A brief history of the disk instability model for dwarf nova outburst

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Introduction

A history of the disk instability model for DN outbursts

from my personal point of view,

since there is a good detailed review on this subject "Cataclysmic Variable Stars" by B. Warner (1995)

Past half a century

I	1960s	binary nature: secondary star
II	1970s	two accretion models : competition between them
III	1980s	thermal-viscous instability in the disks
IV	1990s	SU UMa: tidal instability: TTI model: unification model

Dwarf Novae(DN)

DN Quasi-periodic outbursts

amp.: 2-5 mag repetition time: weeks to months

DN belong to cataclysmic variable stars (CV)

Sub-classes of DN

- U Gem (or SS Cyg) : simple quasi-periodic outubursts
- Z Cam: frequent outburst, + standstill
- SU UMa : short normal ouburst , long superoutburst
  - superhump during SO.

Nova-like(UX UMa): no-outburst so far

Two monographs on CV

Warner (1995) Hellier (2001)

DN outburst 1960s (1)

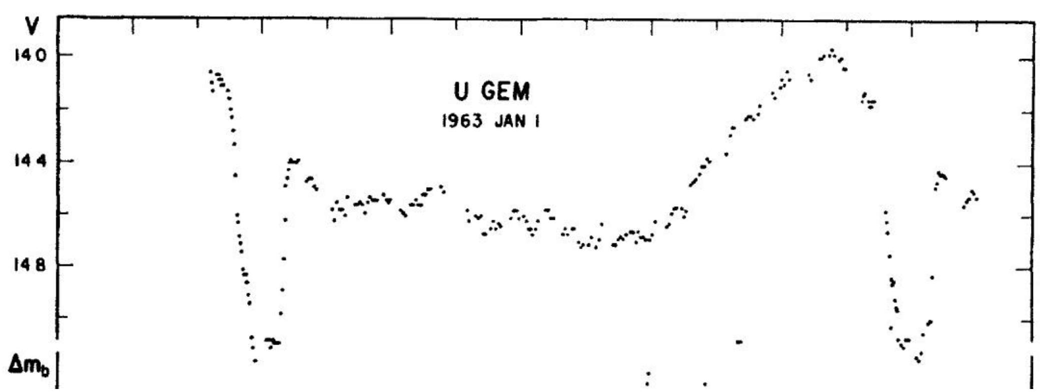
1960s Kraft CV : a special type of close binary

orbital P. several hours

Primary: WD secondary: Roche-lobe filling cool dwarf star

Krzeminski (1965) U Gem eclipse

Quiescence LC: shoulder (orbital hump)



Secondary star as a seat of Outburst

Krzeminski (1965)

shoulder and eclipse in LC disappeared during outburst

=> secondary star is a seat of outburst

DN O. models based on the secondary star by

Paczynski (1965)

Bath (1968)

Osaki (1970)

Standard model for CV (1970s)

J. Smak (1971)

B. Warner and Nather (1971)

Standard model for CV　accretion disk

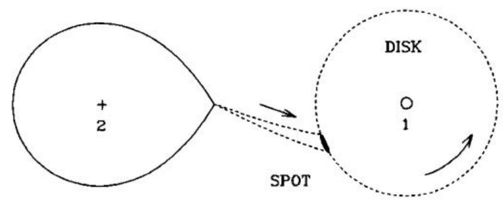
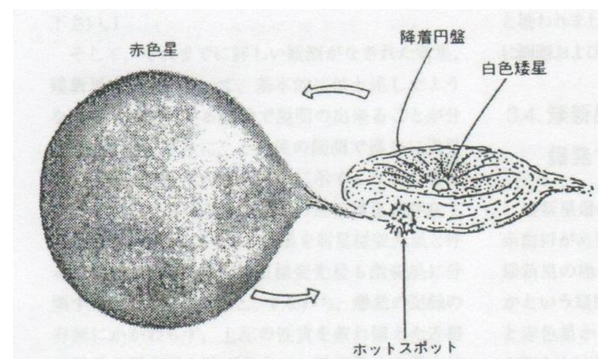


Figure 1 Standard model of a cataclysmic variable.



U Gem:　incl. 60°　WD & AD not eclipsed

DN Outburst・・・・・brightening of accretion disk

two accretion models (1970s)

Based on the standard model by Smak, Warner (1971)

two accretion models for DN Outburst were proposed in early 1970s

models: “outburst” due to brightening of accretion disk

Osaki (1974)

a working model for DN now called “Disk Instability (DI) model”

mass transfer rate from secondary ・・・・constant in all time

1. **in quiescence,** little accretion on the WD, disk accumulate mass transferred from secondary
2. when mass accumulated in disk reaches some critical value, **some instability** sets in
3. stored mass in the disk is dumped onto WD **during outburst,** brightening of accretion disk

G. Bath (1973) mass transfer burst (MTB) model

mass transfer rate from secondary・・・・highly variable

1. enhanced mass transfer from secondary during outburst
2. low mass transfer rate from secondary in quiescence

Two models contested fiercely (in late 1970s)

