Tilted accretion discs in cataclysmic variables: Tidal instabilities and superhumps

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\textbf{ABSTRACT}

We investigate the growth of tidal instabilities in accretion discs in a binary star potential, using three dimensional numerical simulations. As expected from analytic work, the disc is prone to an eccentric instability provided that it is large enough to extend to the 3:1 resonance. The eccentric disc leads to positive superhumps in the light curve. It has been proposed that negative superhumps might arise from a tilted disc, but we find no evidence that the companion gravitational tilt instability can grow fast enough in a fluid disc to create a measurable inclination. The origin of negative superhumps in the light curves of cataclysmic variables remains a puzzle.

\textbf{Key words:}
accretion, accretion discs — instabilities — hydrodynamics — methods: numerical — binaries: close — novae, cataclysmic variables.

\textbf{1 INTRODUCTION}

Classical superhumps are large amplitude variations in the optical light curves of close binary systems. The superhump period is typically a few per cent longer than the binary orbital period. The most plausible explanation for these modulations is that resonance of gas orbits in the outer disc with the tidal potential of the secondary star causes the disc to become eccentric (Whitehurst 1988; Hirose & Osaki 1990; Lubow 1991a). Due to a combination of the $m = 0$ mode of the tidal potential, and pressure and viscous effects, the eccentric disc precesses slowly in the prograde direction. Light from the disc is then modulated on the period of the disc motion relative to the binary potential (Murray 1996, 1998).

In this paper we investigate the origin of a second, more puzzling, modulation in the light curves of some cataclysmic variables. These ‘negative superhumps’ have a period a few per cent less than the binary period. Their origin is presently unknown, but Patterson et al. (1993) proposed that this was the signature of the precessional motion of a tilted disc. This is an attractive explanation of the observations, but if correct it poses the difficult question of how such a tilted disc can arise in cataclysmic variable (CV) systems.

In this paper we investigate various methods of exciting a tilt or warp in a CV disc. The next section is a summary of the observations of the new periodicity. In section 3 we discuss the conditions under which tidal instability might induce a disc tilt, which we investigate numerically in sections 4 and 5. Section 6 discusses the differences between CVs and X-ray binaries such as Her X-1, where the existence of warped discs is well established. Section 7 summarises our results, and discusses what observations are required to further investigate the possible existence of tilted discs in CVs.

\textbf{2 OBSERVATIONS OF NEGATIVE SUPERHUMPS}

An optical modulation with a period slightly shorter than the orbital period, $P_{\text{orb}}$, has been seen in several cataclysmic variables (Patterson et al. 1993; Patterson et al. 1997). Here we briefly describe a few systems that exhibit these so-called ‘negative superhumps’.

The nova V603 Aquilae has a high mass transfer rate which implies a hot accretion disc (Patterson & Richman 1991). These systems are likened to dwarf novae in permanent outburst, and by analogy with those systems are expected to have a high ($\sim 0.1$) $\alpha$ viscosity parameter (Shakura & Sunyaev 1973). V603 Aql’s orbital period ($P_{\text{orb}} = 199.0$ minutes) is longward of the period gap but still short enough to suggest that the disc could maintain contact with the 3:1 eccentric Lindblad resonance and become significantly eccentric. Indeed V603 Aql consistently exhibits a photometric signal with period $P_{\text{sh}} = 193.0$ minutes that is thought to be the signature of an eccentric, precessing disc (Patterson & Richman 1991; Patterson et al. 1997). Hence V603 Aql is sometimes referred to as a permanent superhumper.

Patterson et al. (1997) reported the appearance of a second signal, with a period $P_{\text{sh}} = 193.0$ minutes, in the
V603 Aql light curve. This ‘negative superhump’ coexisted with and became brighter than its better known counterpart. They found the positive and negative superhump periods varied on similar time scales and were negatively correlated. In other words the negative superhump period was shortest when the positive superhump was longest. Patterson et al. (1997) hypothesised that the accretion disc was simultaneously eccentric, and tilted. The prograde precession of the disc’s semi-major axis (as viewed in the inertial frame) gave rise to the positive superhump signal, whilst the retrograde precession of the disc’s line of nodes was responsible for the shorter, negative superhump periodicity in the light curve.

The SU UMa type dwarf novae V503 Cyg (Harvey et al. 1995) and V1159 Orionis (Patterson et al. 1995) have both displayed large amplitude negative superhumps during quiescence and normal outburst. In the case of V503 Cyg the normal, positive superhumps were only seen during supermaximum, whereas in V1159 Orionis they persisted well beyond superoutburst and into the next normal outburst. Negative superhumps are not limited to short period systems however. For example TV Cen, with \( P_{\text{orb}} = 5.5 \) hours, displays a photometric period \( P_{\text{li}} = 5.2 \) hours (Hellier 1993).

