Review

The disk instability model for dwarf nova outbursts

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Abstract: The development and the present state of the disk instability model for outbursts of dwarf nova are reviewed. Two intrinsic instabilities are known in dwarf nova accretion disks, i.e., the thermal instability and the tidal instability. The thermal-tidal instability model (abbreviated the TTI model) that combines these two intrinsic instabilities was first proposed in 1989 by Osaki to explain the superoutburst phenomenon of SU UMa stars. In this paper a complete account of the TTI model is presented. We first explain the basic concept of the model and how it works for the superoutburst phenomenon. We then discuss recent refinements of the model, in particular on the start and the end of superoutbursts, by which we are now able to explain wide varieties in superoutburst light curves of different stars and of different superoutbursts within one and the same star. We also discuss some exceptional cases that apparently seem to contradict the theory, such as the 1985 superoutburst of U Gem itself. It is argued that the TTI model can after all explain most of the observed phenomena related to superoutbursts and superhumps in dwarf novae.

Key words: Accretion disks; cataclysmic variables; dwarf novae; SU UMa stars; U Gem stars.

Introduction. The dwarf novae are eruptive variable stars which exhibit repetitive outbursts with a typical outburst interval of some 10 days and a typical amplitude of outburst ranging 2–5 mag. Hundreds of them are now known in our solar neighborhood but their total number in our Galaxy is thought to be enormous as they are not particularly bright stars. They belong to a more general class of variable stars called the cataclysmic variable stars which are semi-detached close binary stars with a typical orbital period of a few hours, consisting of a Roche-lobe filling red-dwarf secondary star and a white dwarf primary star. The secondary star loses mass to the white dwarf through the inner Lagrangian point and the transferred mass is eventually accreted onto the central white dwarf via an accretion disk. General reviews of dwarf novae both in observations and in theories may be found in monographs dealing with the cataclysmic variable stars by Warner[1)] and by Hellier.[2)]

The most fundamental question of dwarf novae is why they undergo repetitive outbursts. It is now well established that an outburst of dwarf novae is due to a sudden brightening of the accretion disk in which mass accretion onto the white dwarf is suddenly increased. An ensuing question is why accretion in dwarf novae is not continuous but intermittent. To explain this, two rival models have been proposed. One, called the mass-transfer burst model ("MTB model"), was first proposed in 1973 by Bath[3)] and the other, called the disk instability model ("DI model"), was first proposed in 1974 by the present author.[4)]

In the MTB model, the variable accretion responsible for the outburst of dwarf novae is considered to be due to a variable mass-transfer rate from the secondary star (i.e., due to some intrinsic instability in the envelope of the secondary star), while in the DI model, intermittent accretion is thought to be caused by intrinsic instabilities in the accretion disk.

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In the latter picture the mass transfer rate from the secondary star to the accretion disk is thought to be always constant but the mass supplied in the accretion disk from the secondary star in quiescence (in a faint state of dwarf nova outburst cycle) is not continuously accreted onto the white dwarf but it is more or less stored within the accretion disk. Once mass thus accumulated in the disk reaches a certain critical state, instability sets in and a large amount of mass in the accretion disk is suddenly accreted onto the white dwarf, which corresponds to an outburst of the dwarf nova.

These two models have been competing with each other for a long time. The disk instability model is now favored *at least for the normal outburst of U Gem-type dwarf novae* because of substantial evidence in both observations and theory, and it is widely accepted as the correct mechanism.[1),2)] However, controversy between these two rival models still continues for the superoutburst of the SU UMa stars.

The SU UMa stars form one sub-class of dwarf novae, characterized by two distinct types of outbursts; a more frequent short outburst called normal outburst typically lasting for a few days, and a less frequent long and large-amplitude outburst called superoutburst lasting for about 2 weeks. In ordinary SU UMa stars, several normal outbursts are sandwiched between two consecutive superoutbursts. A cycle from one superoutburst to the next is called supercycle. The most intriguing feature of superoutbursts is the occurrence of periodic photometric humps called superhumps with an amplitude of 0.2–0.3 mag. and with a period longer than the binary orbital period by a few percent. The SU UMa stars are found among short orbital period cataclysmic binary systems, below the well-known period gap. The superhump phenomenon of SU UMa stars is now well understood in terms of the tidal instability[5)–7)]: The superhumps are produced by periodic tidal stressing of an eccentric precessing disk, which is formed by the 3 : 1 resonance tidal instability.

The short normal outburst of SU UMa stars is thought to be essentially the same as the outburst of U Gem stars and is believed to be caused by the thermal instability in the accretion disk. As for the superoutburst and supercycle of SU UMa stars, Osaki[8)] has proposed the thermal-tidal instability model (TTI model) in which the ordinary thermal instability is coupled with the tidal instability. Based on the TTI model, Osaki[9)] has presented a unification model for outbursts of dwarf novae, in which a rich variety of outburst behaviors of non-magnetic cataclysmic variable stars is understood within the general framework of the disk instability model (DI model). A minor modification to the TTI model was suggested by Hellier.[10)] A further refinement of the TTI model was recently proposed by Osaki and Meyer.[11)]

The TTI model has now attained quite high sophistication and it is robust in explaining successfully various different aspects of the superoutburst phenomenon of the SU UMa stars. However it becomes a little bit difficult to appreciate because the TTI model itself has evolved in time and in particular the last modification to the TTI model was presented in a section of a paper on a different subject[11)] without explaining the main context of the TTI model. Because of this, some misunderstandings of the TTI model are found in literature. The purpose of this paper is to present a full account of the TTI model in its present form including the recent refinement.[11)]

Thermal instability in accretion disks. The development of the disk instability model for dwarf nova outbursts may be divided into two stages: the first stage that lasted until the early 1980s with the discovery and development of the thermal instability of accretion disks, and the second stage which started in the late 1980s with the discovery of another intrinsic instability called the tidal instability.