Bath and his group

strongly advocated MTB model

Polish astronomers (Paczynski & Smak)

supported DI instability model

Main point of dispute

DI instabilty model

orbital hump in q. (U Gem) 0.5 mag

evidence for no effective accretion from the disk to WD in quiescence

Discovery of the physical mechanism for the disk instability (1980s)

R. Hoshi (1979)

cool outer disk thermally unstable

bi-stable states

1. hot high viscosity state (H ionized)
2. cool low viscosity state (H neutral)

DN makes flip-flop between these two states

Hoshi (1935-1999)

Hoshi's calculation unfortunately did not make complete limit cycle

Thermal-viscous instability

Meyer and Meyer-Hofmeister (1981)

(vertical integration of disk structure)

demonstrated

“the thermal limit cycle Instability”

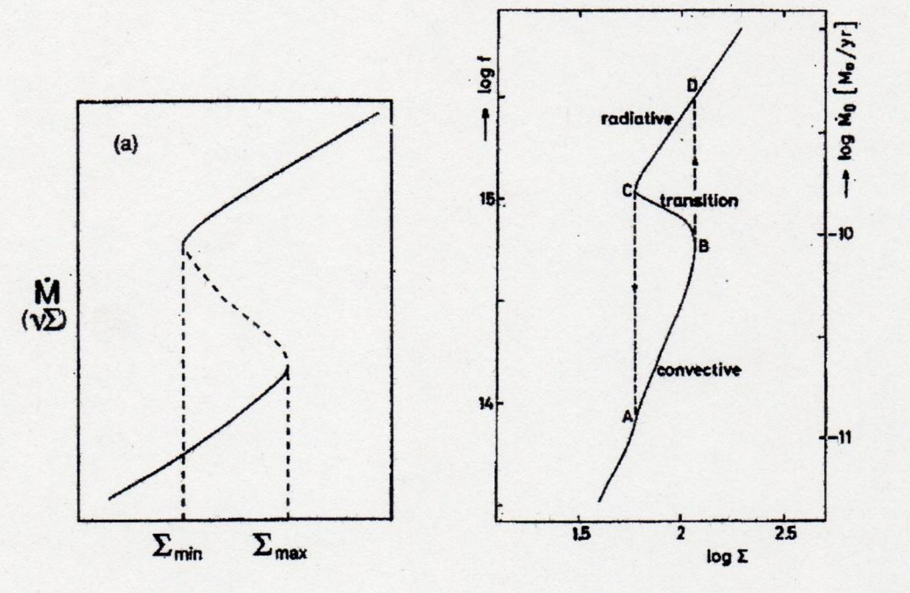


Fig. 1. The S-curve explaining the thermal limit cycle oscillation for dwarf nova outbursts. The left panel shows a schematic S-curve between the surface density Σ and viscosity required for the limit cycle oscillation. The right panel shows the original S-curve obtained by Meyer and Meyer-Hofmeister (1981) who integrated the vertical structure of the accretion disks.

Thermal limit cycle instability

5 groups calculated the thermal instability for O. of DN

1. Meyer and Meyer-Hofmeister (Germany)
2. J. Smak (Poland) (1982)
3. J. Cannizzo et al (Texas in USA) (1982)
4. J. Faulkner, D. Lin, & Papaloizou (England)
5. Mineshige and Osaki (Japan) (1983)

Round table discussions

Superoutburst and Superhump in SU UMa stars

SU UMa stars : observational characteristics

1. DN below the period gap (P_{orb}<2h)
2. two types of outbursts
   normal O. (short duration of a few days)
   super O. (long duration of about 2 weeks)
3. periodic hump called "superhump" during superoutburst
   P_{sh} a few % longer than P_{orb}
4. "supercycle": characteristic light curve
   a few or several NO sandwiched by two SO
5. SO is triggered by NO

Light curve of SU UMa stars (a case of VW Hyi)