3 THE TIDAL INCLINATION INSTABILITY

A fluid disc in a binary potential is subject to both eccentric and tilt instabilities at the 3:1 resonance (Lubow 1992a). Since it appears well-established that positive superhumps are the signature of an eccentric, precessing disc, we first consider whether the companion tilt instability can give rise to a negative superhump signal. In Lubow’s analysis (1992a), the growth rates of these instabilities are (for the idealised case of a narrow gaseous ring at the resonance),

\[
\lambda_{\text{ecc}} = 2.08 \Omega_{\text{orb}} q^2 \frac{r_{\text{res}}}{W} \tag{1}
\]

\[
\lambda_{\text{inc}} = 0.0398 \Omega_{\text{orb}} q^2 \frac{r_{\text{res}}}{W} \tag{2}
\]

where \( W \) is the width of the resonance at radius \( r_{\text{res}} \), \( q \) is the mass ratio \((M_{\text{secondary}}/M_{\text{primary}})\), and \( \Omega_{\text{orb}} \) is the binary angular velocity. To develop a tilt via this instability, we require that the growth time of the tilt \( \tau_{\text{inc}} \approx 1/\lambda_{\text{inc}} \) must be much less than the drift time for material through the resonance, \( \tau_{\text{adv}} = W/|v_r| \). Making use of \( v_r = -3\nu/2r \), and assuming an \( \alpha \) prescription for the viscosity, \( \nu = \alpha c_s^2/\Omega_K \), we obtain,

\[
\alpha \leq \frac{2}{225} q^2 \left( \frac{H}{r} \right)^{-2} \tag{3}
\]

where \( H = c_s/\Omega_K \) is the disc scale height, \( c_s \) is the sound speed, and \( \Omega_K \) is the Keplerian angular velocity. For \( q = 0.25 \) and \( H/r = 1/20 \), the constraint on \( \alpha \) from this analysis is \( \alpha \leq 0.2 \). Given that typical estimates for \( \alpha \) in high-state dwarf novae are \( \geq 0.1 \) (Cannizzo 1993), this immediately suggests that exciting a tilt via the instability is difficult. However it is also clear that these estimates are rather crude, and so in the next section we use numerical simulations to explore whether a gravitational tilt instability can be excited in the conditions of CV discs.

4 NUMERICAL METHOD

4.1 SPH code

A smoothed particle hydrodynamics (SPH) code designed specifically for accretion disc problems has been described in detail in Murray (1996) and Murray (1998). Modifications have been made to extend the code to three dimensions, and to include adaptive resolution (i.e. to allow for variable smoothing length \( h \)). For disc simulations, the standard SPH linear artificial viscosity term (as described in Monaghan 1992) can be modified slightly in order to improve its effectiveness as a source of shear viscosity in the SPH equations of motion. The modifications are described in some detail in Murray (1996) and Murray (1998). By taking the SPH equations to the continuum limit, it can be shown that this artificial viscosity term generates a shear viscosity

\[
\nu = \kappa \zeta c_s h, \tag{4}
\]

where \( h \) is the SPH smoothing length, and \( \zeta \) is the (dimensionless) artificial viscosity parameter. For the cubic spline in three dimensions, \( \kappa \) is analytically found to be 1/10.

In the simulations shown in Murray (1996) and Murray (1998) the smoothing length had a unique fixed value. In the calculation described here we allow \( h \) to vary with both space and time. When evaluating the pressure-viscosity interaction between two particles, \( i \) and \( j \), we choose to symmetrise with respect to the smoothing length and simply use

\[
\overline{h} = \frac{1}{2} (h_i + h_j) \tag{5}
\]

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\[
\rho_i = \sum_j m_j W(r_i - r_j, h_j). \tag{6}
\]

We use

\[
h_i = K \rho_i^{-1/3} \tag{7}
\]

to alter particle smoothing lengths at every time step. Here \( K \) is a constant set at the start of the calculation to ensure that each particle \( i \) has a reasonable number of neighbours, \( N_i \). Neighbour numbers were monitored closely throughout the calculation and averaged near 75. The variable \( h \) implementation of the code was tested against a fixed \( h \) version.

