The Thermal-Viscous Limit Cycle Model in Dwarf Novae

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UMBC & NASA/GSFC

Brief History of Accretion Disks/CVs

1973 - Shakura & Sunyaev: $t_{\varphi r} = \alpha P$

1974 - Osaki: DN outbursts due to disk instability (Smak 1971)

1981 - Pringle described a limit cycle for disks (Santa Cruz)

1982 - Meyer/Meyer-Hofmeister - vertical structure of disk

1988 - Whitehurst - precessing eccentric disk model for superhumps

1989 - Osaki: thermal-tidal model for superoutbursts in SU UMa stars

1991 - Balbus-Hawley - magnetorotational instability (MRI)

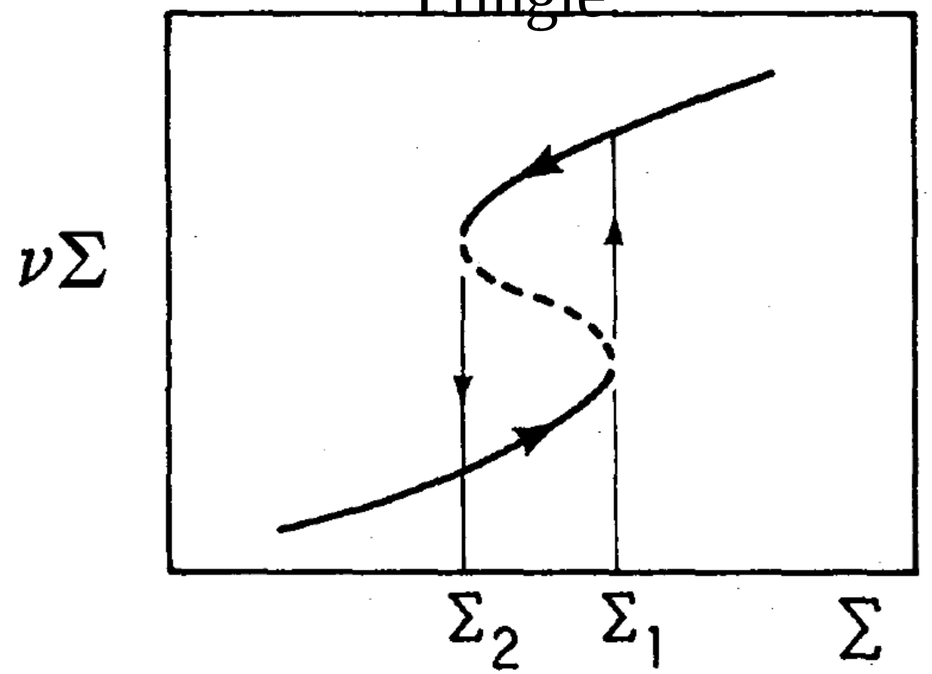
2000 - Menou: attempted self-consistent model d.i. + MRI (failed)

Brief History: Accretion Disk Limit Cycle

July 1981 - 6th North

American CV Meeting.

Pringle:



Dec 1981 - Meyer &

Meyer-Hofmeister

1981

Dwarf Novae:

--Smak
--Lin, Faulkner, & Papaloizou
--Mineshige & Osaki
--Meyer & Meyer-Hofmeister
--Pringle, Verbunt, & Wade
--JKC + Ghosh, Wheeler, Shafter, Polidan, Kenyon
--Angelini & Verbunt
--Pojmanski
--Duschl & Livio
--Adam, Stoerzer, & Duschl
--Osaki, Ichikawa, Hirose
--Hameury, Lasota, Dubus, Menou, Schreiber

Soft X-ray Transients:

--JKC+Wheeler, Ghosh
--Lin, Taam
--Huang, Wheeler
--Mineshige + Wheeler, Tuchman, Nomoto, Ichikawa, Kato, Kim, Yamasaki, Ishizaka,
--JKC, Chen, Livio
--van Paradijs
--Lasota, Narayan, Yi
--King, Ritter
--Menou, Hameury, Stehle
--Meyer, Meyer-Hofmeister
--Dubus, Hameury, Lasota

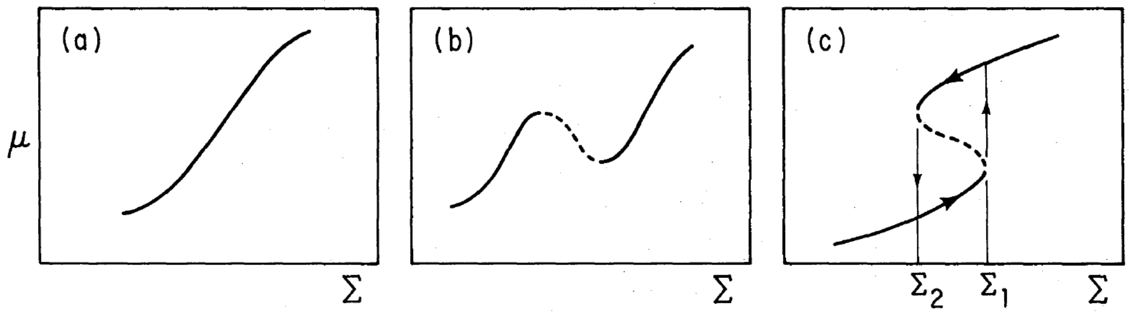
FU Ori stars:

--Mineshige, Kawazoe
--Bell, Lin, Kenyon, Hartmann
--Lin, Papaloizou
--Okuda,Fujita, Sakashita
--D'Alessio, Canto, Calvet,Lizano
--Armitage, Livio, Pringle
--Fromang, Terquem, Balbus
--Zhu, Hartmann, Gammie, McKinney

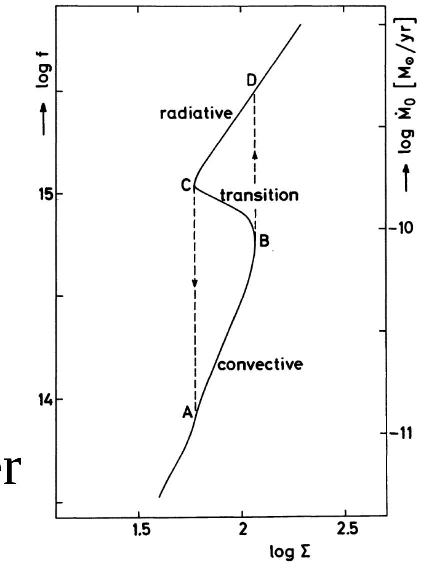
AGN:

--Lin, Shields
--Clarke, Shields
--Mineshige, Shields
--JKC, Reiff
--Siemiginowska, Czerny, Kostyunin
--Burderi, King, Szuszkiewicz
--Rozanska, Czerny, Zycki, Pojmanski
--Hatziminaoglu, Siemiginowska, Elvis
--Hameury, Lasota, Viallet

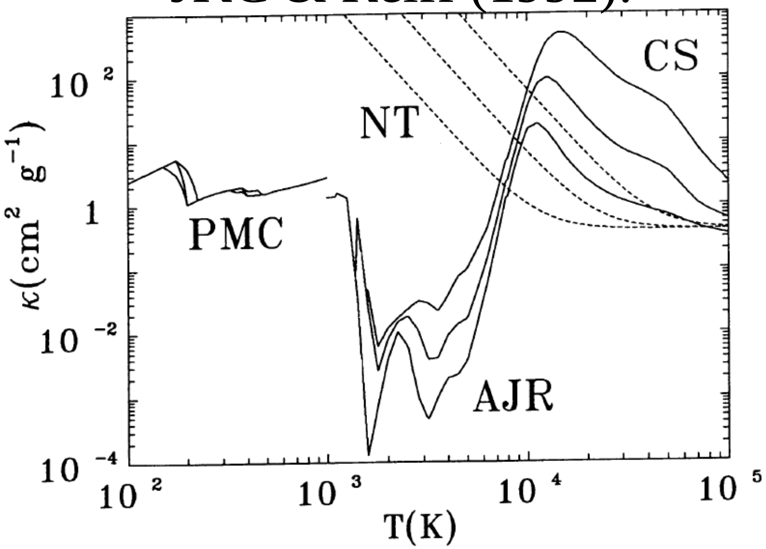
Bath & Pringle (1982):



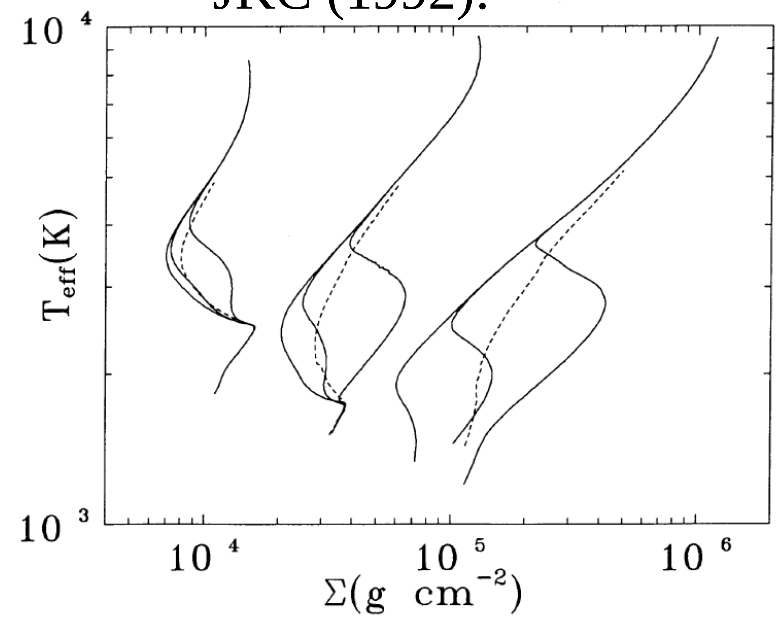
Meyer & Meyer-Hofmeister (1981):