Supercycle

a cycle from one superoutburst to the next superoutburst

VW Hyi about 180 days

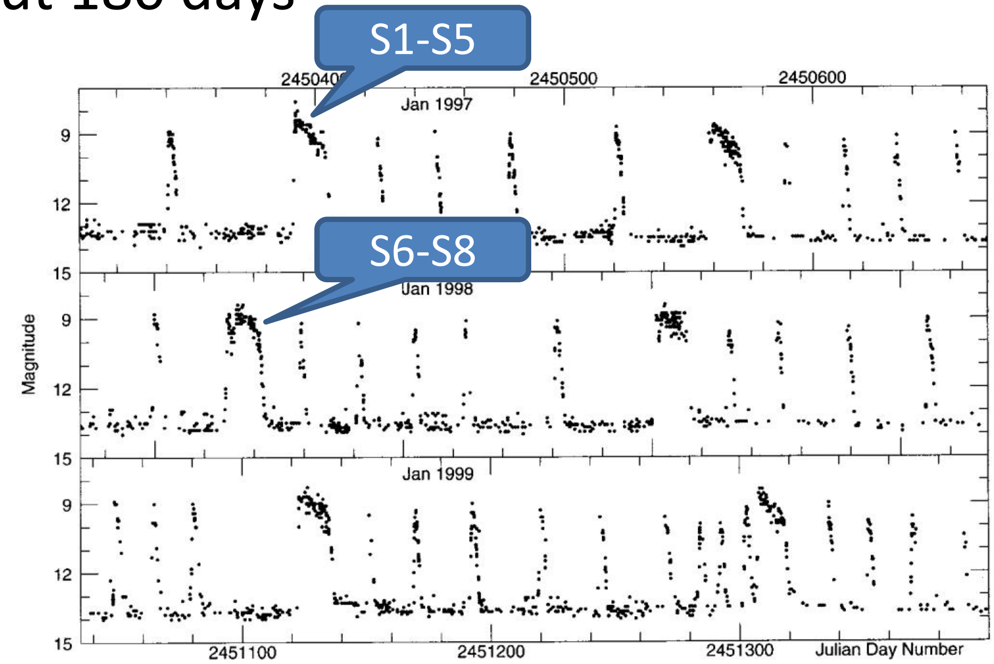


Fig. 6.1: A 3-yr section of VW Hyi's lightcurve showing both normal outbursts and superoutbursts. (Data by the Royal Astronomical Society of New Zealand.)

superhumps

Superhumps

1. only during superoutburst
2. period: a few % longer than P_{orb}
3. Amplitude: 0.2-0.3 mag.

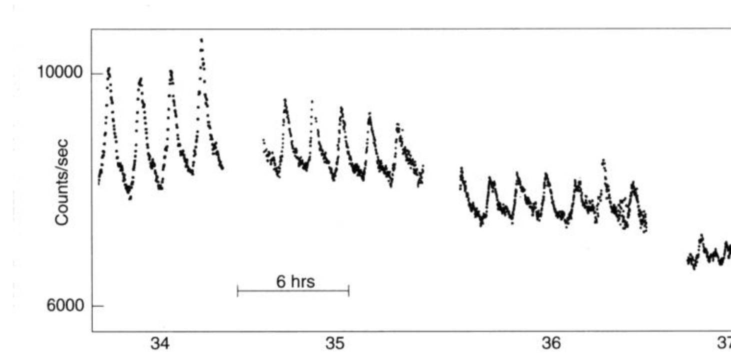


Fig. 6.8: The evolution of superhumps over five nights of t
superoutburst of V1159 Ori. Much space has been delete
segment (add 244 9300 to the day to obtain JD). (Adapte
Patterson and colleagues.[10])

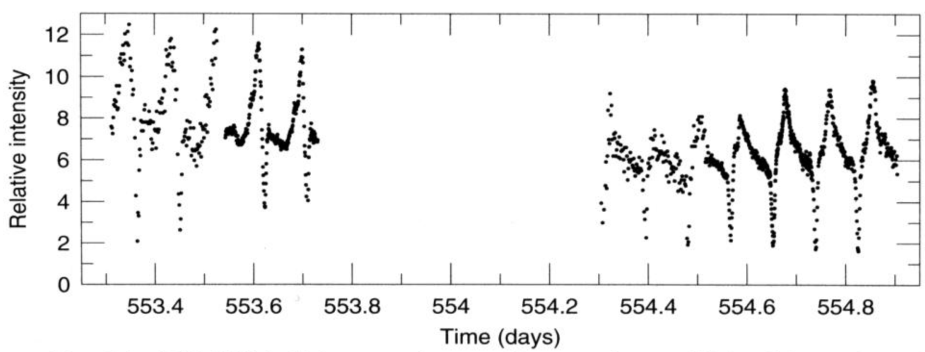


Fig. 6.2: DV UMa's lightcurve shows eclipses and an additional 'superhump' modulation. Since the superhump maxima occur at different phases with respect to the eclipse on different nights, the superhump period is slightly longer than the orbital period. [Data by the Center for Backyard Astrophysics[2] (the quality varies because data from different telescopes were combined).]

Superhump models

precessing eccentric disk model

first suggested by Vogt (1982)

Osaki (1985) examined this model and found a relation between precession rate and binary mass ratio $q=M_2/M_1$

Discovery of physical mechanism for the eccentric disk

Whitehurst (1988)

numerical simulations of accretion disk ($q=M_2/M_1<0.25$)

disk becomes unstable and takes "precessing eccentric form"

it is caused by the tidal 3:1 resonance effect of the accretion disk by secondary

now called **"tidal instability"**

Tidal instability

Tidal instability discovered by Whitehurst

was confirmed by

Hirose and Osaki (1990)

Lubow (1991)

