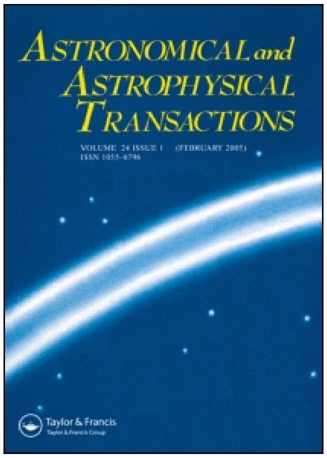

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 February 2007
To cite this Article: Bisikalo, D. V. (2007) 'Numerical modelling of cold accretion discs in cataclysmic variables: the superhump phenomenon', Astronomical & Astrophysical Transactions, 26:1, 47 - 52
To link to this article: DOI: 10.1080/10556790701306576
URL: http://dx.doi.org/10.1080/10556790701306576

Astronomical and Astrophysical Transactions
Vol. 26, Nos. 1–3, February–June 2007, 47–52

Numerical modelling of cold accretion discs in cataclysmic variables: the superhump phenomenon

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(Received 19 February 2007)

The three-dimensional gas dynamic simulations of flow structure in binaries show the formation of the precessional spiral density wave in inner parts of a cold accretion disc. The precessional wave model is able to explain all types of observed superhump.

Keywords: Close binary; Accretion disc; Superhump

1. Introduction

Superhumps are the modulations of light curves of binary systems with periods that differ from orbital periods by several per cent and are observed mainly during superoutbursts in SU UMa systems. The main observational features of superhumps have been described in [1].

As a rule, five types of superhump observed in cataclysmic variables can be distinguished [2].

(i) *Positive* (or ordinary) superhumps have a period that is a few per cent longer than the orbital period. Such superhumps were first observed in SU UMa during a superoutburst.
(ii) *Orbital* superhumps represent modulations of luminosity with the orbital period.
(iii) *Permanent* superhumps have the same features as positive superhumps but are observed in stars that lack superoutbursts.
(iv) *Late* superhumps are observed after the end of a superoutburst and have the same velocity as the positive superhump but are shifted by half a period relative to the latter.
(v) *Negative* superhumps have a period that is several per cent shorter than the orbital period. Such superhumps were first discovered during the monitoring of systems with permanent superhumps. Various researchers have put forward different models to explain the superhump phenomenon (a brief description of various models and their problems have been given, for instance, in [1]).

The qualitative analysis and three-dimensional gas dynamic simulations of the flow structure in semidetached binaries for low gas temperatures (approximately 10^4 K) enabled us to identify characteristic features of the structure of cold accretion discs [3–5]. In general, the flow

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790701306576

structure is qualitatively the same as for high gas temperatures [6–8]. The gas dynamic structure of the flow is governed by the stream of matter from the inner Lagrange point, the accretion disc, the circumdisc halo and the circumbinary envelope. The computations indicate that the solution for the cold disc displays the same following qualitative features as in the case when outer parts of the disc are hot: the interaction between the stream and the disc is shockless, a region of enhanced energy release formed by the interaction between the circumdisc halo and the stream is located beyond the disc, and the shock wave that is formed is rather extended and can be considered as a 'hot line'. However, a reduction in the gas temperature leads to several differences as well. The cold accretion disc becomes considerably denser (compared with the matter in the stream) and thinner, and its shape becomes nearly circular rather than quasi-elliptical. The second arm of the tidal spiral shock is formed.

Considering the influence of the stream on the dense inner parts of the disc to be weak and taking into account the fact that all the shocks (the hot line and the two arms of the tidal shock) are located in outer parts of the disc, we can distinguish the following additional element of the flow structure in the cold case: the presence of an inner region of the accretion disc where the influence of the gas dynamic perturbations noted above is negligible. The formation of such a region enables us to treat this zone simply as a slightly eccentric disc immersed in the gravitational field of the binary. It is known that particles revolving around one of the binary components will precess owing to the influence of the companion. This precession is retrograde, and the rate of the precession decreases as the particle approaches the accretor. For the accretion disc the orbits must be replaced by flow lines. If the orbits precess in such a way that the precession of distant flow lines tends to be faster, these distant flow lines will constantly overtake those with smaller semimajor axes. Since the flow lines in a gas dynamic disc cannot intersect, an equilibrium solution is established with time and all the flow lines begin to precess with the same angular velocity, *i.e.* to display a rigid-body rotation. Accordingly, distant flow lines must turn through a larger angle opposite to the direction of the rotation of the disc material, since the precession is retrograde. It is obvious that such a solution should contain spiral structures. In particular, because of the non-uniformity of the motion along the streamline and the formation of a maximum density at the apastron, the curve connecting the apastrons will form a spiral density wave. The idea of the formation of spiral patterns in the accretion disc was considered by Lyubarskij *et al.* [9] and was later confirmed by Ogilvie [10].