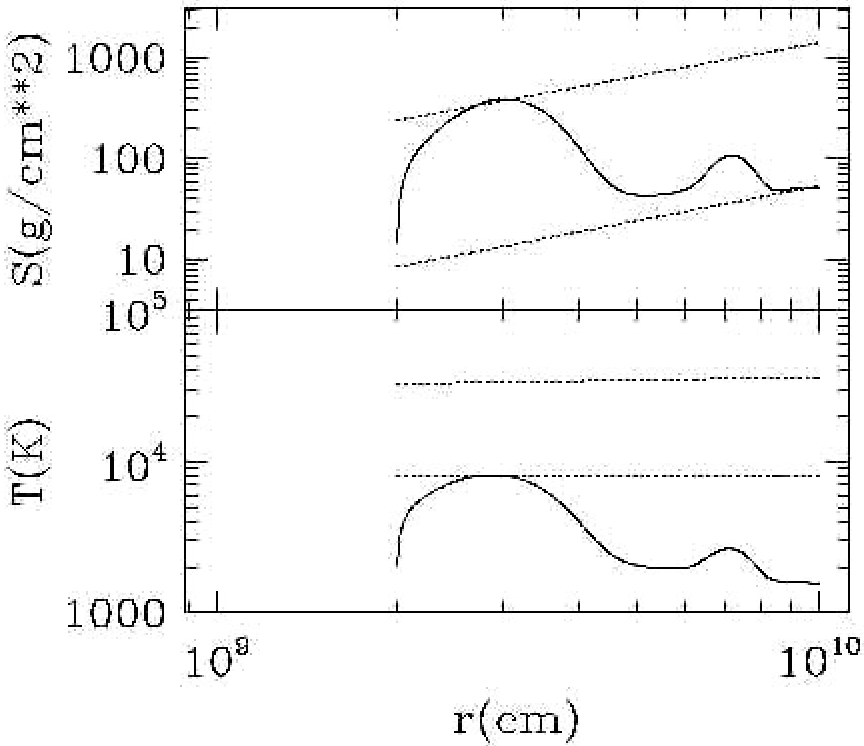


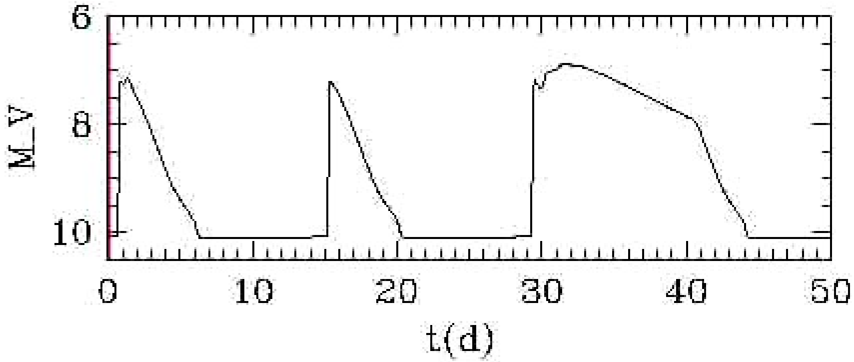
JKC & Reiff (1992):

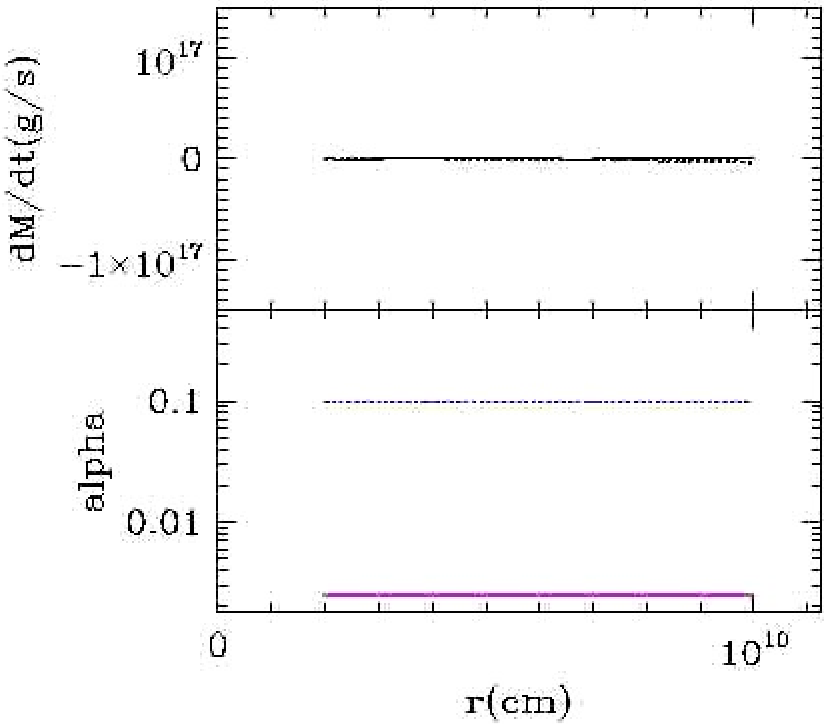


JKC (1992):

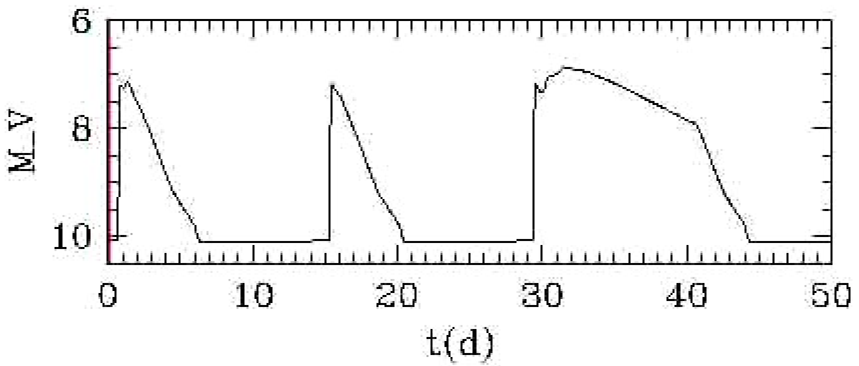



S(g/cm**2)
1000
100
10
T(K)
10^5
10^4
1000
10^9
10^{10}
r(cm)


M_V
6
8
10
0
10
20
30
40
50
t(d)



dM/dt(g/s)
10^{17}
0
-1×10^{17}
alpha
0.1
0.01
0
10^{10}
r(cm)



M_V
6
8
10
0
10
20
30
40
50
t(d)

Smak 1984

Acta Astron.

34, 161

Accretion in Cataclysmic Binaries.
IV. Accretion Disks in Dwarf Novae

by

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Received November 15, 1983[2]

ABSTRACT

Time-dependent disk models are constructed, including the effects of thermal instability due to the ionization of hydrogen. The results are very sensitive to the assumptions concerning the viscosity. It is argued that by comparing models based on different viscosity prescriptions with the observational data for dwarf novae it should be possible to get an insight into the nature of viscosity. In the first approximation it is found that models based essentially on the α-disk approach with $\alpha \approx 0.2$, but with lower viscosity at low temperatures, reproduce reasonably well the dwarf novae behavior.

Two types of outbursts are predicted by the models: Type A, with the onset of instability in the *outer* parts of the disk, and Type B, with the onset of instability in the inner parts. The two types are tentatively identified with observed examples of dwarf nova outbursts. Using a range of binary system parameters and mass-transfer rates applicable to dwarf novae it is possible to reproduce the observed *outburst period* versus *amplitude* and the *decline rate* versus *orbital period* relations. The absolute magnitudes at minimum are also consistent with the observational evidence.

1. Introduction

Meyer and Meyer-Hofmeister (1981) found that in the temperature range corresponding to the ionization of hydrogen the accretion disk models are unstable (cf. also Bath and Pringle 1982; Cannizzo, Ghosh, and

[1] JILA Visiting Fellow 1982-83.

[2] This paper was originally submitted in June 1983 to the Astrophysical Journal. After 5 months, with no report from the referee to be expected in the near future, the author decided to re-submit his manuscript to Acta Astronomica.