3:1 resonance between the disk flow

and the orbiting secondary

Further simulations

Murray, M. Wood, Smith et al, Kley et al

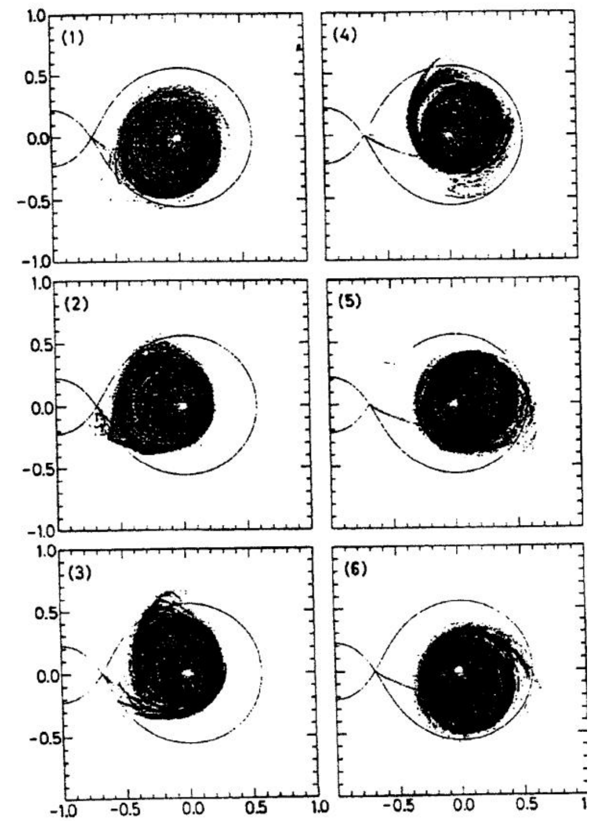


図3．スーパーハンプの際に出来る離心楕円円盤の数値シミュレーション．連星系の公転に同期した回転座標系から見た楕円円盤のスーパーハンプ周期での振動の様子．

Superoutburst models

three different models for superoutburst of SU UMa

1. thermal-tidal instability (TTI) model

    by Osaki

2. thermal limit cycle model (a view by van Paradijs 1983)

    by Cannizzo and his group

3. enhanced mass transfer model (EMT) model

    by Smak

Thermal-tidal Instability model (TTI model)

TTI model is basically the disk instability model

mass transfer rate from the secondary is assumed to be constant

If two intrinsic instabilities in the disk

(1. thermal instability and 2. tidal instability)

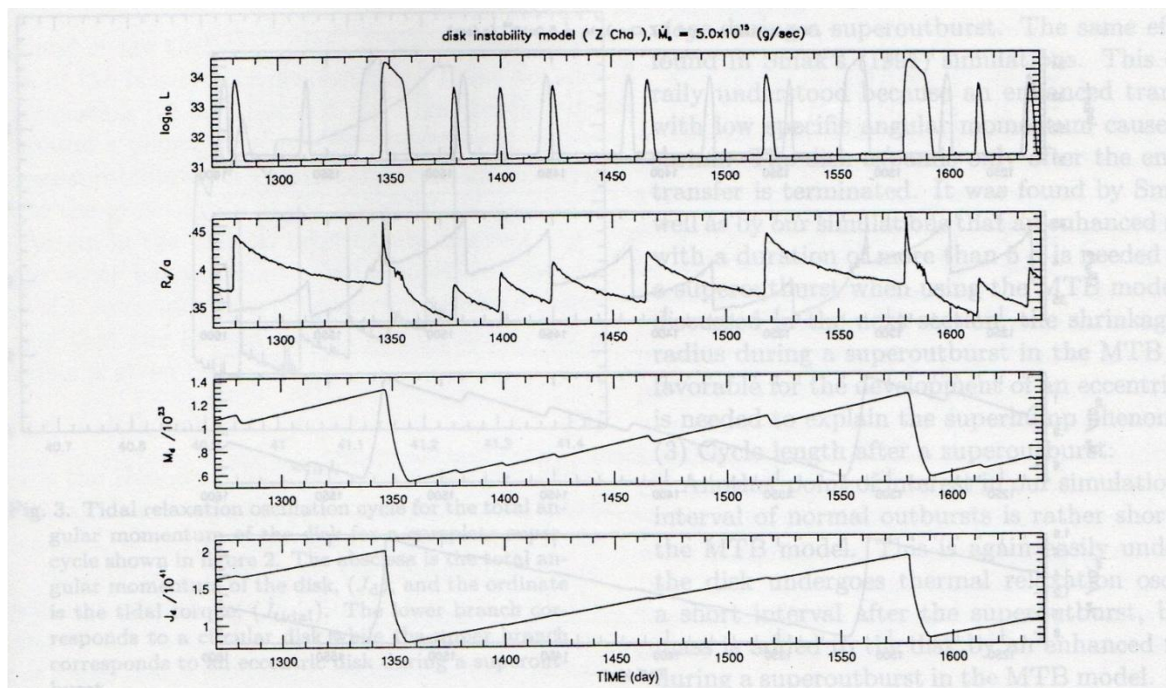
are properly combined, it will result in the charactaristic LC of SU UMa stars

Simulations based on TTI model

Ichikawa, Hirose, Osaki (1993)
Two simulations with different viscosity parameters

(1) Case A: viscosity parameter $\alpha_{cold} = 0.03 (r/r_{tid})^{0.3}$
All outburst: “outside-in”
outburst interval and outburst amp. increase with SC phase

(2) Case B: $\alpha_{cold} = 0.03$
outburst: “inside-out”
O. Interval is constant



Case A simulations

Double cycles

TTI model : Double cycle

thermal limit cycle : normal outburst

tidal limit cycle: superoutburst

circular disk (steady)

eccentric disk (highly variable)

phase transition between two states

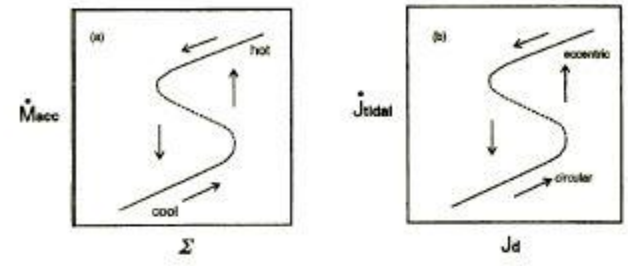


FIG. 9—Schematic diagrams showing (a) the thermal relaxation oscillation for outburst of ordinary U Gem stars and (b) the angular momentum (or the tidal torque) relaxation oscillation for the supercycle of SU UMa stars adapted from Osaki (1994).