4.2 Disc tilt and eccentricity

We follow the evolution of tilt and eccentricity in the disc simulations by decomposing the particle distribution into Fourier components with argument \((\theta - m \Omega_{\text{orb}} t)\), where \( t \) and \( m \) are integers, and \( \theta \) is azimuth in the inertial frame. As in Lubow (1991b) we define the strength of the \((l,m)\) mode

\[
S_{l,m}(t) = (S_{\cos,\cos,l,m}(t))^2 + (S_{\cos,\sin,l,m}(t))^2 + (S_{\sin,\cos,l,m}(t))^2 + (S_{\sin,\sin,l,m}(t))^2. \tag{8}
\]

The disc tilt is the \((1,0)\) Fourier component of the vertical displacement of the particles. The component modes of the vertical displacement are defined as follows:

\[
S_{\sin,\cos,l,m}(t) = \frac{2 \Omega_{\text{orb}}}{\pi N(1 + \delta_{l,0})(1 + \delta_{m,0})} \tag{9}
\]
\[ \times \int_{t}^{t+2\pi\Omega_{\text{orb}}^{-1}} \sum_{p=1}^{N} z_p(t) \sin(\theta_p) \cos(m\Omega_{\text{orb}} t') \, dt'. \] (8)

where \( \theta_p \) is the angular position of particle \( p \) and \( N \) is the total number of particles. \( \delta \) is the Kronecker delta. We use a superscript \( z \) to distinguish modes of the vertical displacement from planar modes.

As in Murray (1996) and Murray (1998), we use the interstellar separation \( d \), the binary mass \( M \), and the inverse of the orbital angular velocity \( \Omega_{\text{orb}}^{-1} \) as the length, mass and time scalings for our simulations.

### 5 RESULTS

The tidal warping of accretion discs was studied by Larwood et al. (1996). They used three-dimensional SPH simulations to investigate the warping, precession and truncation of a
5.1 Initial conditions

The initial condition for this simulation was an annulus composed of 21 concentric rings of particles spaced $\Delta r = 0.01 \, d$ apart. Each ring consisted of 9 layers of particles centred on the midplane, spaced $\Delta z = 0.01 \, d$ apart. The disc then initially contained 29592 particles. Thereafter mass was added to the disc midplane at the circularisation radius $r_{circ} = 0.1781 \, d$ at the rate of one particle per time step $\Delta t = 0.01 \, \Omega_{orb}^{-1}$. We assumed the disc to be isothermal, with the sound speed $c_s = 0.05 \, d \Omega_{orb}$. A binary mass ratio $q = 3/17$ was used. In previously described simulations (Murray 1998) with this value $q$, the disc rapidly became eccentric. We set the maximum value for particle smoothing lengths to be $h_{max} = 0.02 \, d$. We used an open inner boundary at $r_{wd} = 0.05 \, d$. Particles ending a time step with $r < r_{wd}$ were considered to have been accreted by the white dwarf and were removed from the simulation. Particles that either returned to the secondary or were flung to very large radii ($r > 0.9 \, d$) were also removed from the calculation. The parameter settings used in the simulation are summarised in Table 1. The calculation ran for $800 \, \Omega_{orb}^{-1}$ (approximately 127 orbits of the binary).

5.2 Disc structure

Figures 1 through 4 summarise the structure of the model disc. Fig. 1 is a sequence of surface density maps showing the initial condition; the short time scale response; the later evolution; and the final state of the calculation. As expected for this mass ratio, the disc rapidly expanded to reach the Roche lobe of the primary, and to overlap the 3:1 eccentric resonance. Although there is considerable strength in the eccentric mode by the end of the simulation (see below), it is the $(2,2)$ tidal mode that is most apparent in each of the frames.

Fig. 2 plots the azimuthally averaged vertical density profile for the annulus $0.348 \, d < r < 0.352 \, d$ for comparison against the density profile of the corresponding isothermal atmosphere. With this particle number and choice of disc sound speed we obtain acceptable resolution of the disc’s vertical structure over almost an order of magnitude in density. Vertical velocities were subsonic everywhere in the disc, further indicating that the vertical resolution is satisfactory. For a cooler disc, with $c_s = 0.02 \, d \Omega_{orb}$ we were unable to adequately resolve the vertical structure.