Smak 1984

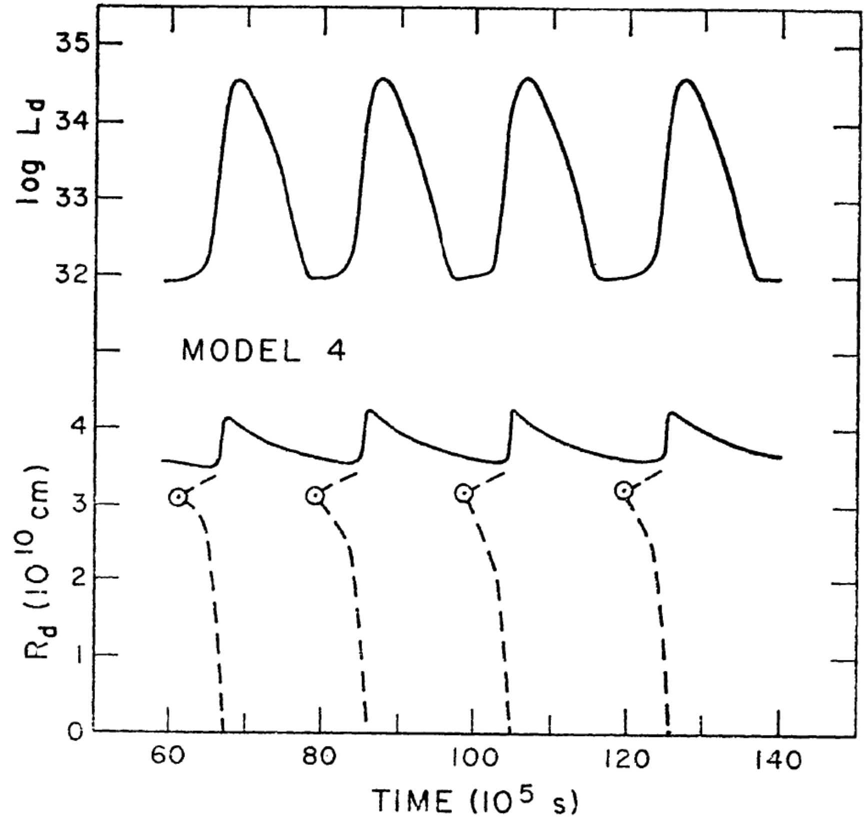


Fig. 2. Dwarf nova behavior of Model 4. Upper part shows the bolometric luminosity variations. Lower part – the disk radius variations. Circled points in the lower part indicate times and places where the instability first sets in, while the broken lines – how it propagates throughout the disk.

Disk radius variations:

Anderson 1988

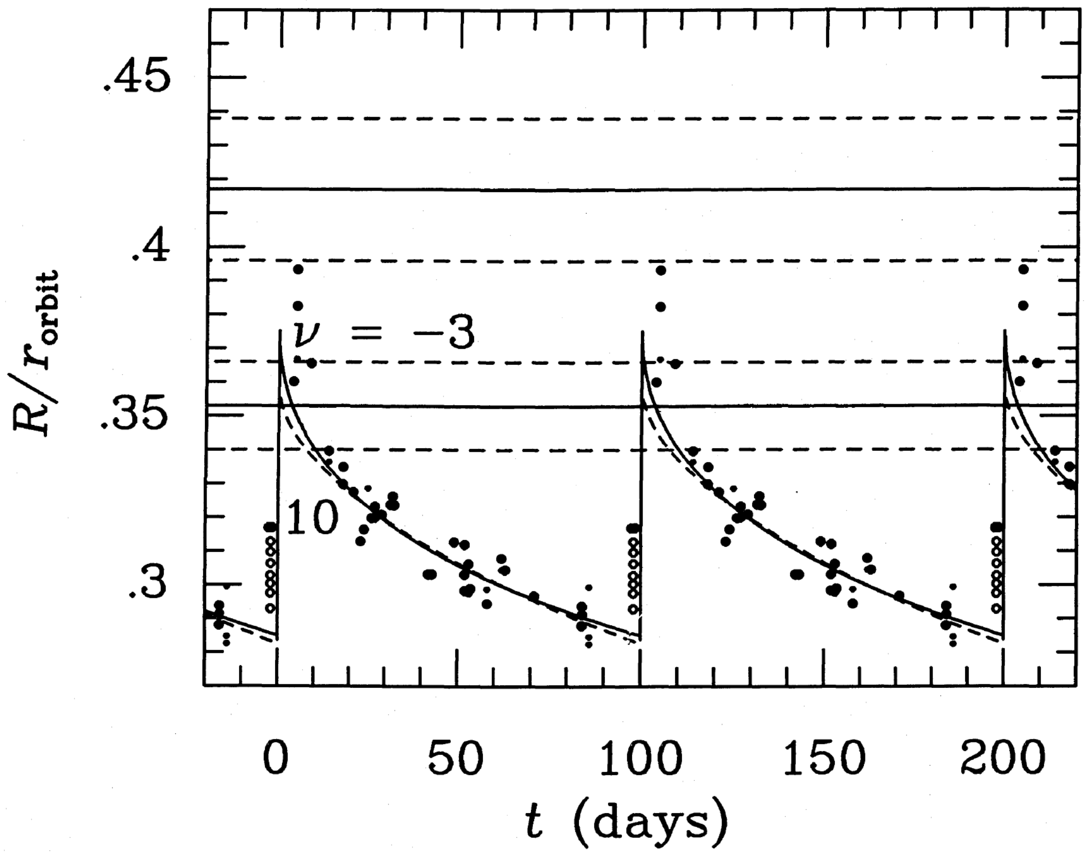
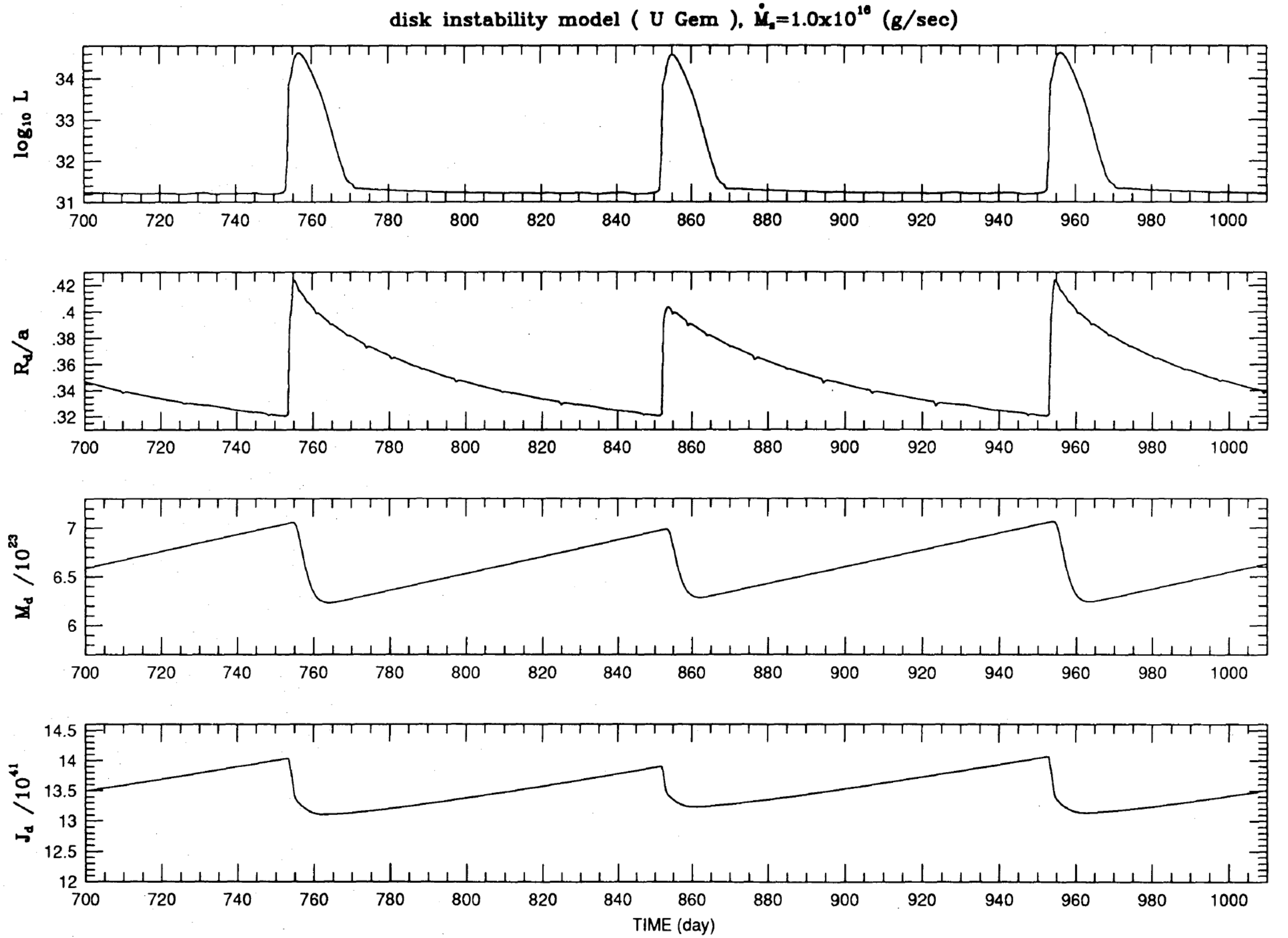


FIG. 1.—U Gem disk radius as a fraction of the orbital separation between the two stars. Smak's (1984*b*) radii are indicated by large filled circles for high-accuracy determinations, small filled circles for low-accuracy determinations, and open circles for lower limits. Solid horizontal lines at $R/r_{\rm orbit} = 0.353$ and 0.418 indicate the tidal radii of the disk on the line joining the two stars and 90° away from it, respectively. The dotted horizontal lines indicate the 1 σ uncertainties in the tidal radii. Fitted models with the indicated values of ν and $\tau_0 = \infty$ are shown. Finite values of τ_0 give very similar results.