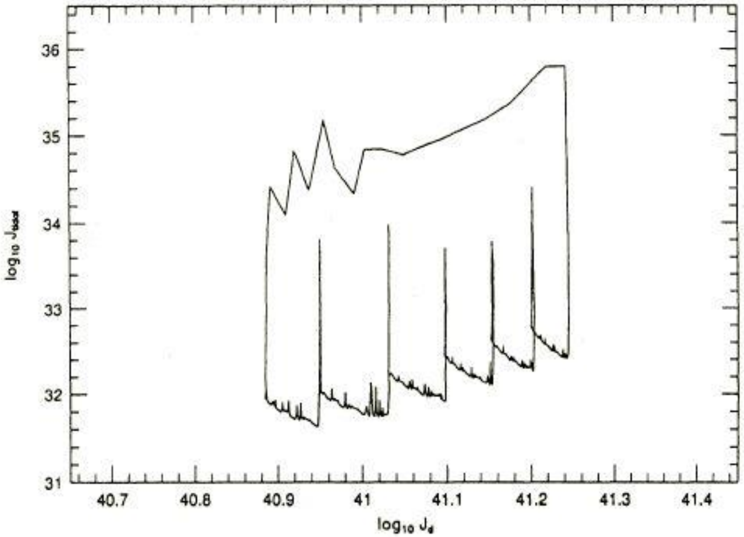


Fig. 3. Tidal relaxation oscillation cycle for the total angular momentum of the disk for a complete supercycle shown in figure 2. The abscissa is the total angular momentum of the disk, $(J_{\rm d})$, and the ordinate is the tidal torque, $(\dot{J}_{\rm tidal})$. The lower branch corresponds to a circular disk while the upper branch corresponds to an eccentric disk during a superout-

Criticism to TTI model

I know many papers which criticized TTI model.

Since observations of SU UMa stars show such a variety in LC, obviously it is very easy to find some examples that contradict simplified simulations based on TTI model.

Most important is whether the criticism is to the essential points of TTI model or just to some minor points.

Essential points of TTI model

1. disk radius (R) variation during supercycle (SC)

(1) in early phases of SC, disk is compact ($R<R_{3:1}$, $R<R_{tid}$):

tidal removal of A.M. from the disk is ineffective, the expansion of the disk quickly starts cooling wave at the outer edge . That is the reason why the outburst is so short

disk radius increases with SC phase

(2) R approaches to $R_{3:1}$

eventually the last normal outburst causes the disk radius (R) to exceeds $R_{3:1}$,

then tidal instability sets in, deforms the disk into eccentric precessing disk, greatly enhanced tidal torques, keeps the disk in hot state longer

that is the reason why the outburst is so long, “superoutburst”

Criticism to TTI model (1)

An example of such criticism (Cannizzo)

Normal outburst intervals in SuperC

TTI simulations: interval monotonically increases with SC phase

Observations of VW Hyi (Smak (1985) classified SC into two types L and S)

(1) Type L the interval increases monotonically with phase

(2) Type S the interval increases monotonically to half way but it then decreased during the later half

Type L fits with TTI model

Type S apparently contradicts with TTI

How is the recurrence time of NO determined?

two types of NO : (1) outside-in O: tmass

(2) inside-out O: t_{diff}

Simulations are those due to outside-in type

My suggestion for Type S (1989)

Type S: (1) first half due to tmass : outside-in outburst

(2) second half due to tdiff: inside-out outburst

(due to tilted disk?)

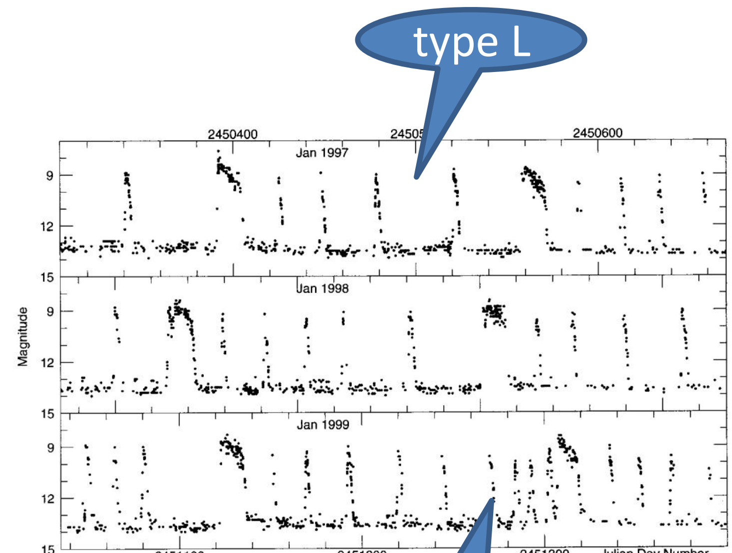


Fig. 6.1: A 3-yr section of VW Hyi's lightcurv ... ng both normal outbursts and superoutbursts. (Data by the ... f New Zealand.)