The very mechanism of the intrinsic instability in the disk was not known when Osaki[4)] proposed his DI model and it remained one of the working models. The physical mechanism responsible for the disk instability was discovered around 1980 by Hoshi[12)] and by Meyer and Meyer-Hofmeister[13)] who showed that the accretion disk becomes thermally unstable due to the hydrogen partial ionization and that the disk exhibits bi-stable states (a hot hydrogen ionized state with high viscosity and a cold hydrogen neutral state with low viscosity). The accretion disk would jump between these two states discontinuously showing a limit-cycle oscillation characterized by a well known S-shaped thermal equilibrium curve (see Fig. 1). Shortly thereafter, articles on the DI model based on this thermal limit cycle instability were published by several groups[14)–17)] and time-dependent calculations to simulate outburst light curves of dwarf novae were performed.[18)–21)] The thermal limit cycle instability is now well accepted

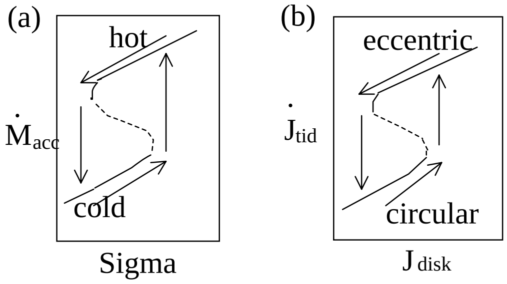

Fig. 1. Schematic diagram showing (a) the thermal limit cycle oscillation for the normal outburst of U Gem stars, and (b) the tidal-torque relaxation oscillation for the supercycle of SU UMa stars.

as the correct mechanism for the normal outburst of the U Gem stars. A theoretical review of the thermal limit cycle model of dwarf nova outbursts may be found in Cannizzo.[22]

Tidal instability in accretion disks. Another intrinsic instability within the accretion disk, which is now called the tidal instability, was discovered in the late 1980s by Whitehurst.[5] The tidal instability was further studied and confirmed by Hirose and Osaki,[6] Lubow,[7] and Whitehurst and King.[23] In this instability, the accretion disk is deformed to an eccentric form, and its eccentric pattern slowly precesses in the prograde direction in the inertial frame of reference. The superhump phenomenon observed during the superoutburst of the SU UMa stars is now understood as due to periodic tidal stressing of the eccentric disk by the orbiting secondary star where the clock of this phenomenon is given by the synodic period between the progradely precessing disk and the orbital period. The cause of the tidal instability is now well understood as due to the 3 : 1 resonance between the fluid flow in the disk and the orbiting secondary star. This resonance condition is only realized when the disk is large enough to accommodate the 3 : 1 resonance radius, which is about 0.47 in units of the binary separation. This condition is in turn met only for a low mass secondary with the mass ratio $q = M_2/M_1 < 0.25$.

The author[8] has proposed a model to explain the superoutburst cycle of SU UMa stars based on the basic framework of the disk instability model. This model uses two intrinsic instabilities of an accretion disk: thermal instability and tidal instability, and it is thus called the thermal-tidal instability (TTI) model. The TTI model will be examined in detail later.

Unification model for dwarf nova outbursts based on the disk instability model. Furthermore, the author[9] has proposed a unification model for dwarf nova outbursts based on the disk instability paradigm. In this unification model, different outburst behaviors among non-magnetic cataclysmic binary systems are basically classified by two parameters characterizing accretion disks in these systems: the orbital period of the system $P_{\rm orb}$, and the mass transfer rate $\dot{M}$ from the secondary. For a given orbital period the mass transfer rate determines the thermal stability nature of the accretion disk[24] in the sense that systems with a high mass transfer rate exhibit hot "stable" disks, corresponding to nova-like systems, while those with a mass transfer rate below a critical one give rise to thermally unstable disks, producing dwarf nova outbursts. The critical mass transfer rate that divides stable and unstable disks is approximately given by[9]

$$\dot{M}_{\rm crit} \simeq 2.7 \times 10^{17}\,{\rm g\ s^{-1}} (P_{\rm orb}/4\,{\rm hr})^{1.7}. \quad [1]$$

On the other hand, the orbital period of a binary system determines whether the tidal instability is possible or not. The period gap of the cataclysmic variable stars gives approximately the dividing line between the tidally stable systems (above the period gap) and the tidally unstable ones (below the gap).

Figure 2 illustrates the $(P_{\rm orb}, \dot{M})$ diagram showing the two critical lines discussed above. The two critical lines divide the diagram into four regions different with respect to the stability nature of accretion disks: the upper right region (region 1) is a region with thermally and tidally stable disks, the lower right region (region 2) with thermally unstable but tidally stable disks, the upper left region (region 3) with thermally stable but tidally unstable disks, and the lower left region (region 4) with both thermally and tidally unstable disks.

Observationally, we find in region 1 the nova-like (or UX UMa) stars with stable disks which show neither dwarf nova outbursts nor the superhump phenomenon, in region 2 U Gem-type dwarf novae, which show ordinary dwarf nova outbursts but do not show any superhump phenomenon. We find in region 3 the so-called permanent-superhumpers which do not show dwarf nova outbursts but exhibit superhump-like periodic photometric variation called the permanent superhumps. Finally in region 4 we find the SU

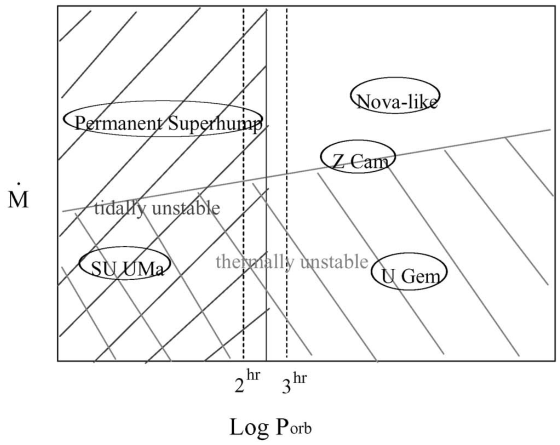

Fig. 2. ($P_{\rm orb}, \dot{M}$) diagram showing the two critical lines for stabilities of disks, which divide the diagram into four regions. The region surrounded by dotted vertical lines shows that of the cataclysmic variable's period gap with 2–3 hr.

UMa stars which exhibit both dwarf nova outbursts and the superhump phenomenon. The good coincidence between the stability nature of the accretion disk with respect to the two intrinsic instabilities and the different observational classes of cataclysmic variable stars strongly suggests that the superoutburst (and supercycle) phenomenon of the SU UMa stars is also produced by these two intrinsic instabilities, and the TTI model is a natural consequence along this line, which will be discussed below.