Anderson 1988



Ichikawa & Osaki 1992

Smak 1984

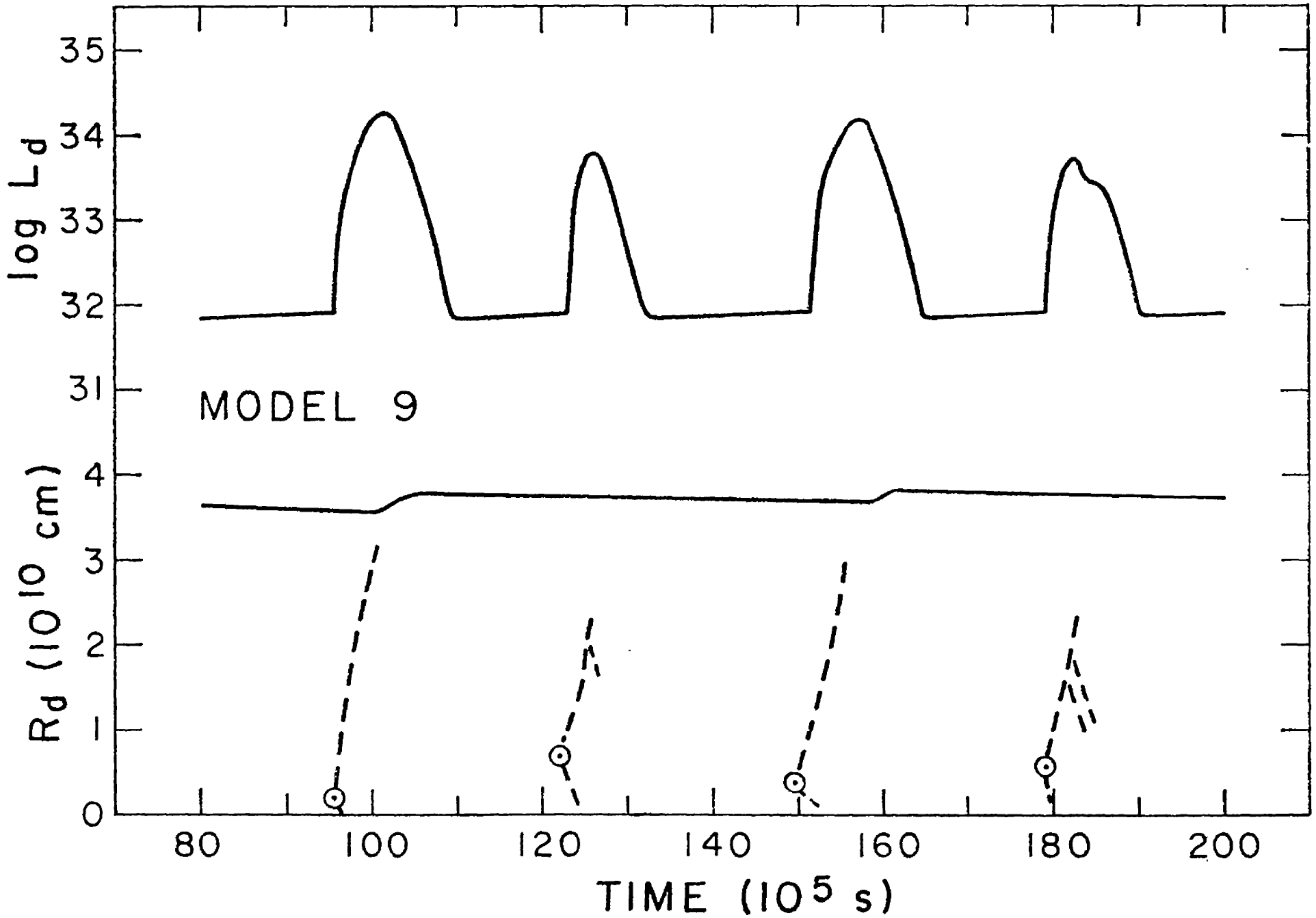
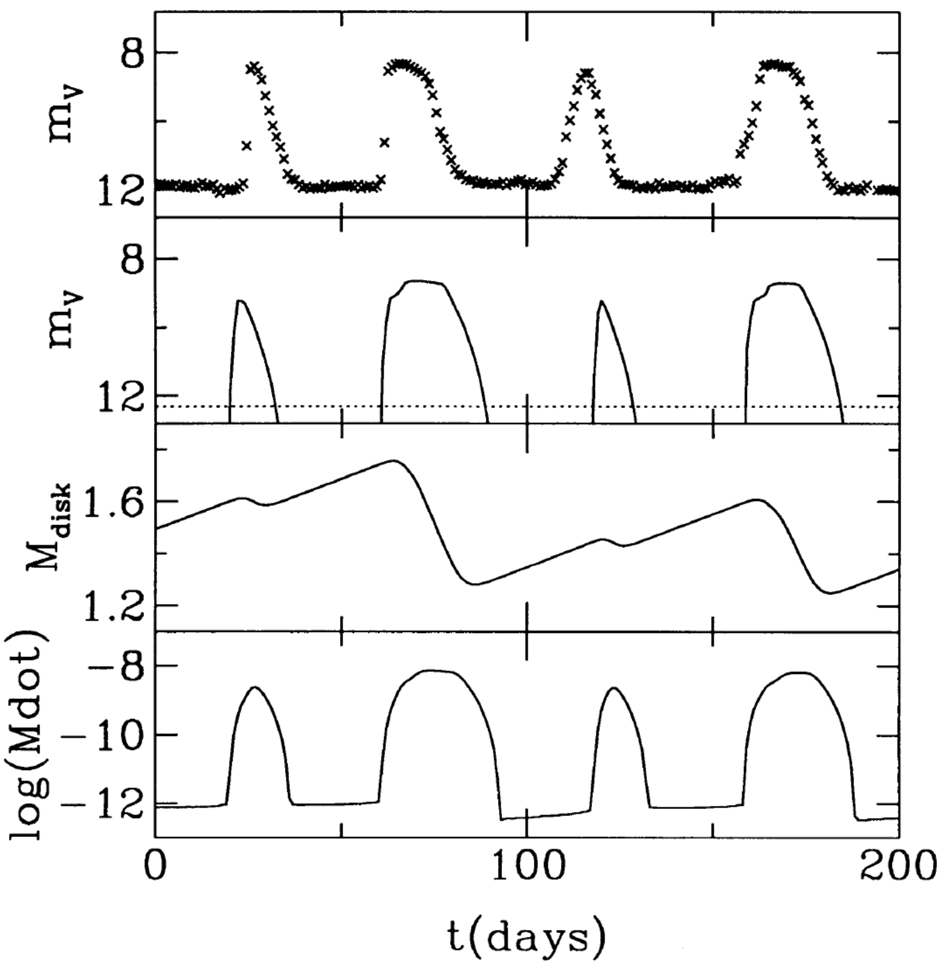
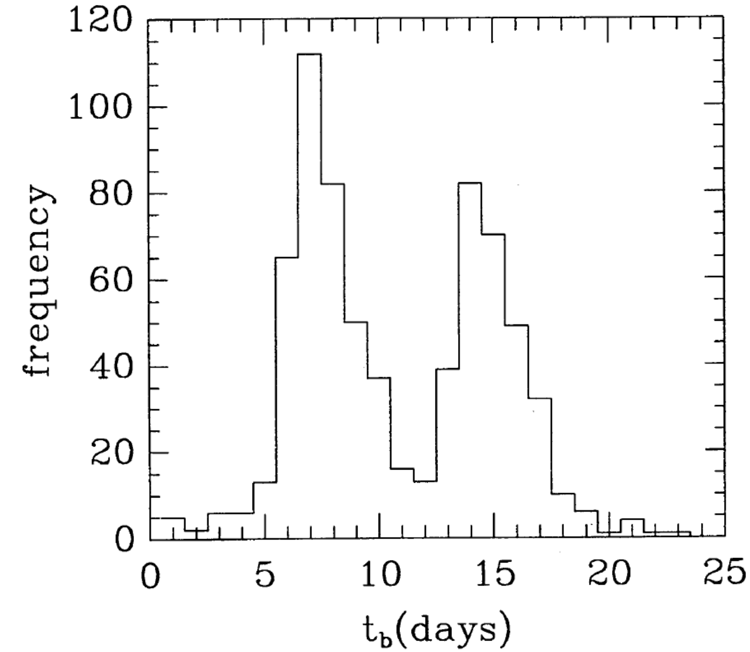


Fig. 3. Dwarf nova behavior of Model 9 (cf. caption for Fig. 2).