Simulations by Ichikawa, Hirose, and Osaki (1993)

Two simulations with two different viscosity prescriptions

Fig. 1 NO: outside-in

Interval: increases with SC phase

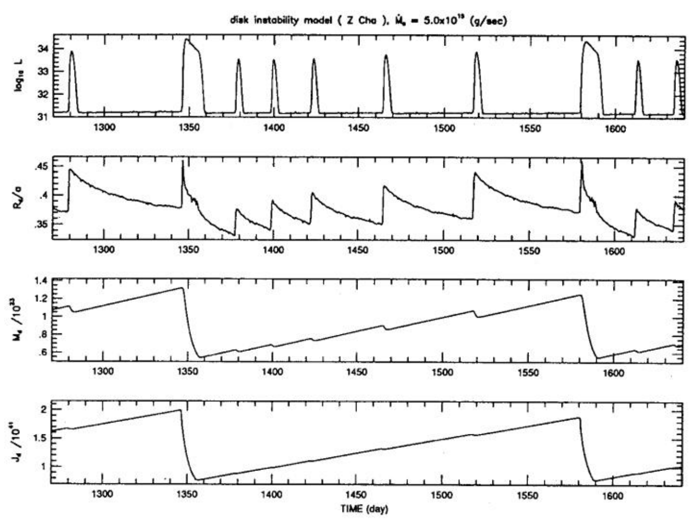
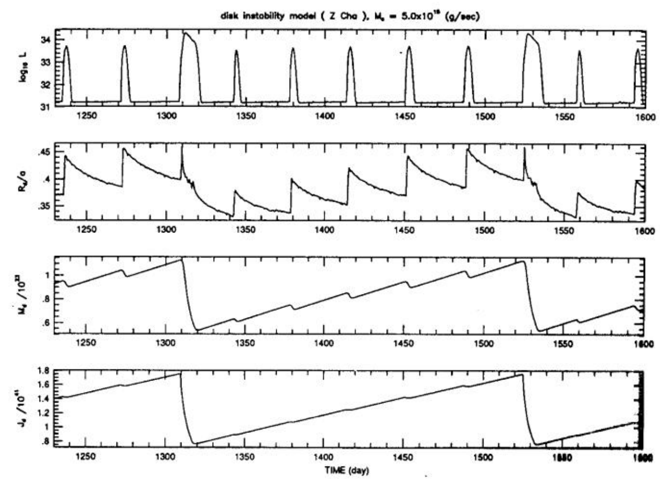


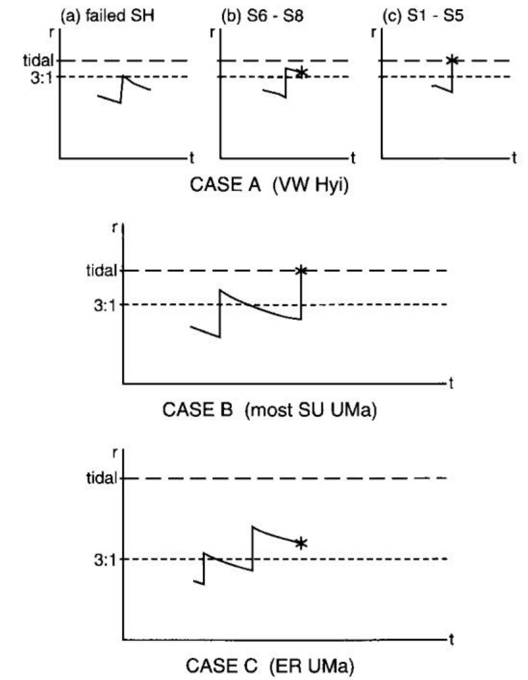
Fig.2 NO: inside-out

interval: constant



Cannizzo did not mention Fig.2

Criticism to TTI model (2)



Smak's criticism

Superhumps start a few days after SO maximum

while SH should first appear in TTI model

Two types of SO (after Bateson)

(1) precursor–main type superoutburst (S6-S8):

(2) one continuous outburst (S1-S5)

SH appear a few days after supermax

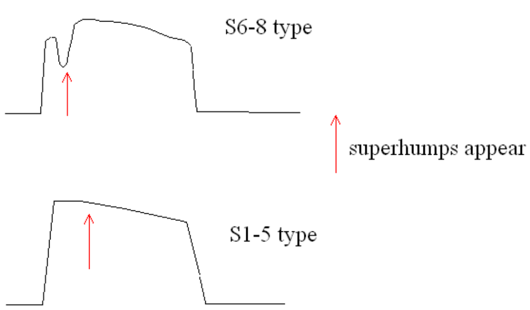
New proposal (Osaki & Meyer 2003)