Here we comment on a few exceptional cases from the general picture of the unification model. These are permanent superhumpers above the period gap, and a problem of the unusually long 1985 outburst of U Gem itself. The latter problem will be discussed later. There exist a number of permanent superhumpers above the period gap. Some of them might be explained by systems with a very high mass of the white dwarf, near the Chandrasekhar limit, but all can not be explained in this way. The critical mass ratio $q_{\rm crit}$ above which the 3 : 1 resonance radius lies above the tidal truncation radius is determined by calculating Paczynski's periodic particle orbits[25]: the 3 : 1 resonance radius corresponds to the last stable orbit, and the tidal truncation radius corresponds to the last non-intersecting orbit. The critical mass ratio $q_{\rm crit}$ above which the resonance radius (the last stable orbit) lies above the tidal truncation radius (the last non-intersecting orbit) is then given by $q_{\rm crit} = 0.25$. In Paczynski's approach the disk is assumed to be cold. Once periodic orbits begin to intersect, strong shocks are formed and this gives rise to a strong dissipation and thus gives rise to strong tidal extraction of angular momentum from the disk. This terminates the disk at the tidal truncation radius (the last non-intersecting orbits). However, if the disk is hot enough and the pressure effects are strong enough, shocks at the last non-intersecting orbit weaken and the disk can expand beyond the tidal truncation radius. In fact, Murray *et al.*[26] proposed that superhumps in VY Scl stars are produced by a sudden reduction of the mass transfer stream where the mass stream has acted to compress the disk outer edge. As a result of easing the compressing effect of mass stream, the disk can expand beyond the tidal truncation radius to reach the 3 : 1 resonance radius, thereby exciting the eccentric disk. They found by the SPH simulations that the critical mass ratio, below which the disk can become tidally unstable, is increased up to $q_{\rm crit} = 1/3$ by considering non-steady disks such as in a sudden reduction of the mass transfer stream. This explains some superhumpers above the period gap. The problem as to how high we can push this critical mass ratio by considering hot disks still remains to be investigated.

Disk radius variation during a dwarf nova outburst. Before presenting the TTI model, we discuss disk radius variation in an outburst cycle of the ordinary U Gem stars because understanding the disk radius variation is essential for the TTI model.

The outer edge of the disk in dwarf novae is determined by three different effects. The first effect is accretion of matter in the disk which must be accompanied by outward transport of angular momentum in the disk and it tends to expand its outer edge. The second effect is addition of mass to the disk by the gas stream from the secondary star, which tends to contract the disk edge because the specific angular momentum of the gas stream is usually smaller than that of the outer edge of the disk. The third effect is the tidal removal of angular momentum from the disk by the orbiting secondary star, which tends to contract the outer edge of the disk.

In the steady state disk of nova-like stars (or the UX UMa stars) the outer edge of the disk is kept steady because the outward transport of angular momentum by viscosity is just balanced by tidal removal of angular momentum plus the effect of mass addition from the gas stream. The outer edge of the disk in nova-like stars is thought to reach the tidal truncation radius. In the case of ordinary dwarf novae, both observations and the theory of the DI model[27] demonstrate that the disk expands and reaches the tidal truncation radius during an outburst. The viscous plateau stage in the outburst light curve corresponds to a stage in which the disk outer edge is kept at the tidal truncation radius. On the other hand, the disk continuously contracts during quiescence. This is easily understood in the DI model because the sudden accretion of matter during an outburst pushes the disk radius outward, while addition of mass with low specific angular momentum together with inefficient viscous transport of mass in the disk compress the disk outer edge during quiescence.

The thermal-tidal instability model of the SU UMa stars. The SU UMa stars exhibit a well-organized outburst pattern: one superoutburst is followed by a few to several short normal outbursts before the next superoutburst. We summarize several well-established observational facts of the superoutburst and supercycle phenomenon.

(1) The superoutburst is brighter than the normal outburst by 0.5 to 1 mag. and the former lasts longer than the latter by a factor 5 (more than ten days versus a few days).

(2) Superoutbursts occur less frequently compared to normal outbursts, the typical repetition time (i.e., the supercycle length) is a few hundred days. Superoutbursts repeat more regularly than normal outbursts.

(3) There is no observational difference in the initial rise phase to outburst between normal outburst and superoutburst. The superoutburst seems to be triggered by a normal outburst.

(4) Superoutbursts are always accompanied by superhumps. Superhumps exclusively occur during superoutbursts and they are observed neither in normal outbursts nor in quiescence, and thus superoutbursts and superhump are intimately related to each other.

These are general rules and there exist some exceptions to the rules. We will discuss them in their appropriate context.

I. The basic picture of the TTI model. The thermal-tidal instability (TTI) model was first proposed in 1989 by Osaki,[8] immediately after the discovery of the tidal instability by Whitehurst.[5] The supercycle of the SU UMa stars is explained by this model in the following way. The TTI model is based on the disk instability model in which the mass-transfer rate is supposed to be constant in time, and all outburst activities are caused by intrinsic instabilities within the accretion disk. In this model, both the normal outburst and the superoutburst are caused by the thermal instability in accretion disks. Superoutbursts are those outbursts which are accompanied by the tidal instability while normal outbursts are those without the tidal instability. In the early stage of a supercycle, the disk is compact and thermal instabilities produce quasi-periodic episodes of mass accretion observed as normal outbursts. But the accreted mass in each outburst is less than that transferred during quiescence because of inefficient tidal removal of angular momentum from the disk. Both mass and angular momentum of the disk are gradually built up. The disk radius expands with each successive outburst until it eventually exceeds the critical radius for the 3 : 1 resonance; this final outburst triggers the tidal instability, producing a superoutburst because of the greatly increased tidal torques due to the eccentric disk. The mass of the disk is greatly depleted during the superoutburst. The disk eventually makes a downward thermal transition from the hot to the cold state at the outer edge. A cooling wave propagates from the outer edge to the inner part extinguishing the outburst, and this is the end of the superoutburst. The eccentric disk returns back to circular shape because of the addition of matter of low specific angular momentum from the secondary. After the end of the superoutburst, the disk returns to the starting compact state. This is the basic idea of the TTI model for the superoutburst phenomenon of the SU UMa stars.

Based on this TTI model Osaki[8] have calculated light curves of SU UMa stars using a simplified semi-analytic model with a torus plus a disk having power-law surface-density distribution. Figure 3 illustrates results thus obtained in which the light curve, the disk radius variation, and the disk-mass variation are shown. We can see that light curves of SU UMa stars are well reproduced by this model. It may be noted here that a time delay of two days between the triggering normal outburst and the start of the superoutburst was introduced in this calculation so that all of resulting superoutbursts were of precursor-main type. Full one-dimensional numerical simulations (i.e., the standard form of numerical simulations for outbursts