JKC & Mattei 1992

JKC 1993

Smak 1984

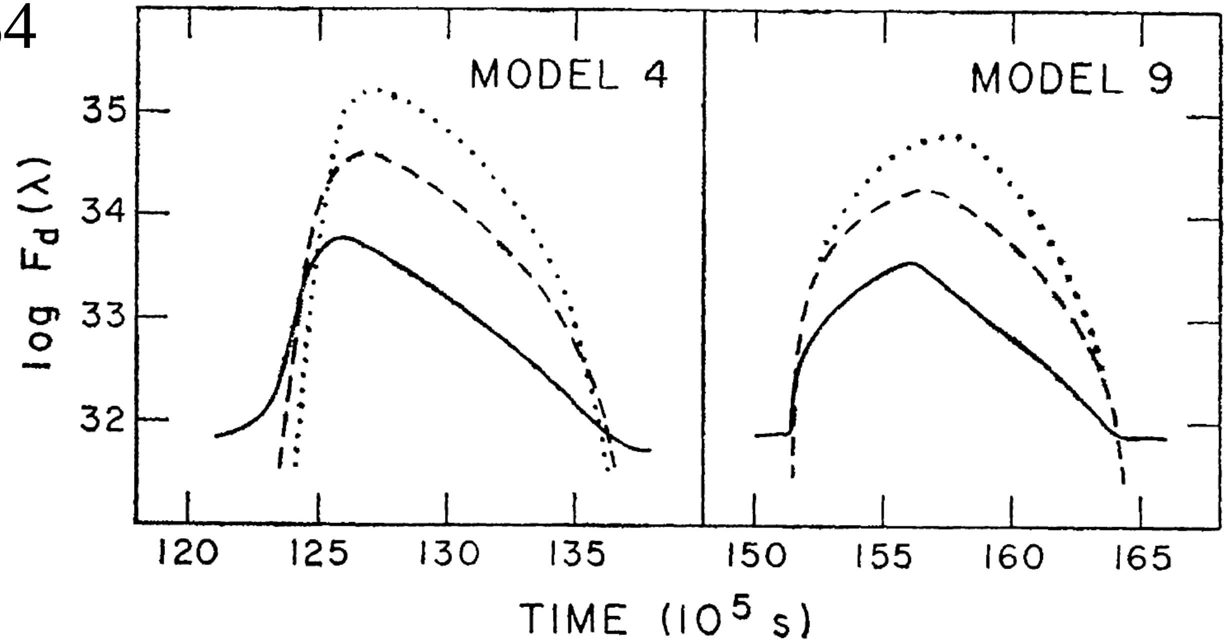
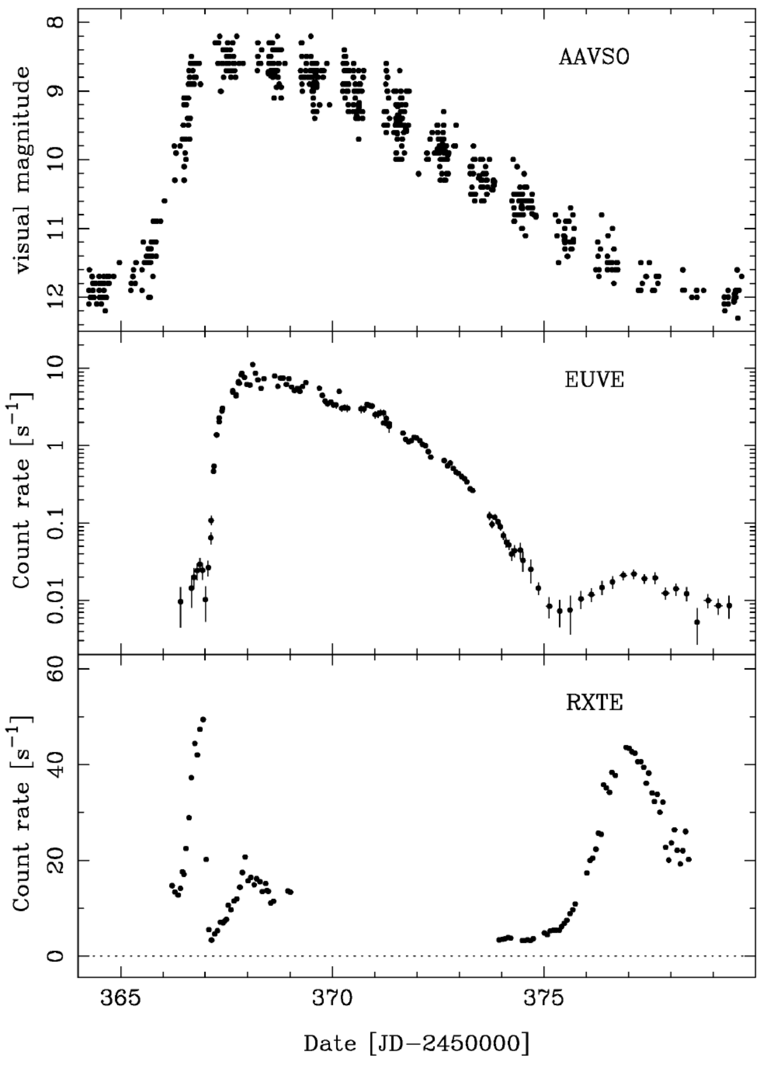
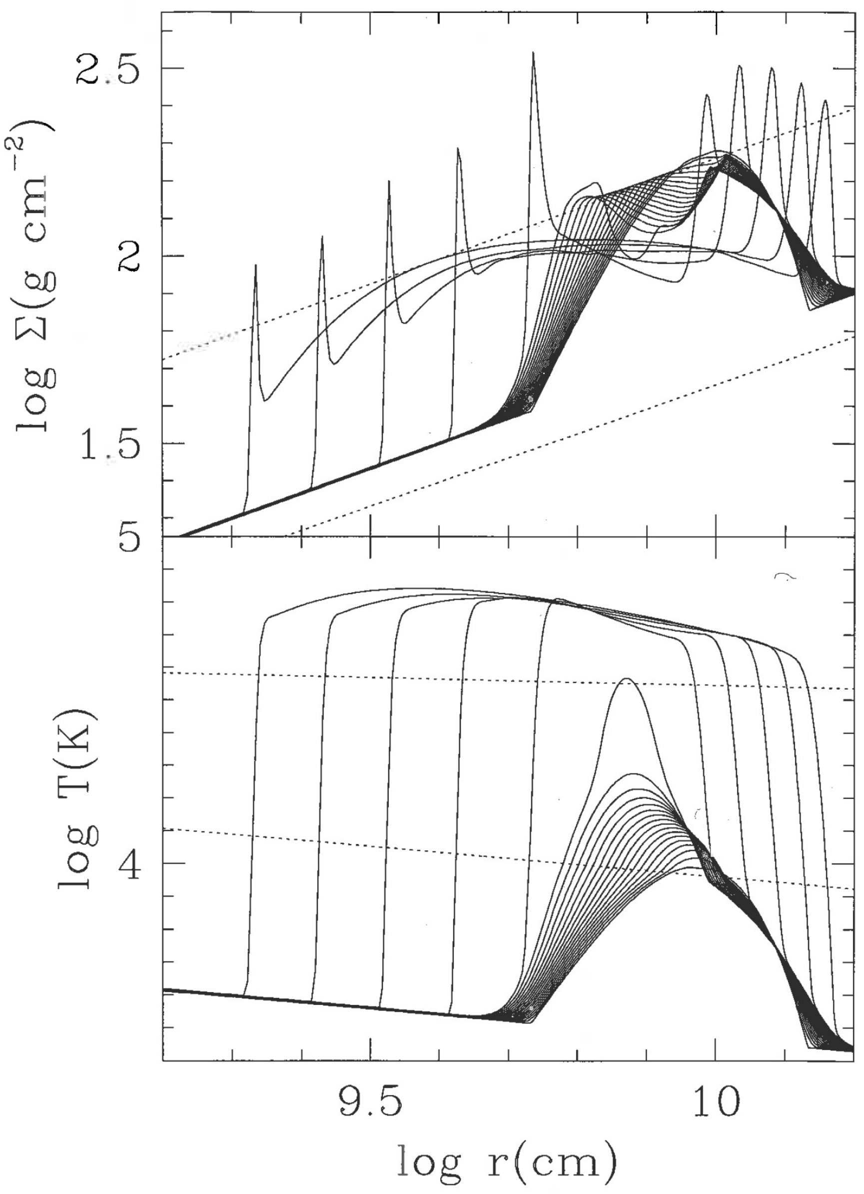


Fig. 5. Monochromatic light curves of model outbursts of Type A (Model 4) and Type B (Model 9). Solid line is for 5500 Å, broken line – 2500 Å, and dotted line – 1200 Å. Note the progression with wavelength in Model 4.