(1) S6-S8 original TTI model CASE A (b) $R_{3:1}<R<R_{tidal}$

(2) S1-S5 CASE A (c) R reaches R_{tidal}

disk hits tidal wall and a long outburst ensues

and then an eccentric disk grows after a few days

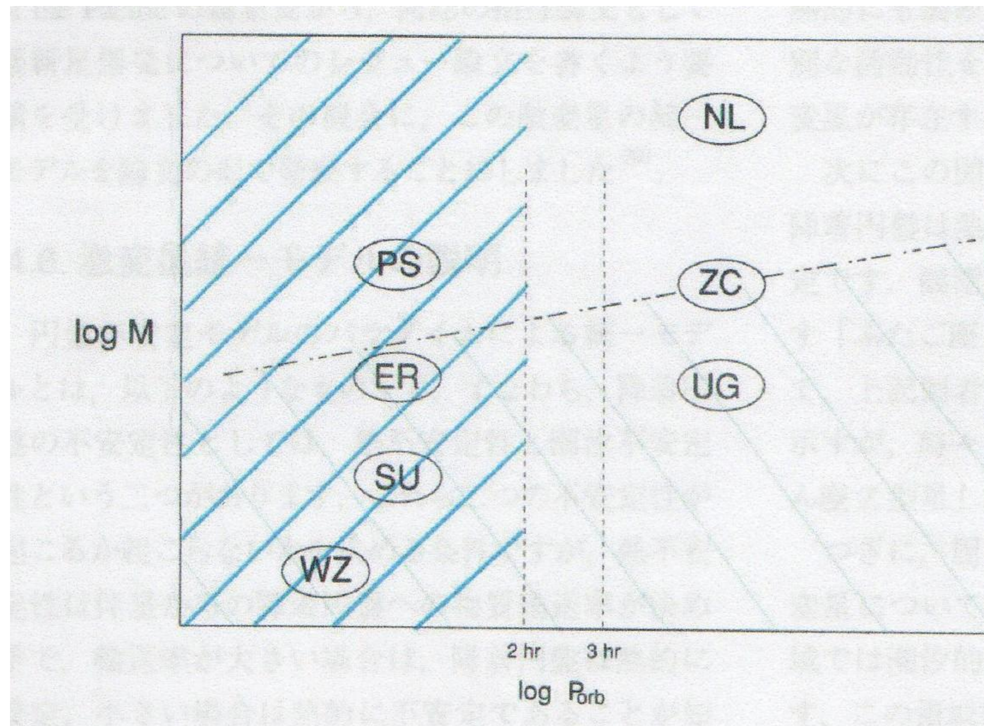


Unification model for CVs

Unification model based on TTI model

(P_{orb}-M_{dot} diagram)

M_{dot}: mass transfer rate
from the secondary



Two critical lines

1. Thermal instability: mass transfer rate Mdot(crit)
2. Tidal instability

mass ratio $q_{crit} = M_2/M_1 < 0.25$

$P_{orb} <$ 2hrs

Unification for SU UMa stars

Quite variety in LC of SU UMa stars

activity seq.: ER UMa => SU UMa => W Sge

SC length (T_S) <50d a few 100 d several yrs-30 yrs

TTI model

most important input parameter: mass transfer rate (M_{dot})

$T_S \sim (M_{dot})^{-1}$ $T_N \sim (M_{dot})^{-2}$ No. of NO inversely prop. T_S

(1) M_{dot} very high : ER UMa SC length is very short

No. of normal O. many

(1) M_{dot} middle : SU UMa No. of normal O. decrease with T_S

(3) M_{dot} low: WZ Sge SC length very long only SO

TN-TS relations by Warner (1995)

SYSTEMATICS OF SUPEROUTBURSTS IN DWARF NOVAE 193

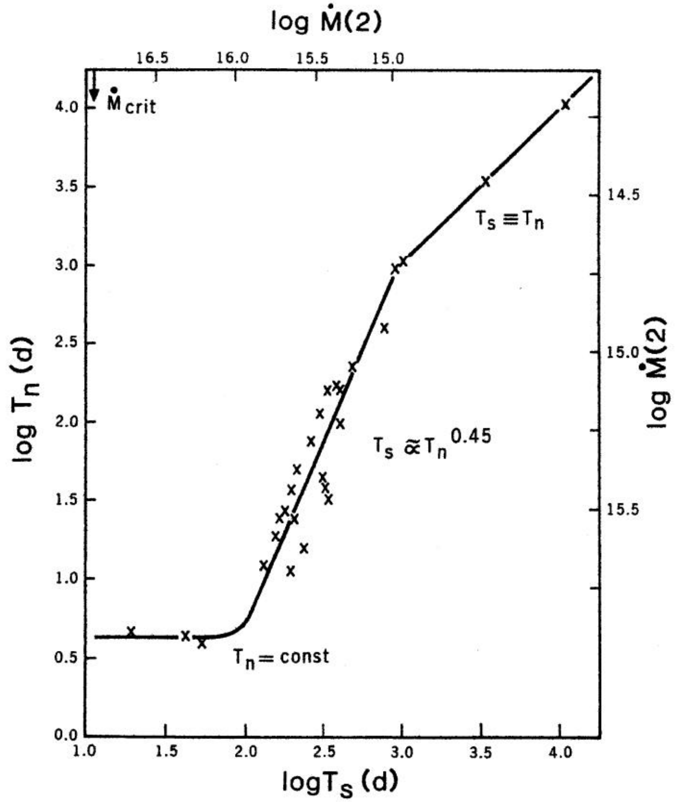


Fig. 2. Relationship between normal outburst and superoutburst recurrence times. Approximate mass transfer rates have been added.