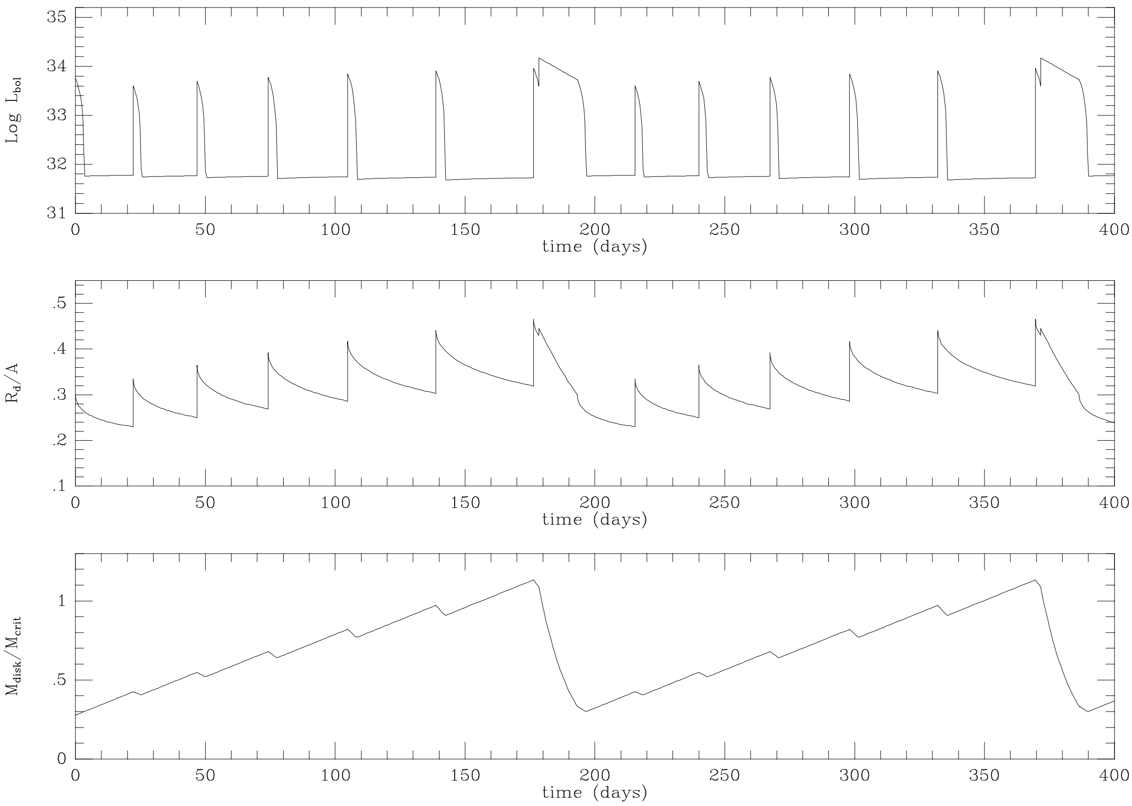

Fig. 3. Time evolution of an accretion disk in a supercycle based on the simplified form of the TTI model (Osaki 1989). The model parameters used are those of VW Hyi, a prototype of SU UMa stars. From the top to the bottom; (a) bolometric light curve, (b) the disk radius R_d in units of the binary separation A, (c) the total disk mass $M_{\rm disk}$, normalized by the critical mass $M_{\rm crit}$ above which the disk can be tidally unstable.

of the dwarf novae) based on the TTI model were performed by Ichikawa, Hirose, and Osaki[28] and by Buat-Ménard and Hameury,[29] basically confirming results by Osaki.[8] Two-dimensional SPH (SPH: "smoothed particle hydrodynamics" code) simulations of superhumps and superoutbursts of SU UMa stars were performed by Murray[30] and Truss, Murray, and Wynn,[31] confirming that the superoutburst and superhump phenomenon is a direct result of the tidal instability without need of any enhanced mass transfer.

Some refinements to the basic TTI model were later introduced by Hellier[10] and by Osaki and Meyer[11] and these concern problems how superoutbursts start and end, and will be discussed in the next section. Despite these refinements the basic backbone of the TTI model has remained the same.

II. Double cycle nature of the superoutburst phenomenon. The most important characteristics of the superoutburst phenomenon is its double-cycle nature (i.e., the short normal outburst cycle and the long supercycle). The double cycle is understood in the TTI model as a combination of two limit-cycles, the ordinary thermal limit-cycle and a "tidal" limit-cycle. It is well established that the short normal outburst cycle is due to the thermal limit cycle instability based on the so-called S-curve. In the same sense, the supercycle is understood in the TTI model as due to the tidal limit-cycle instability in which the tidal torques have a double-valued functional form with a low tidal-torque branch of the ordinary circular disk and a high tidal-torque branch of the eccentric precessing disk, shown schematically in Fig. 1b. The disk makes transitions between these two states discontinuously due to the 3 : 1 resonance instability. This jump of the disk between circular and eccentric form is understood as a kind of "phase transition" and is the cause for the supercycle of the SU UMa star in the TTI model. The supercycle of the SU UMa stars is understood as a cyclic variation in the disk radius. During a supercycle the disk radius increases secularly with an advance of supercycle phase; superimposed on it is a saw-tooth form of variation of the disk radius during each normal outburst cycle. This theoretical prediction is one of the most important observational tests of the TTI model.

The essential feature is that the tidal torques are assumed to be much enhanced when the disk jumps from the circular form to the eccentric form. This assumption of enhanced tidal torques in the TTI model was sometimes criticized as "artificial" or arbitrary. Here we argue that it is a natural consequence of the tidal instability. Observations of SU UMa stars show that amplitudes of superhumps reach 0.2–0.3 mag. in visual light. That means that the superhump light source contributes 30 to 40 % to the total visual light. It is now well accepted that superhumps are produced by *tidal dissipation* in the eccentric disk. However the tidal torques $\dot{J}_{\rm tidal}$ and the tidal dissipation $D_{\rm tidal}$ are directly related to each other by the relation $\dot{J}_{\rm tidal} = D_{\rm tidal}/(\Omega - \omega_{\rm orb})$ where Ω is the local angular velocity of rotation of fluid in the disk and $\omega_{\rm orb}$ is that of the secondary star. Thus it is a natural assumption that the tidal torques are enhanced when the disk becomes eccentric. Hydrodynamic simulations of accretion disks by Murray[30] demonstrate that tidal torques are very much enhanced when an eccentric disk develops due to the 3 : 1 resonance. Once we accept the concept of enhanced tidal torques of the TTI model, the superoutburst (and supercycle) phenomenon is a straightforward and a natural consequence.

The long duration of the superoutburst is now explained in the TTI model as due to the enhanced tidal torques in the eccentric disk, which keep the disk in hot state for a long time as long as about two weeks. Matter in the disk is then greatly depleted when the superoutburst ends. Thus the long duration of the superoutburst is a result of the tidal instability. As discussed in a previous paper,[11] another important aspect of the TTI model lies in the explanation of the shortness of the normal outburst. In the late phase of the supercycle, the disk mass is already built up very much and as far as the disk mass is concerned, the difference between the superoutburst and the preceding normal outburst is not large. Nevertheless, the duration of the normal outburst is very short. In the TTI model, normal outbursts are understood as those outbursts which are not accompanied by tidal instability. This means that in this case tidal torques are very ineffective. Thus, when the normal outburst starts and the disk jumps from the cold to the hot state, the disk radius expands. An expansion of the disk without any effective tidal torques thins out matter at the outer edge, immediately leading the disk to jump back to the cold state, a result demonstrated both analytically by Osaki,[8] using a simplified model, and numerically by simulations[28),29] in which the disk radius variations have been properly treated.