The presence of the density wave, together with the fact that the velocity of the particles increases after passing the apastron, leads to an increase in the radial component of the mass flux due to the increases in both the density and the radial velocity component. The increase in the radial component of the mass flux behind the wave increases the accretion rate in the region where the precessional wave approaches the accretor. The increase in the accretion rate due to the density wave explains both the development of a superoutburst and the appearance of superhumps of different types.

2. Three-dimensional gas dynamic modelling of cold accretion discs

To investigate the possible existence of a spiral precessional wave in the inner regions of cold accretion discs, we performed a three-dimensional gas dynamic simulation of the disc structure for the case when radiative cooling reduces the gas temperature to approximately 10^4 K [4, 11–13]. The results are presented in figure 1. Figure 1(a) shows the density distribution and velocity vectors in the equatorial plane for the steady-state solution. Figure 1(b) presents the bird's-eye view of the radial flux of matter in central regions of the disc for the same time. The precessional spiral wave in the inner part of the disc is clearly visible. These simulations were made for a binary with characteristics close to those of the dwarf nova IP Peg. The computation results show that the precession of the inner spiral wave is retrograde and the velocity of its revolution in the inertial frame is about 0.13 of a revolution per binary orbital period. The distribution of the radial flux of matter in the disc shows that, starting from the outer radius of the wave, this flux increases as it approaches the accretor and reaches a maximum that is more than an order of magnitude higher than the flux in regions of the disc outside the wave.

