993). It may have even larger room to decline, if the progenitor had the magnitude $m_B = 21$ (Fig. 2 - lower horizontal line - Skiff 1997). Naturally, the possibility that V1974 Cyg changes its rate of decline, or even reverses it into brightening, before reaching the critical visual magnitude, cannot be ruled out. In this case PSH will continue to prevail in the LC of this system, much like they do in the LCs of V603 Aql and CP Pup.

3.6 A proposed evolution scenario

Based on the example of the three classical novae V603 Aql, CP Pup and V1974 Cyg, and on the calculations presented in this letter, we may speculate that short period novae with non-magnetic WDs may be the progenitors of PSH systems. This quasi-stable stage in nova life might take a few decades or centuries, before the system returns to its quiescent state, and then becomes a regular SU UMa star. Naturally, such a scenario must be checked quantitatively by a proper statistical analysis of the population of the involved classes of stars.

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