Refinements to the TTI model and comparisons with observations. Although the original TTI model is successful in explaining the basic pattern of the superoutburst cycle of SU UMa stars, some modifications and refinements are needed for explaining some details and a wide variety in light curves of different stars and of different superoutbursts within one and the same star. They concern problems how superoutbursts start[11] and how they end.[10] In the original TTI model superoutbursts were supposed to start with the tidal instability and to end together with a termination of the eccentric disk. It has turned out that as far as the start and the end of superoutbursts are concerned quite different situations are possible depending on different systems and different conditions.

I. The start of superoutbursts. We first discuss problems of the start of superoutbursts. As discussed below, there are four different ways of how superoutbursts start. In the original TTI model, when a normal outburst pushes the disk's outer edge to reach the 3 : 1 resonance radius in the late stage of a supercycle, the tidal instability was assumed to always occur, first resulting in the development of an eccentric disk (and thus superhumps), and then followed by a superoutburst. The TTI model was criticized by Smak[32),33] who argued that "the TTI model faces a serious problem with the sequence of events it predicts: the superhumps should appear at an early phase of a superoutburst, while observations show that it happens only one or two days *after* maximum".

In response to this criticism, we have proposed in a previous paper[11] a refinement of the TTI model to remedy the weakness of the original TTI model pointed out by Smak. This refinement is due to a recognition that merely reaching the 3 : 1 resonance radius does not necessarily produce the superhumps.

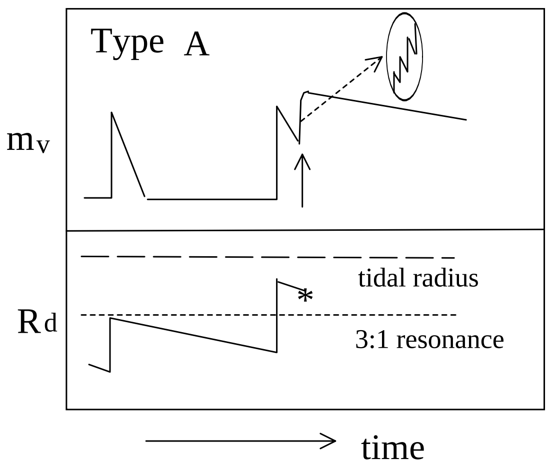

Fig. 4. Schematic picture for the Type A superoutburst, showing (a) the light curve in the upper panel, and (b) the disk radius variation in the lower panel. The arrow indicates the start of the eccentric disk. The asterisk (*) in (b) marks the start of the superoutburst. Superhump light variations are exaggeratedly shown in an oval.

The growth of the eccentric disk to a finite amplitude by the tidal instability is thought to take a few days while the cooling wave at the outer edge of the disk in a normal outburst starts almost immediately after light maximum and the outer edge of the disk begins to shrink. Therefore a competition occurs between growth of the eccentric disk by the tidal instability and shrinkage of the disk below the 3 : 1 resonance radius. Two different scenarios now become possible depending on which effect wins.

Type A superoutburst. If the tidal instability wins and an eccentric disk grows to a finite amplitude, increased tidal dissipation and tidal torques by the eccentric disk now bring the outer part of the disk back into the hot state, leading to a superoutburst. This type of outburst is the precursor-main type outburst (i.e., the S6-8 type superoutbursts of VW Hyi in Bateson's[34] classification). Such outbursts are observed in V436 Cen,[35] T Leo,[36] TV Crv[37] besides the S6-8 type superoutbursts of VW Hyi.[34] Observations in this case show that the superhumps grow together with the rise to maximum of the main superoutburst, in accordance with the TTI model. The original TTI model assumed always this type of behavior shown in light curves of the simplified model.[8] Let us call this type of superoutburst "Type A superoutburst", illustrated in Fig. 4.

It may be noted here that in the so-called enhanced mass transfer model a superoutburst with a long duration is first produced by enhanced mass transfer from the secondary star and the long duration of the superoutburst then gives the disk enough time to develop superhumps. Thus the long duration of superoutbursts is the cause and the superhump is the result in the EMT model. Observations of the precursor-main type superoutburst contradict this scenario of the EMT model because superhumps are already visible on the rising branch of the main superoutburst.

Type B superoutburst. On the other hand, if the shrinkage of disk below the 3 : 1 resonance wins, the normal outburst fails to trigger a superoutburst even if it pushes the disk's outer edge beyond the 3 : 1 resonance radius. Observationally such normal outbursts are either indistinguishable from those normal outbursts in which the outer edge does not reach the 3 : 1 resonance at all or they are those normal outbursts accompanied with "aborted superhumps" in decline stage from outburst maximum, as discussed by Osaki and Meyer.[11] The disk then continues to expand passing the 3 : 1 resonance radius with each normal outburst. If later normal outbursts still fail to develop an eccentric precessing disk, the disk radius eventually reaches the tidal truncation radius at the last normal outburst. The disk is now fully in hot state and the viscous plateau stage of the hot disk then ensues because of enhanced tidal torques at the tidal truncation radius. The triggering normal outburst and the resulting superoutburst completely merge into one outburst in this case. The long duration of the viscous plateau stage now allows the disk to develop an eccentric structure (and thus superhumps) a few days *after* the superoutburst maximum. In this case the enhanced tidal torques are due to the ordinary tidal truncation in the early phase of the superoutburst and they are taken over later by those of the eccentric disk due to the tidal instability. Although the enhanced tidal torques at the tidal truncation radius in the early stage of the superoutburst can produce the viscous plateau stage, the change-over to those of the tidally driven eccentric disk is essential in producing the much longer duration of the superoutburst. Observationally this type of superoutbursts corresponds to the S1-5 type superoutbursts of Bateson's classification, and superoutbursts of most SU UMa stars. Let us call this type of superoutburst "Type B superoutburst". Figure 5 illustrates the Type B superoutburst. The recogni-