Recent development
(Kepler observations)

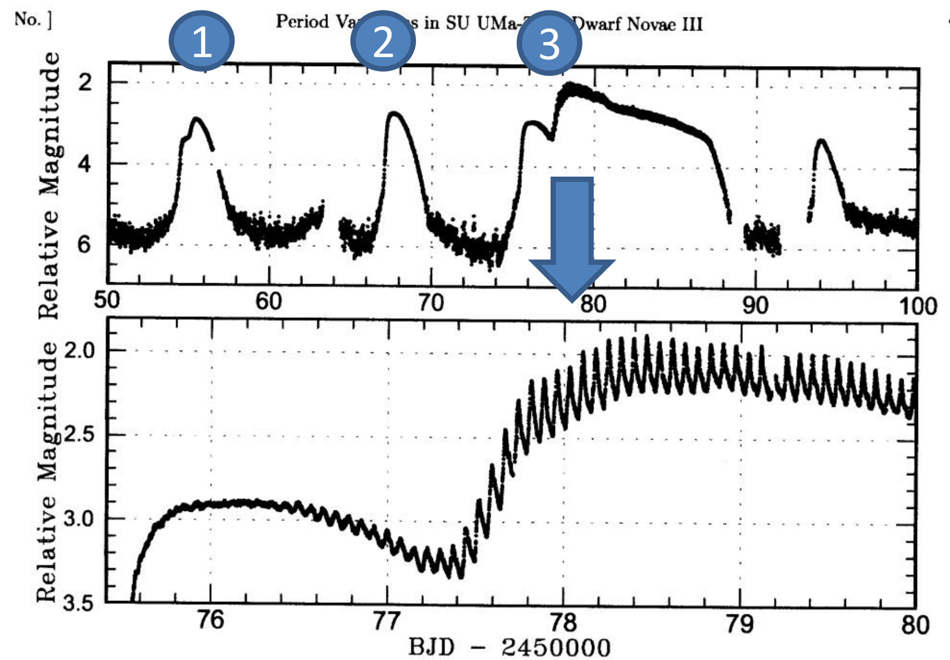
Kepler light curve of V1504 Cyg (September 2009)

3 precursor-main SO

(1) SH appears in the descending branch of normal outburst
(2) it grows in amplitude
(3) SH seems to trigger SO

2 Normal O. with Periodic hump with SH period
in the descending branch of normal outburst (failed SH)

It is exactly what TTI model predicts.



V1504 Cyg (Kato et al. 2012)

Conclusion

The disk instability model (i.e., TTI model)

can basically explain most of the DN outburst phenom. including various SU UMa sub-classes.

I am now more confident in TTI model than before (8 yrs ago).

Two review papers

1. Osaki (1996) PASP, **108**, p.39
2. Osaki (2005) Pub. Japan Academy, **81**, p.291

J. Smak and J. Cannizzo will tell us their own models for superoutbursts and superhumps of SU UMa stars

The end

Thank you for your attention

Comparison of 3 models

model	advocator	(Mdot)tr	SH	SO	Major point	Major premise
TTI	Osaki	Const.	Eccentric disk	Enhanced tidal torque	Variation in disk radius	Tidal instability and enhanced tidal torque
EMT	Smak	variable	variable hot spot	Enhanced mass transfer	EMT due to irradiation heating	EMT and variable hot spot
Pure T-V	Cannizzo	Const.	Eccentric disk ?	Short(NO) & long(SO)	Pure T –V instability	(1)pure T-V instability (2)SH (tidal inst.) is of the secondary importance

Osaki(1985) paper ?

"Irradiation-induced mass-overflow instability as a possible cause of superoutbursts in SU UMa stars" Osaki A&A, **144** (1985)

EMT model:

superoutbursts due to enhanced mass transfer

Osaki (1989):

I abandoned this model and switched to TTI model. the reasons are

(1) I needed double limit cycle and I have found another better limit cycle, that is, tidal instability naturally gives us the second limit cycle beside Thermal-Viscous Instability

(2) questioning on the assumption of "irradiation-induced mass-overflow instability"

"all radiation from the disk and the white dwarf is intercepted by the secondary and it is assumed to be used to heat the secondary stars, enhancing the mass overflow"

My encounter with DN O.

Since the outburst mechanism of DN was my life work (more than 30 years), let me tell you how I was involved in this problem firstly.

I spent two years in Columbia University from 1967 to 1969. There Krzeminski gave a talk on his famous observations of U Gem.
I was very much interested in the outburst mechanism of DN and started my research on this problem.

I published my first model for DN O. based on the secondary star as a seat of outburst in 1970.