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The Formation of Precessional Spiral Density Wave in Accretion Disks and a New Model for Superoutbursts in SU UMa-type Binaries

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Abstract The three-dimensional gas dynamic simulations in SU UMa-type binaries show the formation of the precessional spiral density wave in inner parts of the accretion disk that are not subjected to gas dynamic perturbations. The features of the precessional spiral wave can explain both the energy release in the superoutburst and appearance of a superhump on the orbital light curve.

Key words: novae, cataclysmic variables – stars: individual (SU UMa-type CVs)–methods: numerical

1 INTRODUCTION

SU UMa-type variables are dwarf novae with orbital periods shorter than three hours displaying both normal and superoutbursts. The normal outbursts in binaries of this type are fairly short and irregular and are well explained by standard models of dwarf novae. Superoutbursts are longer, rarer, and periodic. For instance, OY Car displays normal outbursts with amplitudes up to $\sim 3^m$ and durations of about three days every 25–50 days. The recurrence period of the superoutbursts is ~ 300 days, their amplitudes reach 4^m, and they can last up to two weeks. The observational data show that most of the superoutbursts have very similar profiles: the brightness rises sharply in a time that is $\sim 1/10$ of the superoutburst duration, after which the brightness declines very slowly over 0.8 of the superoutburst duration, and then the system rapidly returns to the quiescent state. The most enigmatic feature of superoutbursts is an occurrence of periodic photometric light humps with amplitude of about $0.3 \div 0.4^{\rm m}$ called superhumps which repeat with a period $P_{\rm s}$ very near to the orbital period of the binary $P_{\rm orb}$ but always longer that by a few percent (Warner 1995). The presence of periodic superoutbursts accompanied by superhumps places SU UMa dwarf novae among the most interesting phenomena in astronomy. Despite the abundance of observational data and theoretical models our understanding of the nature of the SU UMa phenomenon is far from complete.

We suggest here a new mechanism for the superoutbursts and superhumps in SU UMa stars. The mechanism assumes that a precessional spiral density wave forms in the unperturbed part of the disk, accompanied by a substantial (by up to an order of magnitude) increase in the accretion rate. The growth of the accretion rate leads to a brightening of the star, i.e., to the development of a superoutburst. The retrograde precession of the density wave at a rate of a few hundredths of a revolution per binary orbital period as well as the compactness of energy release zone can explain the formation of the superhump, as well as it's observational features.

2 FEATURES OF THE PRECESSIONAL SPIRAL DENSITY WAVE

The three-dimensional gas dynamic simulations (Bisikalo et al. 2003) show that the structure of the flow is governed by the stream of matter from L_1, the accretion disk, the circumdisk halo, and the circumbinary envelope. The interaction between the stream and disk is shockless, and the interaction of the matter of the

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circumdisk halo and circumbinary envelope with the stream leads to the formation of a shock with the form of a “hot line”. The simulated cool accretion disk ($T \sim 10^4$ K) is rather dense (compared to the matter in the stream) and thin, and it’s shape is nearly circular. The absence of appreciable action of the stream on the dense inner regions of the disk and the fact that all the shocks (the “hot line” and two arms of the tidal shock) are located in the outer part of the disk result in a new element of the flow structure in the low-temperature case: there is an inner region of the accretion disk where the influence of the gas dynamic perturbations noted above is negligible. It is known (see, e.g., Warner 1995, Hirose & Osaki 1990) that particles revolving around one of the binary components will precess due to the influence of the companion. This precession is retrograde, and the rate of precession is proportional to the orbit radius; i.e., it decreases with approach to the accretor. Retrograde precession of the flowline results in the formation of a precessional spiral density wave in the inner part of the disk (Bisikalo et al. 2004a). This wave is formed by the locus of the apastrons of the stream lines (see left panel of Figure 1). The presence of the density wave together with the fact that the velocity of the particles increases after passing apastron leads to an increase in the radial component of the mass flux $F_{\rm rad} = \rho v_{\rm r}$ due to the increase of both the density ρ and the radial velocity component $v_{\rm r}$. The increase in the radial component of the mass flux behind the wave increases the accretion rate by more than a factor of ten in the region where the precessional wave approaches the accretor (see right panel of Figure 1). Our results also show that the precession of the inner spiral wave is retrograde and the velocity of it’s revolution in the inertial frame is $\approx 0.03 \div 0.04$ of a revolution per binary orbital period for a typical SU UMa binary with component-mass ratio of ≈ 0.1. The beating between orbital motion of the binary and precessional motion of the density waves is displayed as a superhump on the orbital light curve (Bisikalo et al. 2004b).