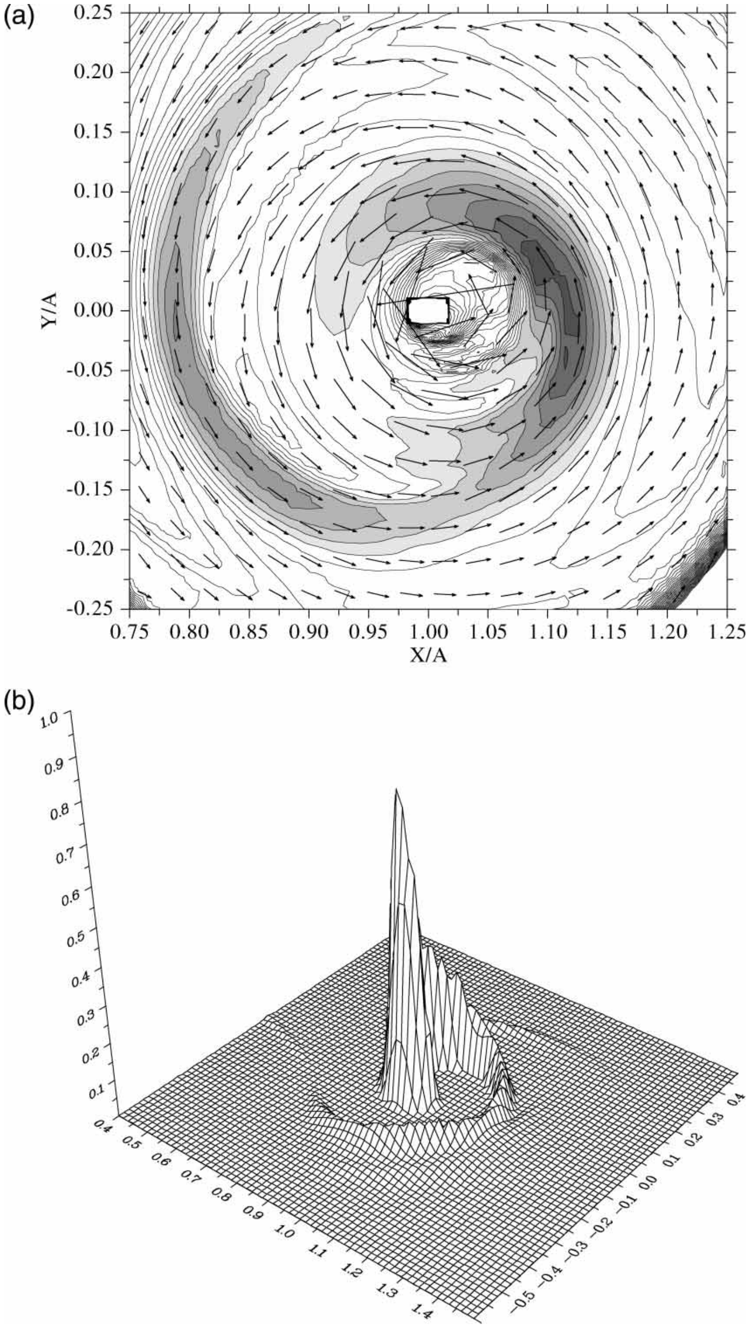

Figure 1. (a) Contours of density and velocity vectors in the central parts of the disc (in the equatorial plane of the binary); (b) bird's-eye view of the radial flux of matter in the central parts of the disc.

Thus, the accretion rate will be enhanced by a factor of more than 10 owing to the formation of this wave.

Our numerical modelling [14, 15] has shown that precessional density waves can form in the accretion discs of systems with large component mass ratios, up to $q = 0.93$.

3. Connection between superhumps and precessional waves

The precessional spiral wave model is able to explain all types of observed superhump. The main observational features of *positive* superhumps are the direct consequence of the formation of a precessional spiral wave in the disc, as has been explained in [11]. The increase in the accretion rate behind the wave is spatially localized in the azimuth, so that matter approaches the surface of the accretor within a fairly compact zone. As the outburst develops, both heating of the gas and the difference of the rotational velocities of the accretor and wave will increase this impact zone, forming a closed belt. However, in any case, the system will have a core in the region of energy release, where the accretion rate will be enhanced. This core is fairly compact and is located at the accretor surface, so that it will be eclipsed at some orbital phases. The detection (formation) of the superhump occurs when the core emerges from eclipse and is oriented towards the observer. The core is associated with the precessional spiral wave, and its rotational velocity is determined by the velocity of the wave.

According to current theory, positive superhumps can only appear in binaries with tidally unstable accretion discs. Simulations show that the tidal instability can only occur if the disc radius exceeds a certain value, the 3:1 resonance radius. This implies that eccentric discs (which generate superhumps according to current theory) can exist only in cataclysmic variables with small mass ratios: $q = M_2/M_1 \leq 0.33$. There are binary systems with superhumps where the mass ratio is well above the critical value, namely U Gem and TV Col. The mass ratio for U Gem is equal to 0.36–0.47 and the estimates of the mass ratio for TV Col show that q can be as much as 0.6–0.9. The precessional wave is formed even in systems with large mass ratio [12–15], and this mechanism can be useful for interpretation of superhumps in systems with different mass ratios.

The *orbital* superhump can be explained by the release of energy in stationary shocks in the disc and circumdisc halo, such as the ‘hot-line’ and tidal shocks; the existence of tidal shocks is not precluded in the precessional wave model. *Permanent* superhumps can also be explained, if the mass-transfer rate in the system is high enough to sustain a high accretion rate owing to a prolonged existence of the precessional spiral wave.

In some SU UMa stars, both normal orbital humps and a modulation with the superhump period shifted in phase by approximately 180° are observed after the end of a superoutburst. This phenomenon is known as the *late* superhump. Our model can explain the formation of the late superhump as follows [11].