JKC, Wheeler, Polidan 1986 -- Voyager

Pringle, Verbunt, & Wade 1986 -- IUE





Wheatley et al. 2003 -- SS Cyg

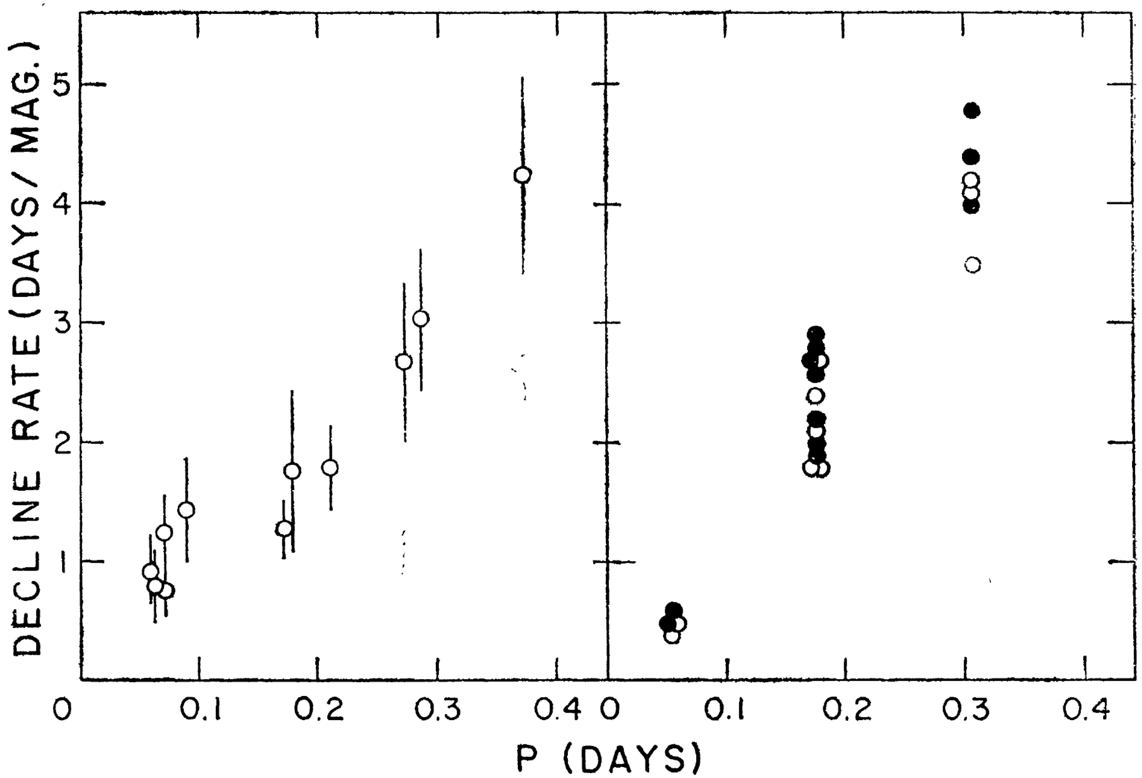


Fig. 9. The rate of decline versus the orbital period relations. Left panel shows the observational data for dwarf novae (Mattei and Klavetter 1982). Right panel — results from models; open circles are for the disk, filled circles — for the disk+spot combination.

King, Pringle, Livio 2007, MNRAS, 376, 1740

``Accretion disc viscosity: how big is alpha?"

Kepler launch:

March 6, 2009

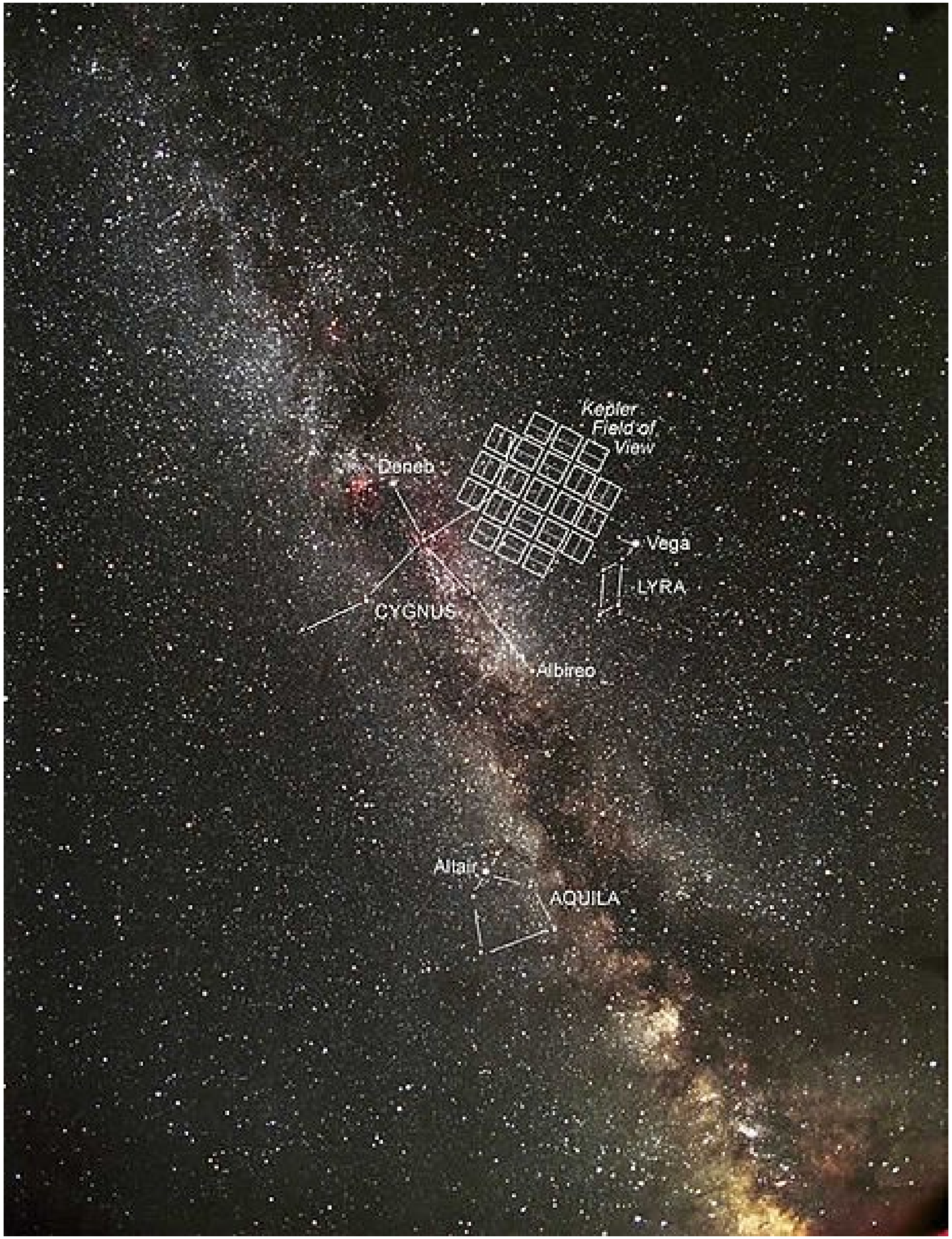
FOV: of 105 deg^2

(~0.25% of sky)

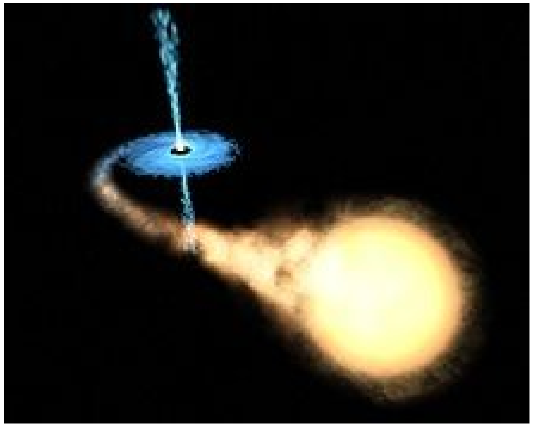
no LMXBs,

HMXBs, WRs, ULXs;

does have ~10 CVs.



Cataclysmic Variables



Semi-detached binaries in which a Roche-lobe overflowing K or M type dwarf loses material onto a WD primary.

Subtypes:

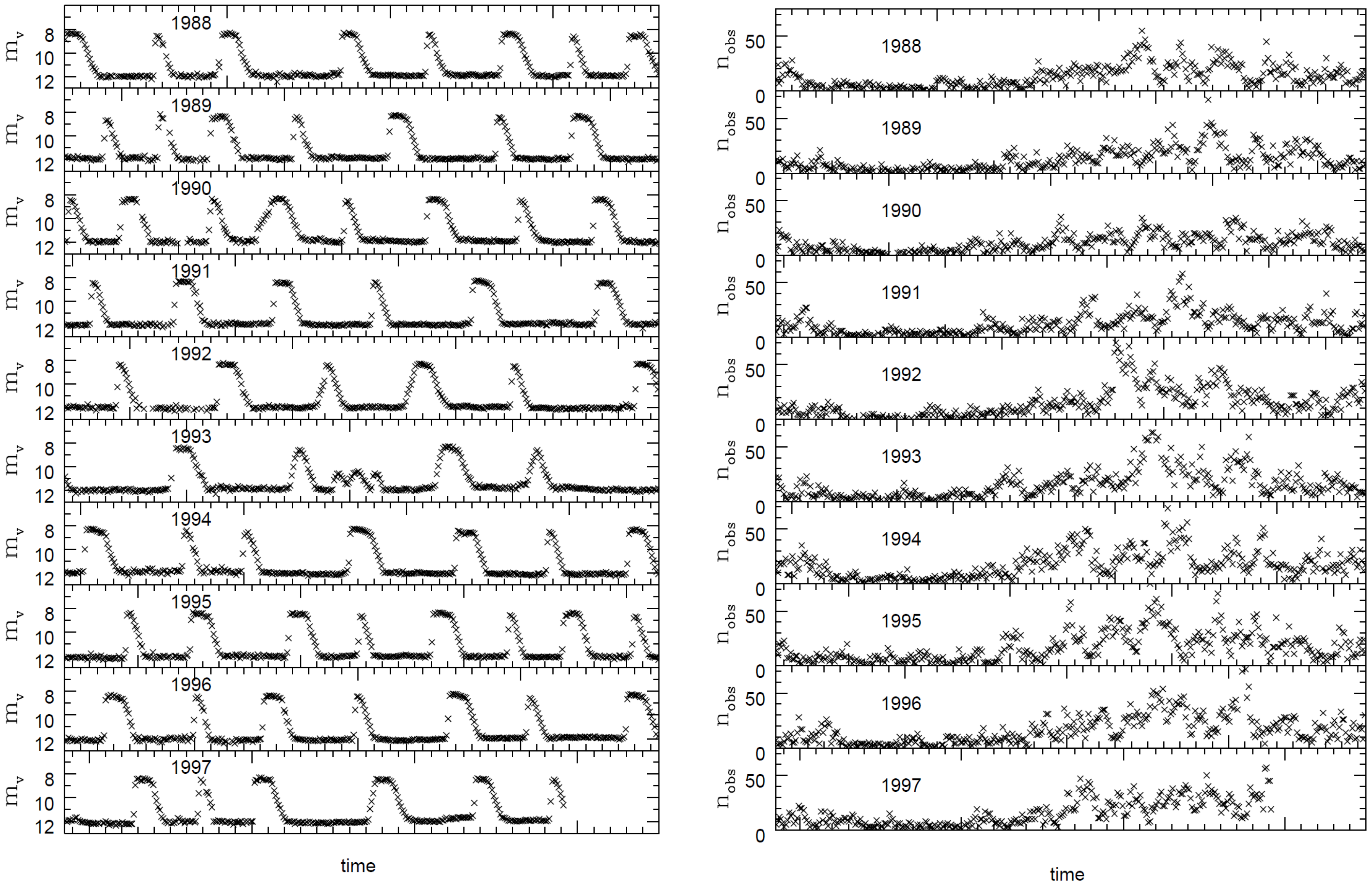
--Nova-like - high dM(2)/dt - disk always in "high state"