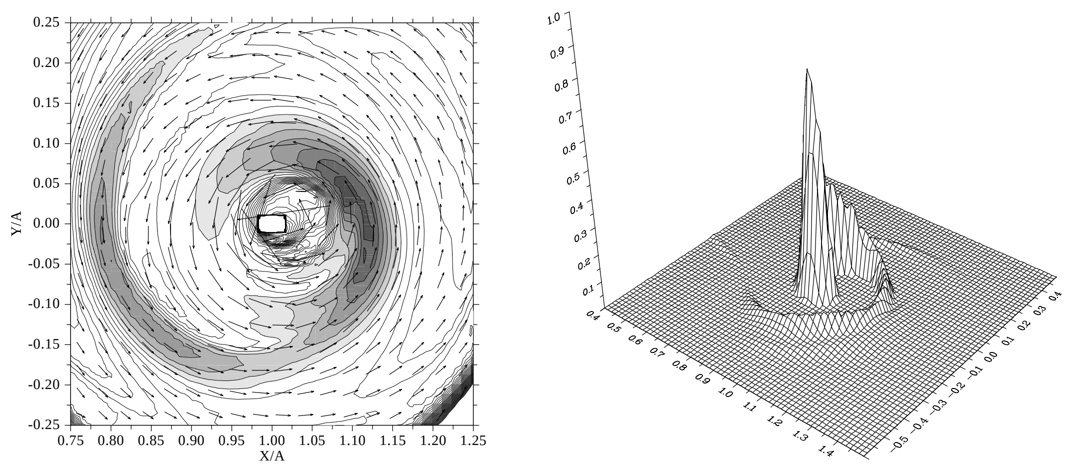

Fig. 1 Left: contours of density and velocity vectors in the central parts of the disk (in the equatorial plane of the binary); right: bird-eye view of the radial flux of matter in the central parts of the disk.

3 BASIS OF THE NEW MECHANISM FOR SUPEROUTBURSTS

Energy release, recurrence time, and duration of superoutbursts. Our mechanism proposes that the energy released in superoutbursts and their periodicity are determined by the mass and accumulation time of the accretion disk. About 50% of the disk mass is accreted during a superoutburst (see, e.g., Warner 1995), resulting in an energy release of $E \simeq 10^{40}$ erg. Hence, assuming that about half of the energy is radiated away, we can estimate the mass of the accreted part of the disk $\frac{1}{2}m_{\rm d}$ via the formula $E \simeq \frac{1}{2}\frac{GM_1}{R_1}\frac{1}{2}m_{\rm d}$. Adopting values typical for SU UMa stars, $M_1 \simeq 1M_\odot$ and $R_1 \simeq 10^9$ cm, we obtain for the mass of the disk $m_d \simeq 1.5 \times 10^{-10} M_\odot$. Since the outburst recurrence time (i.e., the time for the accumulation of the mass $\frac{1}{2}m_d$) is close to one year, the average mass–ransfer rate is close to $10^{-10}M_\odot$/year. This estimate is consistent with estimates for the mass-transfer rates in cataclysmic variables. Differences in the recurrence times for different systems are easily explained by differences in the mass-transfer rate. The high regularity of superoutbursts is determined by the constancy of the mass-transfer rate within a given binary. The duration of a superoutburst is determined by the ratio of the mass of accreted matter and the accretion rate. In a steady-state regime, the accretion rate is approximately equal to the mass-transfer rate, so that an increase in the accretion rate by an order of magnitude or more during a superoutburst implies ratios of the recurrence time and superoutburst time of $10 \div 20$, in good agreement with observations.