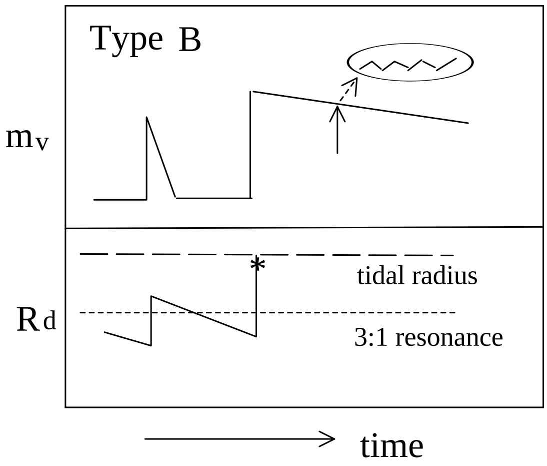

Fig. 5. The same as Fig. 4 but for the Type B superoutburst.

tion of the Type B superoutburst is the refinement of the TTI model proposed by Osaki and Meyer.[11] This refinement can now solve the difficulty of the original TTI model pointed out by Smak.[32),33)]

Let us now consider what conditions determine which type of superoutbursts, (i.e., Type A or Type B), occurs. As discussed above, this is determined by a competition between the growth rate of an eccentric disk by the tidal instability and the rate of shrinkage of the disk below the 3:1 resonance after the normal outburst. The growth rate of an eccentric disk by the tidal instability was discussed by Lubow[7] who showed that the growth rate, λ_0 of an ideal narrow fluid ring at the resonance radius, is given by

$$\lambda_0 = 2.08\omega_{\rm orb} q^2 \left(\frac{r_{\rm res}}{\delta r_{\rm res}}\right), \qquad [2]$$

where $\omega_{\rm orb}$ is the orbital angular frequency, $q = M_2/M_1$ is the binary mass ratio, $r_{\rm res}$ is the $3:1$ resonance radius, $\delta r_{\rm res}$ is the radial extent of the ring. The growth rate, λ, of a disk is given by

$$\lambda = C\lambda_0, \qquad [3]$$

where the correction factor to the disk, C,

$$C = \frac{M_{\rm res} e_{\rm res}}{M_{\rm d}\langle e\rangle}, \qquad [4]$$

where $M_{\rm res}$ is the mass in the resonance region, $M_{\rm d}$ is the total disk mass, $e_{\rm res}$ is the eccentricity at the resonance radius, and $\langle e\rangle$ is the mass-averaged eccentricity of the entire disk. The growth rate of eccentricity in the disk is then

$$\lambda = 2.08\omega_{\rm orb} q^2 \frac{2\pi r_{\rm res}^2 \Sigma_{\rm res} e_{\rm res}}{M_{\rm d}\langle e\rangle}, \qquad [5]$$

where $\Sigma_{\rm res}$ is the surface density of matter at the resonance radius. Here the most important factor is the dependence of the growth rate λ on the binary mass ratio, q: the growth rate is proportional to the square of mass ratio q, under the condition that all other factors remain similar. Both observations of growth of superhumps in SU UMa stars and theoretical estimates of growth of the eccentric mode (1,0) in the two-dimensional SPH simulations by Murray[30] and by Truss *et al.*[31] show that the growth rate of eccentricity is of the order of a day to a few days.

The time for the disk edge to shrink back below the 3 : 1 resonance radius after a normal outburst depends on the extent of maximum expansion of the disk by a normal outburst and the rate of decrease in the disk radius after the outer edge of the disk returns back to cool state. If the disk edge reaches the 3:1 resonance radius with a sufficient margin and the growth of eccentricity by the tidal instability is rapid enough, it is most likely that the eccentricity growth wins over the shrinkage of the disk below the 3 : 1 resonance radius, and thus the development of superhumps occurs, leading to the Type A superoutburst. On the other hand, if the disk expands to the 3 : 1 resonance with only a little margin in a normal outburst and the growth of eccentricity is slow, the tidal instability most likely fails to excite eccentricity in the disk.

In a previous paper,[11] we have discussed various possibilities how superoutbursts are triggered. There we considered three different cases depending on different binary mass ratios, q (see Fig. 4 of that paper). The binary mass ratio affects the problem in two ways: one is the distance between the 3 : 1 resonance radius and the tidal truncation radius, and the other is the eccentricity growth rate; the smaller the mass ratio q is, the larger is the distance between the 3 : 1 resonance radius and the tidal truncation radius, and the smaller q is, the lower is the eccentricity growth rate (see eq. [5]).

The star VW Hyi is the best observed SU UMa system in which two different types of superoutbursts (the S1-5 type superoutbursts and the S6-8 type superoutbursts) are observed in one and the same system. We have identified VW Hyi as a system having a relatively high mass ratio around $q{\sim}0.20$, where the eccentricity growth rate is high enough so that the Type A superoutburst is possible. In this case, if a normal outburst pushes the disk edge beyond the 3 : 1 resonance radius with a wide margin but still below the tidal truncation radius, that normal outburst can excite an eccentric disk (and thus superhumps), leading to the precursor-main type superoutburst (i.e., the S6-8 type superoutburst or our Type A superoutburst). On the other hand, if a normal outburst pushes the disk edge beyond the 3 : 1 resonance radius with a small margin, it may fail to excite eccentricity in the disk and it remains a mere normal outburst. If in the next normal outburst the disk expands to reach the tidal truncation radius, its expansion is stopped there and the hot viscous plateau stage ensues even when the eccentric disk has not yet developed to finite amplitude. The long duration of the viscous plateau stage now allows the disk to develop fully grown superhumps a few days after the light maximum (i.e., the S1-5 type superoutburst or our Type B superoutburst). Thus depending on different conditions of triggering normal outbursts we have two different types of superoutburst in one and the same system.

In systems of slightly lower mass ratio, the eccentricity growth rate may not be large enough to trigger the eccentric disk within the normal outburst duration. The disk continues to expand passing the 3 : 1 resonance radius with each normal outburst and it eventually reaches the tidal truncation radius at the last normal outburst, resulting in the Type B superoutburst in the same way discussed above in the case of VW Hyi. Most SU UMa stars show only the Type B superoutburst and they correspond to this case.

Type C superoutburst. In our previous paper,[11] we have proposed a third possibility for systems of an extremely small mass ratio q in which normal outbursts occur frequently. In this case the tidal truncation radius is far away from the 3 : 1 resonance radius. As discussed above, the normal outburst, in which the disk's outer radius reaches the 3 : 1 resonance radius, can not excite the superhumps to large amplitude during the normal outburst because of the low eccentricity growth rate. The same thing may repeat in the next outburst as well. However, since the disk expands more and more beyond the 3 : 1 resonance radius with each normal outburst, it may finally not shrink below the 3 : 1 resonance radius even in quiescence and the tidal instability continues to operate in quiescence. Eventually the eccentric disk and the superhumps grow to a large amplitude. Tidal heating at the outer edge of the disk will then force the upward thermal transition to the hot state, starting a new outburst. This outburst is of outside-in type and it develops always to a superoutburst because the disk is now fully eccentric, that is, a superoutburst triggered not by a normal outburst but rather by the tidal instability. In this case, the superhumps should be visible in large amplitude even during the rising branch of the outburst. Let us call this type of superoutburst "Type C superoutburst". Figure 6 illustrates the Type C superoutburst.