(i) The precessional spiral wave forms in the region of the apastrons of the eccentric flow lines.
(ii) During the superoutburst, the accretion of matter forms an empty zone in the inner part of the disc (or, more precisely, a zone of reduced density), which is non-circular in shape; it is elongated where the wave passed and closer to the accretor on the opposite side (in the region of the flow-line periastrons).
(iii) After the disappearance of the wave and the completion of the superoutburst, the accretion disc has been replaced by an elliptical ring of matter, with the periastron of the ellipse shifted in phase by about 180° compared with the former location of the wave (or, in other words, compared with the superhump phase).

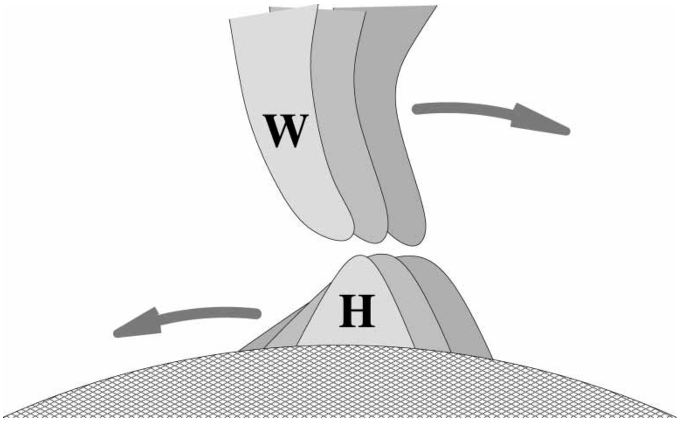

Figure 2. Formation of a negative superhump. The positions of the precessional wave (W) and bright (hot) spot (H) are shown for three different times. The directions in which the wave and leading edge of the superhump move are shown by arrows.

(iv) After the completion of the superoutburst, the transport of angular momentum and, consequently, accretion are due to viscosity, *i.e.* processes with uniform azimuthal distributions. Therefore, matter that loses angular momentum axisymmetrically will reach the surface of the accretor more readily if it was initially closer to the accretor, *i.e.* in the region of the periastron of the elliptical ring. This results in the formation of the late superhump, which will manifest itself as a brightness modulation with the superhump period but shifted in phase by about 180°. The lifetime of the late superhump is determined by the timescale for circularization of the flow lines in the disc.

The existence of luminosity modulations whose period is shorter than the orbital period, *i.e.* of *negative* superhumps, can also be plausibly explained in this model [14]. In the model, the superhump radiation arises from a relatively compact region near the surface of the accretor, into which matter flows along the precessional wave. If the bright spot arising in this region is located above the accretor surface (*i.e.* the rotation of the accretor does not influence the motion of the spot) and has a tendency to spread out owing to diffusion, the leading edge of the spot may be observed somewhat earlier after each rotation of the system (figure 2), creating a modulation with a period shorter than the orbital period. The fact that the observed periods of negative superhumps do not display significant scatter can be taken to justify the assumption that energy release occurs above the surface of the accretor. The necessary rate of diffusional spreading can be estimated using the observed period. Our estimates [14] show thus that this model with the diffusional spreading of the spot can adequately explain the observed negative superhumps.

4. Conclusions

Let us briefly summarize the basis of the proposed mechanism for the superoutbursts and superhumps in binaries of SU Uma type:

(1) Between superoutbursts, an accretion disc is formed in the system and, as its mass grows, it becomes denser compared with the matter flowing from the inner Lagrange point, and its inner regions become impervious to gas dynamic perturbations.
(2) A precessional spiral wave is generated in the inner parts of the disc after the gas dynamic perturbations become negligible.

(3) The formation of this spiral density wave is accompanied by a substantial (up to an order of magnitude) increase in the accretion rate and, consequently, by the development of a superoutburst.
(4) The compact size of the inner zone of energy release can explain the appearance of the superhump.

In summary, we conclude that the precessional wave model is able to explain all types (positive, orbital, permanent, late and negative) of observed superhumps.

Acknowledgements

The work was supported by the Russian Foundation for Basic Research (projects 05-02-16123, 05-02-17070, 05-02-17874, 06-02-16097 and 06-02-16234), the Program for Support of Leading Scientific Schools of Russia (grant NSh-162.2003.2), and the basic research programs 'Mathematical modelling and intellectual systems' and 'Origin and evolution of stars and galaxies' of the Presidium of the Russian Academy of Sciences.

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