The superoutburst profile. The rapid growth of the brightness at the onset of a superoutburst is due to the increased accretion rate after the formation of the precessional spiral wave in the disk. In the proposed mechanism, the innermost regions of the disk are accreted first, followed by more distant ones. Since the angular momentum in the disk is distributed as $r^{1/2}$, at constant angular momentum transfer the accretion of matter from distant orbits requires more and more time. As a consequence, the accretion rate will decrease with time, manifesting as the extended sloping plateau of the light curve. Since the angular-momentum transport is determined by the characteristics of the wave rather than the parameters of the binary, our mechanism provides a natural explanation for the similarity of the plateau slope for different systems. The observable slope is $\sim 9 \pm 1$ days/mag; i.e., the brightness declines by one magnitude (the accretion rate decreases by a factor of 2.5) in nine days. This means that, every nine days, the radius of the disk regions that begin to accrete increases by a factor of 2.5^2, i.e., by six to seven accretor radii ($\sim 0.1A$). Using the observed values of the superoutburst duration and the plateau slope, we can estimate the linear size of the wave and derive certain physical characteristics of the disk. If both the wave scale (the radius of the accreted part of the disk) and the energy release during the superoutburst are known, we can estimate both the mass and density of the disk. Variations in the superoutburst duration are due to variations in the wave size. Hence, for given binary parameters and known maximum disk radius, there exists an upper limit for the superoutburst duration in the system. In a typical SU UMa star, $q \simeq 0.1$, so that the maximum radius of the disk and the maximum possible wave scale cannot exceed $\sim 0.54A$ (Paczyński 1977). As a consequence, the maximum brightness variations of a typical star of this type have amplitudes less than $\sim 4.25^m$, and the maximum superoutburst duration is ~ 40 days. Observations to date have not revealed SU UMa stars that do not satisfy these criteria.

Relation between superoutbursts and normal outbursts. The mechanism proposes that superoutbursts are related to a sharp increase in the accretion rate. Normal outbursts are likewise due to enhancements in the accretion rate. Hence, although the physical nature of the increase of the accretion rate in these two cases is different (the formation of the precessional spiral wave in the former case and instability in the disk in the latter case), the observational manifestations of both types of outbursts could be similar, especially in their early stages. This may explain the fact that the superoutbursts begin in the same way as normal outbursts. The absence of normal outbursts during or immediately after superoutbursts does not prove that there is a connection between the two types of outbursts. In our mechanism, normal and superoutbursts have different origins, but we can explain this feature as follows. The superoutburst consumes the entire inner region of the disk, making any kind of outburst impossible before this region is refilled with new material. The rate of filling is determined by the efficiency of the outward transport of angular momentum (for instance, due to turbulent viscosity), but even if the efficiency is high, the refilling time is considerable and comparable to the duration of an outburst.

Formation of the superhump. The formation of a superhump may also be a consequence of the development of the precessional spiral wave in the disk. The increase in the accretion rate behind the wave is spatially localized in 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 toward the observer. The core is associated with the precessional spiral wave, and it's rotational velocity is determined by the velocity of the wave.

Details of the disk structure obtained from observations of superhumps. Observations of superoutbursts in eclipsing SU UMa systems display dips in the light curves at phases $\sim 0.2 \div 0.25$ and $\sim 0.75 \div 0.8$ in both the optical and UV. In the framework of the "hot line" model the formation of thickening of the halo above the disk is possible. 3D gas dynamic simulations (Bisikalo et al. 2005a) show that along the "hot line" the significant part of the matter gets the acceleration in vertical direction. Gas movement in the vertical direction together with its movement along the outer edge of the disk leads to the gradual increase of the near-disk halo width. Maximum of the calculated thickening located above the outer part of the disk corresponds to the 0.7 and 0.2 phases that is in agreement with the observed values.

Formation of the late superhump. In some SU UMa stars, both the normal orbital humps and a brightness modulation with the superhump period but shifted in phase by $\sim 180^\circ$ are observed for several days after completion of the superoutburst. This is known as the late superhump. Our model can explain the formation of the late superhump as follows. (1) The precessional spiral wave forms in the region of the apastrons of the eccentric flow lines. (2) During the superoutburst, the accretion of matter forms an empty zone in the inner part of the disk (or, more precisely, a zone of reduced density), which is noncircular 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). (3) After the disappearance of the wave and the completion of the superoutburst, the accretion disk has been replaced by an elliptical ring of matter, with the periastron of the ellipse shifted in phase by $\sim 180^\circ$ compared to the former location of the wave (or, in other words, compared to the superhump phase). (4) 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 axially symmetrically 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. The lifetime of the late superhump is determined by the time scale for circularization of the flow lines in the disk.