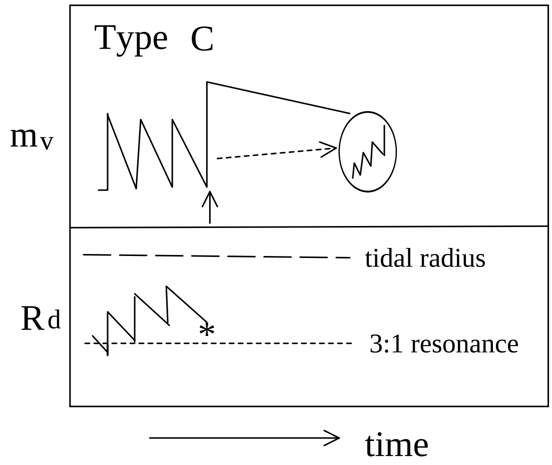

Fig. 6. The same as Fig. 4 but for the Type C superoutburst.

Observationally this last case, the Type C superoutburst, corresponds to that of ER UMa stars. The ER UMa stars are the SU UMa stars with the shortest orbital period and with the shortest supercycle length, of 50 days or shorter, and with a very short normal-outburst cycle as short as 4 days. They are supposed to have a rather low binary mass ratio q. Osaki[38] has demonstrated that the short supercycle and the short normal outburst cycle of ER UMa itself can be explained by the TTI model as a system having a higher mass transfer rate. It was a puzzle in observations of the ER UMa stars that superhumps in large amplitude were observed already during the rising branch of the superoutburst (see, observations of V1159 Ori[39] and ER UMa[40]). In the standard scenario, the superhumps were expected to appear the later during the superoutburst the lower the mass ratio is, because of their slower growth rates. The mystery of these paradoxical observations is now solved by a recognition of the Type C superoutburst.

Type D superoutburst. Another type of superoutbursts was proposed by Osaki and Meyer[41)] in connection with the WZ Sge stars. The WZ Sge stars are extreme SU UMa stars characterized by the largest outburst amplitudes, as large as 8 mag., and by an extremely long recurrence time of outbursts, as long as 30 yrs. Almost all outbursts observed in the WZ Sge stars are superoutbursts and no normal outbursts are observed or if any, they are very rare except for the rebrightening phenomenon (or the so-called echo outbursts) just after superoutbursts. The rebrightening phenomenon will be discussed later. The WZ Sge stars are thought to be of the lowest end of cataclysmic variable's evolution in that they pass the period minimum of the cataclysmic variables, having a degenerate secondary star. The extremely large and rare outbursts of WZ Sge stars are understood in term of extremely low viscosity in quiescence.[42),43)]

As discussed in Osaki and Meyer,[41)] in binary systems like WZ Sge stars with an extremely low mass ratio, $q \leq 0.08$, once an outburst occurs, the outer edge of the hot disk expands greatly, not only passing the 3 : 1 resonance radius but also reaching the 2 : 1 resonance radius. The two-armed spiral density waves are then excited by the 2 : 1 Lindblad resonance, explaining the early hump phenomenon observed in the first ten days in these stars. The ordinary superhumps did appear only after the early humps subsided, that is, twelve days after the start of the outburst in the 2001 superoutburst of WZ Sge itself. The rather late appearance of the ordinary superhumps is understood as due to the suppressing effect of the 2 : 1 resonance by the so-called corotation resonance.[41)] Let us call this type of superoutburst of WZ Sge stars accompanied with the early humps as "Type D superoutburst". Figure 7 illustrates the Type D superoutburst.

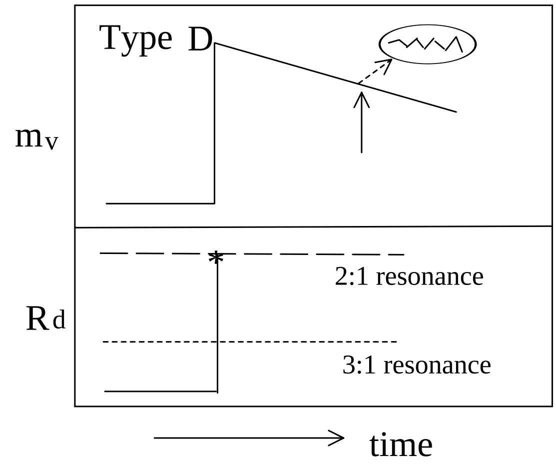

Fig. 7. The same as Fig. 4 but for the Type D superoutburst.

The 1985 superoutburst of U Gem. Finally we discuss the 1985 outburst of U Gem with exceptionally long duration of 45 days (more than a factor 2 longer than usual outbursts of U Gem). This unusual outburst was cited by Lasota[44)] as strong evidence for the enhanced mass transfer and as evidence against the TTI model because such a long-duration outburst is not expected in the simple disk instability model for U Gem stars above the period gap and because the superoutburst-like light curve of long duration was observed in U Gem, i.e., in a dwarf nova other than the short-orbital-period SU UMa stars. However, a very interesting paper has very recently been published by Smak and Waagen[45)] who have detected superhumps in the 1985 superoutburst of U Gem. Thus the 1985 outburst of U Gem has turned out to be a genuine "superoutburst" accompanied with superhumps. Cannizzo *et al.*[46)] examined the 1985 outburst of U Gem and showed that the flat-topped light curve of the 1985 outburst is understood as a simple viscous depletion of gas in the hot disk in dwarf novae, and its only remaining mystery is that the start of the cooling front at the outer edge (which usually occurs around 10–20 days after the maximum) was somehow delayed up to 40 days after the light maximum in the 1985 outburst of U Gem. The cause of delay in the start of the cooling front is finally understood: the disk in the 1985 outburst of U Gem was "eccentric" (as evidenced by appearance of "superhumps") and the resultant enhanced tidal removal of angular momentum from the disk kept the disk in hot state much longer, as long as 40 days. Thus the 1985 superoutburst of U Gem fits in the general scheme of the TTI model and there is no need for enhanced mass transfer to explain the long duration of this outburst.