The radial structure of the disc in the latter stages of the simulation is presented in Figures 3 and 4. From Fig. 3 it is apparent that particle resolution is inadequate at small radii $r \lesssim 0.15 \, d$. Exterior to this radius, the effective Shakura-Sunyaev $\alpha$ parameter,

$$\alpha \simeq \frac{1}{10} \frac{c_s}{\Omega} \frac{H}{\sigma_v},$$

is approximately constant at $\alpha = 0.1$. We expect this to be a reasonable value for alpha for nova-like systems such as V603 Aquilae, which have shown negative superhumps. It might be too high (and, the disc too hot) for dwarf novae in quiescence. In Fig. 4 the mean height of particles above the disc plane is shown as a function of $r$. Out to a radius $r \approx 0.4 \, d$, this profile is consistent with the $r^{3/2}$ scaling of an isothermal axisymmetric disc. At larger radii however, the influence of the companion and the non-axisymmetry of the disc breaks the $r^{3/2}$ scaling relation.

5.3 Mode strengths

Fig. 5 shows the eccentric mode strength in the disc, defined in equation (8), as a function of time. For times $t \lesssim 550 \, \Omega_{orb}^{-1}$ the eccentric mode grew exponentially, with a growth rate of $\lambda_t = 0.0044 \pm 0.0001 \Omega_{orb}$. When equation (8) is corrected to allow for a broad disc (see Lubow 1991a), we obtain the analytic estimate for the growth rate, $\lambda_t \simeq 0.02 \, \Omega_{orb}$. The simulation eccentricity therefore grew significantly more slowly than analysis predicted, and also more slowly than in previous numerical calculations (Murray 1996, 1998). However, the discs described in those papers were colder and more viscous than the disc detailed here. Consequently the tidal modes in those simulations were much weaker than in this calculation. Lubow (1999b) numerically showed that the non-resonant tidal response of the disc weakens the eccentric instability, an effect not accounted for in equation (8). Hence the reduced eccentricity growth rate in this simulation is consistent with our understanding of the resonance.

In Fig. 6 we plot the strength of the disc tilt as defined in equation (9). The variations seen in this plot are of very

\[Figure 2. \text{Mean density (scaled to the midplane density) as a function of height above the midplane for particles in an annulus } 0.348 \, d < r < 0.352 \, d \text{ (filled points) for the simulation at time } t = 446.50 \, \Omega_{orb}^{-1}. \text{ At this time there are 34,406 particles in the disc. The appropriate isothermal atmosphere } \rho(z) = \rho_0 \exp(-z^2/2H^2) \text{ where } H = r c_s /v_\phi \text{ is the density scale height) is shown as a solid line.} \]
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Figure 3. Estimated value of the Shakura-Sunyaev viscosity parameter $\alpha$ as a function of radius for the simulation at time $t = 446.50 \Omega_{\text{orb}}^{-1}$. At this time the disc contained 34405 particles, and the mean number of neighbours was 77.5.

Figure 4. Average height of particles above the midplane $\alpha$ as a function of radius for the simulation at time $t = 446.50 \Omega_{\text{orb}}^{-1}$. The scale height for an isothermal disc with $c_s = 0.05 \Omega_{\text{orb}}$ is plotted as a dashed line.

small ($\ll 1$ degree) amplitude, and are consistent with noise in the simulation. No significant tilt is generated. We ran a short comparison calculation, taking the disc output at $t = 634.50 \Omega_{\text{orb}}^{-1}$ and adding a one degree inclination to it. Mass addition, and all other parameters were kept as before. The subsequent evolution of the tilt mode strength is shown in Fig. 5. With the addition of the tilt, $S_{(1,0)}^z$ is almost two orders of magnitude larger than at any stage of the original simulation. The mode strength however then decayed with a time scale $\approx 400 \Omega_{\text{orb}}^{-1}$, which agrees well with the simple estimate $M_{\text{disc}} / \dot{M} \approx 350 \Omega_{\text{orb}}^{-1}$. This is as expected if the continued addition of mass simply dilutes any initial disc inclination.

6 COMPARISON WITH X-RAY BINARIES

The prototypical example of a warped, precessing accretion disc is that of the X-ray binary Hercules X-1. Recently it has
been suggested that this, and similar systems, develop warps as a result of the radiative warping instability analysed by Pringle (1996; see also Maloney, Begelman & Pringle 1996; Maloney & Begelman 1997). Here, we briefly summarise why the same mechanism does not work for CVs, except in a few, exceptional, circumstances.