Superhump characteristics. The detection of superhumps in all SU UMa stars for which high-speed photometric data have been obtained during superoutbursts provides evidence for a common origin for superhumps and superoutbursts. In our model, both of them are associated with the development of the precessional spiral wave in the disk. Since this wave forms in a region of noncircular flow lines and the velocity of it's rotation is determined by the rate of retrograde precession of the flow lines (of the order of several hundredths of a revolution per orbital period), the relation between the superhump and noncircular rotation of the disk and the fact that the superhump period is $3 \div 7\%$ longer than the orbital period are natural consequences of this superhump mechanism. The superhump period is defined by the period of the wave $P_{\rm wav}$ and the orbital period $P_{\rm orb}$ via the relation $P_{\rm s} = \frac{P_{\rm wav} P_{\rm orb}}{P_{\rm wav} - P_{\rm orb}}$. Decreasing of the superhump period during the superoutburst is also quite natural if the superhump is a consequence of the development of the precessional spiral wave in the disk. Indeed, the precessional period of the wave is determined by both fast outer and slow inner flow lines. As the outburst develops, the linear scale of the wave will be reduced and the slow inner flow lines will exert more influence, making the rate of rotation of the wave decrease (so that $P_{\rm wav}$ will increase), which is observed as a reduction in the superhump period. The presence of superhumps in the light curves independent of the binary inclination can be explained by the existence of a compact core of energy release that is spatially localized in azimuth. In this case, this core will not be observable at certain orbital phases and the brightness of the system will be modulated.

Superhump amplitude. Typical superhump amplitudes are $\sim 0.3 \div 0.4^m$. This means that the energy released in the core of the region of energy generation is 10% higher than at the rest of accretor surface. This is quite natural, since the accretor will have revolved several times and the accretion zone will have acquired the shape of a belt with a small core by the time the superhump is detected. For systems where the superhump is observed immediately after the onset of the superoutburst (Krzeminski & Vogt 1985), the core is visible from the very onset of the superoutburst and the belt forms later, as matter is accreted and smeared over the surface of the accretor. This effect is manifest as a variation of the superhump shape during the outburst: the shape is initially asymmetric (since the rate of energy release and the size of the region of energy release are different for phases before and after the superhump) but becomes symmetric when the belt is formed. The more rapid reduction of the superhump amplitude compared to the brightness of the system is due to the accretion from more and more distant orbits as the superoutburst develops and the consequent stretching of the core in azimuth. This reduces the ratio of the energy release in the compact core and the total energy release; i.e., the superhump amplitude decreases more rapidly than the outburst amplitude.

4 CONCLUSIONS

Let us briefly summarize the basis of the proposed mechanism for the superoutbursts and superhumps in SU UMa stars. (1) Between superoutbursts, an accretion disk is formed in the system and, as it's mass grows, it becomes denser compared to the matter flowing from the inner Lagrange point L_1, and it's inner regions become impervious to gas dynamic perturbations. (2) A precessional spiral wave is generated in the inner parts of the disk after the gas dynamic perturbations become negligible (Bisikalo et al. 2004a). (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 retrograde precession of the spiral density wave and the compact size of the inner zone of energy release can explain (Bisikalo et al. 2004b) the appearance of the superhump and it's features, such as the facts that the superhump period is longer than the orbital period and that the superhump is detectable irrespective of the orbital inclination of the binary.

According to current theory, 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 be present only in CVs with small mass ratios: $q = M_2/M_1 \leq 0.33$ (Whitehurst 1988). 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 (Smak 2004, Naylor et al. 2005, Stover 1981) and the estimates of the mass ratio for TV Col show that q can be as much as 0.6÷0.9 (Hellier 1993, Retter et al. 2003). The precessional wave is formed even in systems with large mass ratio (Bisikalo et al. 2004a, Bisikalo et al. 2005b), and this mechanism can be useful for interpretation of superhumps in systems with different mass ratios. Indeed, application of the precessional spiral wave to the explanation of the observational manifestations in OY Car (SU UMa type binary with $q \simeq 0.147$) was successful. On the other hand, the 3D gas dynamic simulations of the system with $q = 0.49$ show the formation of the precessional spiral density wave in such kind of systems as well.

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