The only remaining problem is why U Gem itself, having an orbital period of 4.25 hours above the period gap, can have the tidal instability. As discussed in section 2 on the unification model of dwarf nova outbursts U Gem belongs to the second region in the $(P_{\rm orb}, \dot{M})$ diagram of Fig. 2 where systems are thermally unstable but tidally stable. In these systems, with $q > 0.3$, the 3 : 1 resonance radius lies beyond the tidal truncation radius. Thus when an outburst occurs, expansion of the disk is stopped at the tidal truncation radius and it never reaches the 3 : 1 resonance radius in an ordinary sense. The unusually long 1985 outburst is an exception in U Gem because it is only one exceptional example in the 100-years observational history of U Gem. The ordinary outbursts of U Gem are thus understood as those in which expansion of the disk is stopped at the tidal truncation radius. We suspect that the 1985 outburst may be an outburst having an unusually large outburst amplitude, i.e., having a very hot disk. Then matter in a very hot disk may overrun the tidal truncation radius because of weaker shocks there and it may reach the 3:1 resonance radius. That may be the reason why the tidal instability occurred in this particular outburst.

There are already some hints for a very hot disk in the case of the 1985 superoutburst of U Gem. Smak and Waagen[45] have noted that the superhump period increased from $P_{\rm SH} = 0.197\,{\rm d}$ to $P_{\rm SH} = 0.203\,{\rm d}$ during about 20 d of the 1985 outburst and that the superhump period excess ratio, defined by $\epsilon = (P_{\rm SH} - P_{\rm orb})/P_{\rm orb}$, was $\epsilon = 0.130$ and that it is smaller than the value expected from Murray's simulations.[47] The precession rate of an eccentric disk was discussed by Lubow[48] and Murray,[47] who identified two major factors in determining the precession rate: (1) prograde precession by the tidal effects of the secondary star, (2) retrograde precession due to pressure effects. The precession rate of an eccentric disk is determined by combination of the two effects. The observed significant increase in the superhump period during the 1985 superoutburst of U Gem may most naturally be understood as due to weaking of the pressure effects with time. This indicates that the pressure effects were quite important in the 1985 superoutburst.

In this subsection, we have demonstrated how diverse the start of superoutbursts is depending on different systems and different circumstances in one and the same system. Let us now turn our attention to the end of superoutbursts.

II. The end of superoutbursts. In the original TTI model[8] the description of the end of the superoutburst was somewhat vague, in particular about the question which instability stops first, the thermal instability or the tidal instability. In the original TTI model it is argued that, as the superoutburst proceeds, the disk shrinks, the non-axisymmetric nature of the eccentric disk weakens and the tidal torque is reduced accordingly. Eventually, the cooling transition occurs at the outer edge of the disk and the cooling wave propagates inward, extinguishing the superoutburst, and the eccentric disk may terminate together with this, although a remnant eccentricity could remain for a little while as the "late superhumps". In this picture the hot disk due to the thermal instability and the eccentric disk due to the tidal instability end almost simultaneously at the end of the superoutburst. A modification to this picture was suggested by Hellier[10] for binary systems with extremely low mass ratio q in connection with problems of the so-called echo outbursts of WZ Sge stars and extremely short supercycle lengths of some ER UMa stars, RZ LMi and DI UMa.

We adopt Hellier's modification of the TTI model, i.e., the decoupling of thermal and tidal instabilities at the end of the superoutburst. In this new picture, as the superoutburst proceeds, mass of the disk is depleted and finally the cooling transition occurs at the outer edge while the disk is still eccentric. The cooling wave propagates all the way to the inner edge of the disk, extinguishing the superoutburst. That is, the end of the superoutburst is the end of the hot disk, but it is not the end of the eccentric disk. Hellier[10] suggested that this decoupling occurs only in binary systems with extremely low mass ratio $q < 0.08$. Here we suggest that the decoupling occurs for *systems with any mass ratio*.

A new question then arises about how the eccentricity ends after the superoutburst. As discussed in the previous section, the transition between the circular and eccentric disk is a kind of phase transition. As shown in the S-shaped tidal torque curve, two different disk shapes (circular and eccentric) are possible for a given total angular momentum of the disk and the disk can take either of the two, depending on its past history (i.e., hysteresis effect). We already discussed the transition from the circular to the eccentric disk. We now discuss how an eccentric disk is brought back to a circular disk. To do so, we examine angular momentum balance in the outer part of the accretion disk. During a superoutburst, outward transport of angular momentum by viscosity in the disk is balanced by the tidal removal of angular momentum in the eccentric disk together with addition of mass of low specific angular momentum from the gas stream. When the disk returns to the cold state at the end of the superoutburst, outward transport of angular momentum by shear stress stops because of the very low viscosity in the cold disk. However, this effect itself is not enough to bring the disk back to a circular state. Here we propose that besides the low viscosity, addition of matter with low specific angular momentum by the gas stream from the secondary is vital in terminating the eccentricity. Ichikawa *et al.*[28] demonstrated by numerical simulations that enhanced mass transfer by a gas stream terminates disk eccentricity because mass addition with low specific angular momentum contracts the disk's outer edge and thus terminates the disk eccentricity. Lubow[49] has shown that after the end of a superoutburst the eccentricity of the disk damps on a time scale of order $M_d/\dot{M}$ where M_d and $\dot{M}$ are the disk mass and the mass-transfer rate.

In ordinary SU UMa stars, the eccentric disk may survive for a little while after the end of superoutburst. However mass addition from the gas stream eventually terminates the eccentricity and the disk is brought back to a compact circular shape. In the case of WZ Sge stars, the mass transfer rate from the secondary star is supposed to be low, $\dot{M} \simeq 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$, as compared with those of ordinary SU UMa stars with $\dot{M} \simeq 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. Because of the low mass transfer rate the eccentric disk (and superhumps) survived well after the end of the main superoutburst. The tidal removal of angular momentum from the disk then fed mass from the outer disk to the inner disk and this triggered the thermal instability in the inner disk, producing an outburst. The heating wave propagating outward could be reflected as a cooling wave before reaching the outer edge of the disk because matter in the disk had already been greatly depleted in the main superoutburst. However since the disk remains still eccentric, the mini-outburst would then be repeated. This is the picture for echo outbursts of WZ Sge stars proposed by Hellier[10] and a similar model was also proposed by Osaki *et al.*[50] A sudden cessation of repetitive mini-outbursts in WZ Sge stars could be explained as due to viscosity decay in the cold disk.[50]

Conclusion. In this paper we have reviewed the present state of the disk instability model for outbursts of dwarf novae. In particular, we have presented the TTI model, which combines two intrinsic instabilities (thermal and tidal instabilities) in dwarf nova accretion disks, in its full account. We have first explained the basic concept of the TTI model and how it works for the superoutburst phenomenon. We have then discussed recent refinements of the model, in particular for the start and the end of superoutbursts, by which we are now able to explain wide varieties in superoutburst light curves of different stars and of different superoutbursts within one and the same star. The disk instability model can after all explain most of the outburst phenomena observed in dwarf novae.

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Profile

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