The radiative warping instability arises because reprocessed radiation from a central luminous source is re-emitted non-axisymmetrically from an optically thick disc possessing a warp. Growth occurs if the disc is larger than some critical radius, $r_{\text{crit}}$, given for an isothermal disc (Pringle 1997; for the general case see Maloney, Begelman & Nowak 1997) by,

$$r_{\text{crit}} \approx 2\pi^2 \left( \frac{\eta^2}{\epsilon^2} \right),$$

(10)

where $r_s = 2GM/c^2$ is the Schwarzschild radius of the accretor, $\epsilon = L/\dot{M}c^2$ is the radiative efficiency of the flow, and $\eta$ is the ratio of the ‘vertical’ viscosity (that acting to reduce the relative inclination of disc annuli) to the shear viscosity in the plane (see Papaloizou & Pringle 1983 for a formal definition). For accretion powered cataclysmic variables,

$$\epsilon \approx \frac{GM}{r_{\text{acc}}c^2} \sim 10^{-4},$$

(11)

and the instability criterion, equation (10), requires $r_{\text{crit}}$ prohibitively large, of order $10^{14}$ cm – much greater than the actual extent of the disc. Steady CV discs are thus generally stable against radiative warping.

Evading this conclusion requires either a higher radiative efficiency or an appeal to non-steady-state conditions. The former is possible if there is steady nuclear burning of accreted material on the surface of the white dwarf. The radiative efficiency in this regime is as high as $\epsilon \approx 7 \times 10^{-3}$, leading to an estimate for $r_{\text{crit}}$ of the order of $10^{11}$ cm. With the substantial theoretical uncertainties, for example in $\eta$, this could lead to warping provided the disc was large enough and optically thick. However the requirement for nuclear burning limits these possibilities to supersoft X-ray sources (Southwell, Livio & Pringle 1997) rather than lower accretion rate CVs.

The wide range of transient behaviour seen in CVs suggests a number of scenarios where non-steady-state warping effects might be important. For example, the outer cool parts of a dwarf nova disc might be susceptible to warping from the radiation emitted by hotter inner regions that were decaying from outburst, or from radiation from a cooling white dwarf heated during the high state accretion event. Unfortunately, while these scenarios produce a disc that is formally unstable by equation (10), the time scale for growth is generally much greater than the duration of the transient state. The time scale for growth is (Pringle 1996),

$$\tau_{\text{rad}} = \frac{12\pi \Sigma^2 \Omega K c^2}{L},$$

(12)

which for highly optimistic CV parameters is,

$$\tau_{\text{rad}} \approx 5 \times 10^7 \left( \frac{M}{0.6 M_\odot} \right)^{1/2} \left( \frac{\Sigma}{10 \text{ g cm}^{-2}} \right) \left( \frac{r}{10^{10} \text{ cm}} \right)^{3/2} \left( \frac{L}{2 \times 10^{33} \text{ erg s}^{-1}} \right)^{-1} \text{s}.$$

We therefore conclude that there is insufficient luminosity to generate a finite warp in this manner. Moreover there is no sign that the systems with observed negative superhump signals are universally prone to dramatic transient changes in accretion rate, as would certainly be required for this mechanism to operate.

7 DISCUSSION

We have found that the tidal inclination instability is too weak to generate a significant tilt in an accretion disc in the high state. However, neither our time scale analysis, nor our simulations can rule out such instability occurring in short period systems with quiescent discs. In a disc of very weakly interacting particles, vertical instability as opposed to tilt instability was relatively easy to excite at the 3 : 1 resonance. Thus, although it seems unlikely that the inclination instability discussed by Lubow (1992a) can account for the negative superhump phenomenon in currently observed systems, the instability might be important in low state dwarf nova, particularly those such as WZ Sge systems where the quiescent $\alpha$ parameter is thought to be very low (though see also Warner, Livio & Tout 1997 for a contrary view). Although the contribution to the observed emission from the disc is small in these systems, they are likely to be the best places to investigate tidally-driven disc tilts.

Although this work does not categorically rule out the possibility of tilted discs in cataclysmic variables, their origin is somewhat doubtful. The radiative torques speculated to be responsible for the better established warps in X-ray binaries definitely do not generally operate in CVs, leaving no clear mechanism that is known to be effective in creating a tilted disc. We note that of those systems that do show negative superhumps, TV Col is a known intermediate polar (Hellier 1993), and V603 Aql is a suspected one (Schwarzenberg-Czerny, Udalski & Monier 1992). That
then implies that the dynamics of the inner disc are significantly influenced by the magnetic field. The details of the rôle a magnetic field might play in creating a warped disc are not clear, however we note that Agapitou, Papaloizou & Terquem (1997) have shown that strongly magnetised thin discs are unstable to bending modes. Further investigation of the correlation between negative superhumps and weakly magnetic CVs would be very interesting.

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