--Polar or Intermediate Polar - strong WD B-field prevents accretion disk near WD

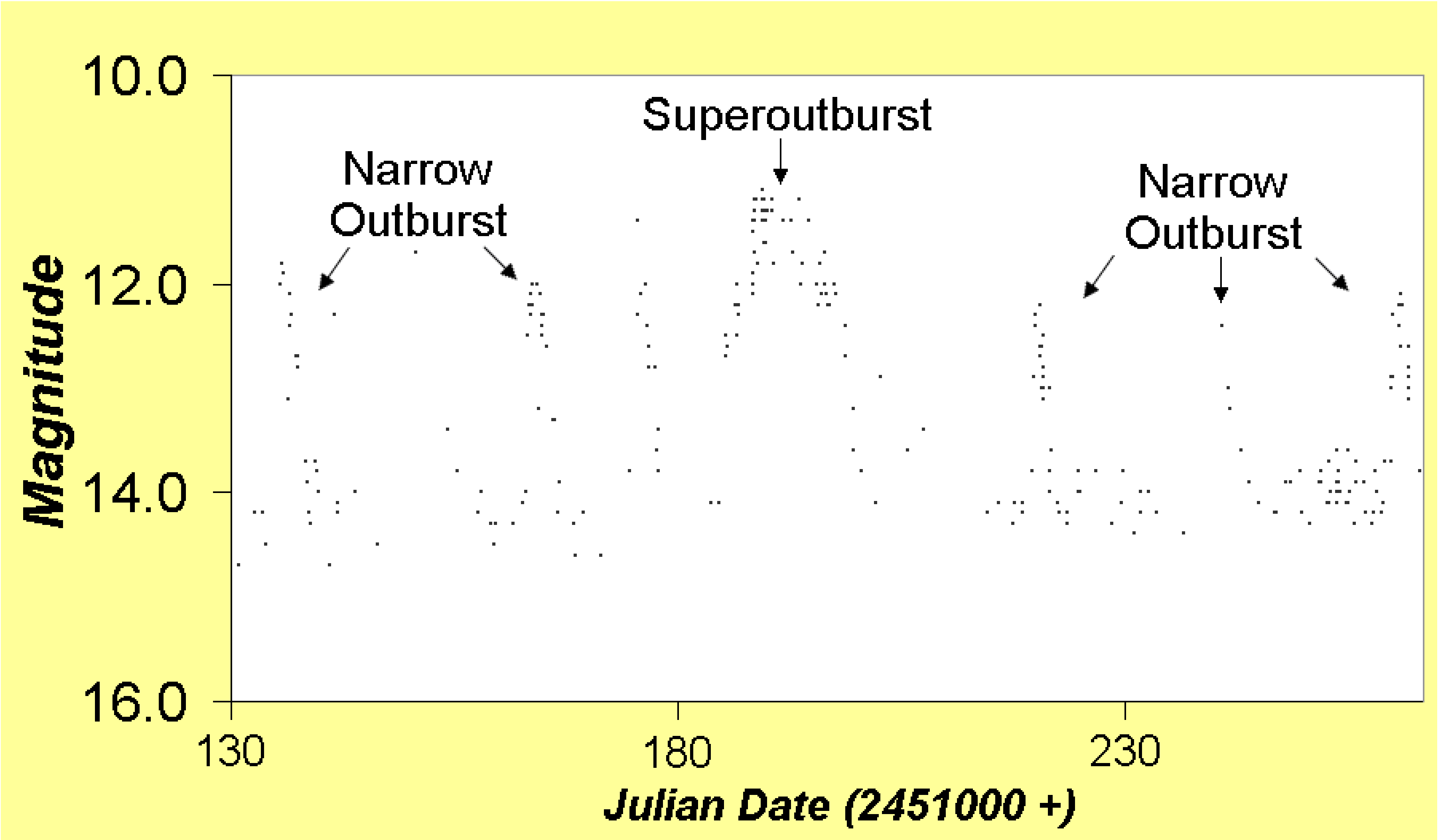
--Dwarf Nova - weak WD B-field, shows outbursts.

Subclass: SU UMa star short orbital period, regular & superoutbursts (superhumps within superoutbursts)

JKC & Mattei (1998)

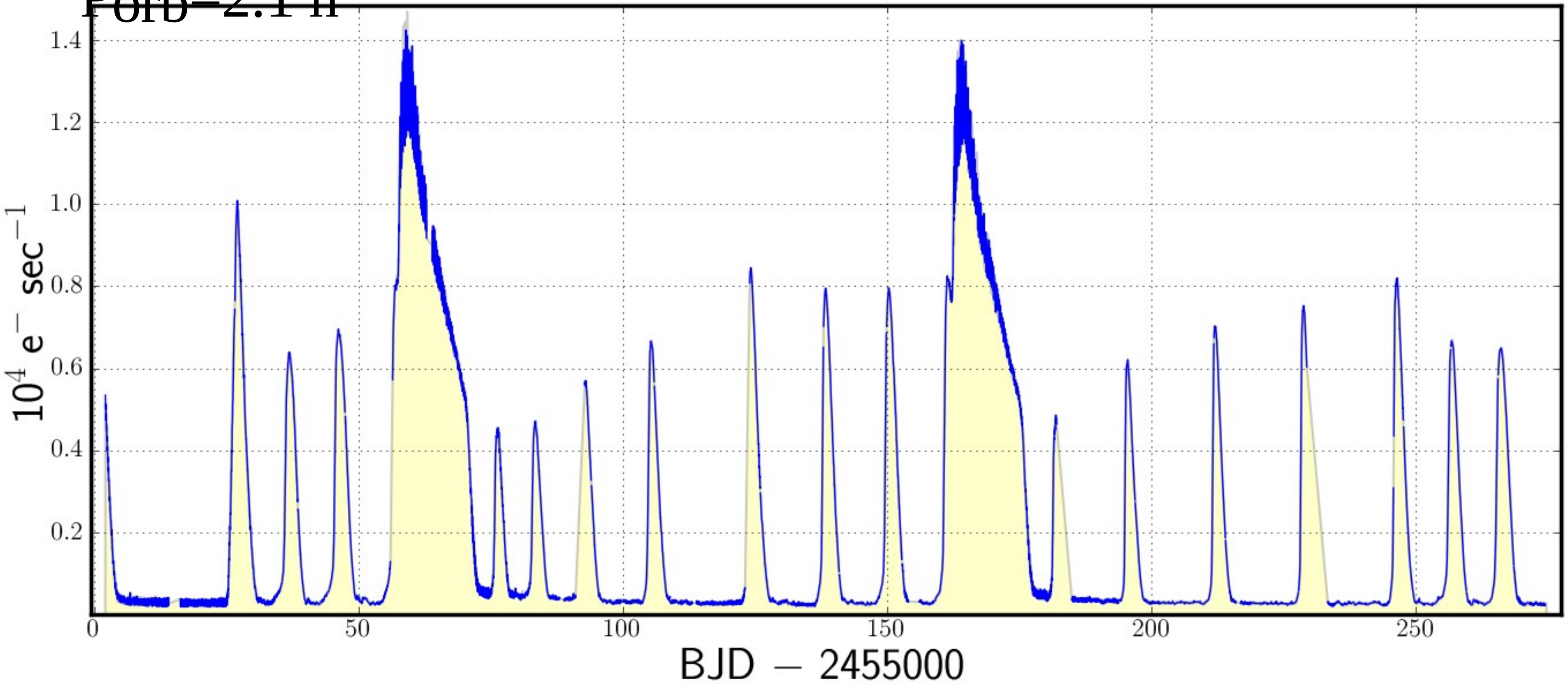


AAVSO light curve of SU UMa (P_{orb}=1.8 h)



Kepler light curve of V344 Lyr: Q2 & Q3

Porb=2.1 h



Aside:

Numerical Modeling of

Dwarf Novae Light Curves:

A few Technical Details

Two Coupled Evolution Equations (1D)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right]$$

where

$$\nu = \frac{2}{3}\frac{\alpha}{\Omega}\frac{\mathcal{R}T}{\mu}$$

$$\frac{\partial T}{\partial t} = \frac{2(A - B + C + D)}{c_p \Sigma} - \frac{\mathcal{R}T}{\mu c_p}\frac{1}{r}\frac{\partial}{\partial r}(r v_r) - v_r \frac{\partial T}{\partial r}$$

$$A = \frac{9}{8}\nu \Omega^2 \Sigma$$

$$C = \frac{3}{2}\frac{1}{r}\frac{\partial}{\partial r}\left(c_p \nu \Sigma r \frac{\partial T}{\partial r}\right)$$

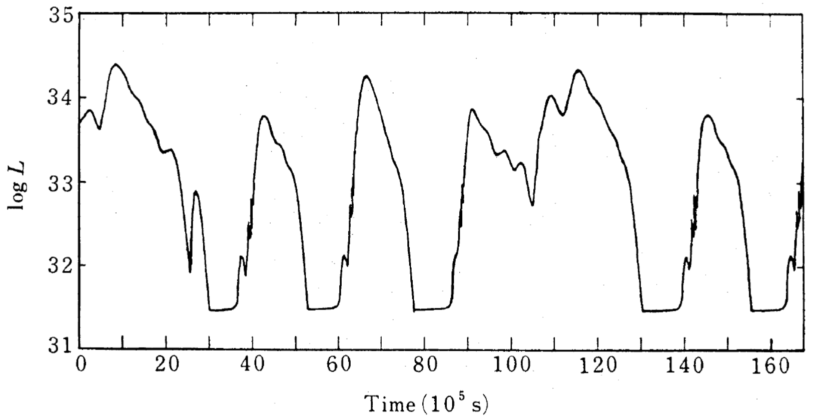
$$B = \sigma T_e^4$$

$$D = \frac{h}{r}\frac{\partial}{\partial r}\left(r \frac{4acT^3}{3\kappa_R \rho}\frac{\partial T}{\partial r}\right)$$

Systematic Effects: Number of Grid Points

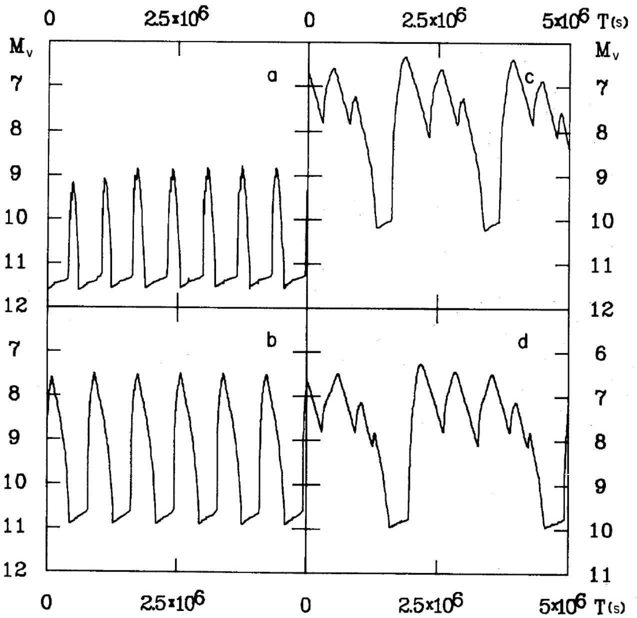
Mineshige & Osaki (1985)

N=22

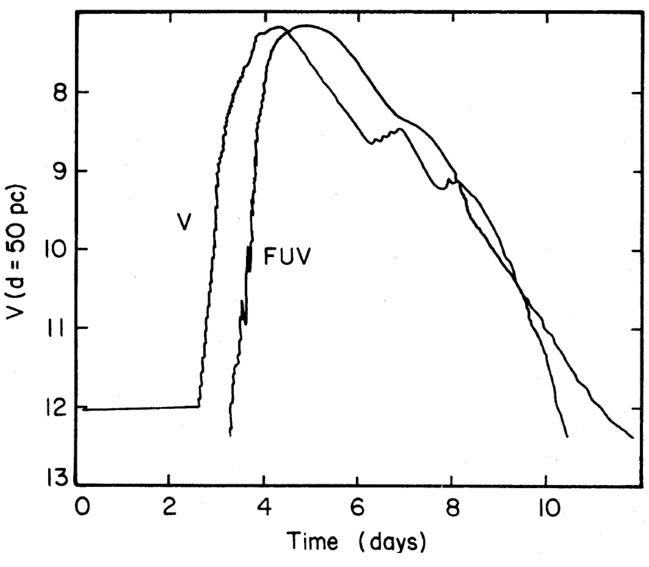


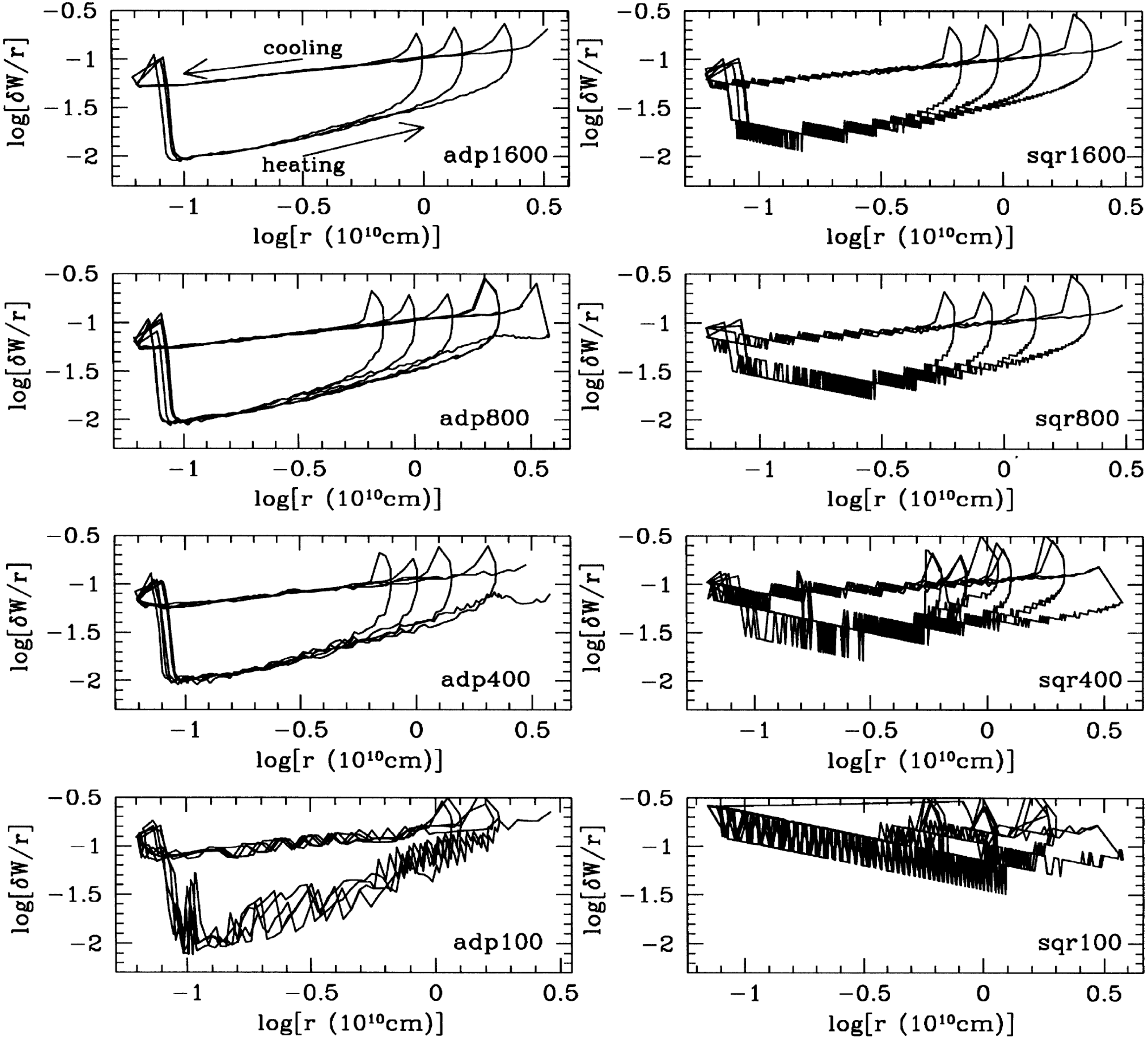
Lin, Papaloizou, & Faulkner (1985)

N=35



JKC, Wheeler, Polidan (1986) N=44





Hameury et al. (1998)

α_{cold} - α_{hot} interpolation:

Logarithmic: $$\log_{10}\alpha(r) = \log_{10}\alpha_{\rm cold} + f$$

$$f = \frac{T - T(\Sigma_{\rm max})}{T(\Sigma_{\rm min}) - T(\Sigma_{\rm max})}(\log_{10}\alpha_{\rm hot} - \log_{10}\alpha_{\rm cold})$$

$$f = \left[1 + \left(\frac{T_0}{T}\right)^8\right]^{-1}(\log_{10}\alpha_{\rm hot} - \log_{10}\alpha_{\rm cold})$$

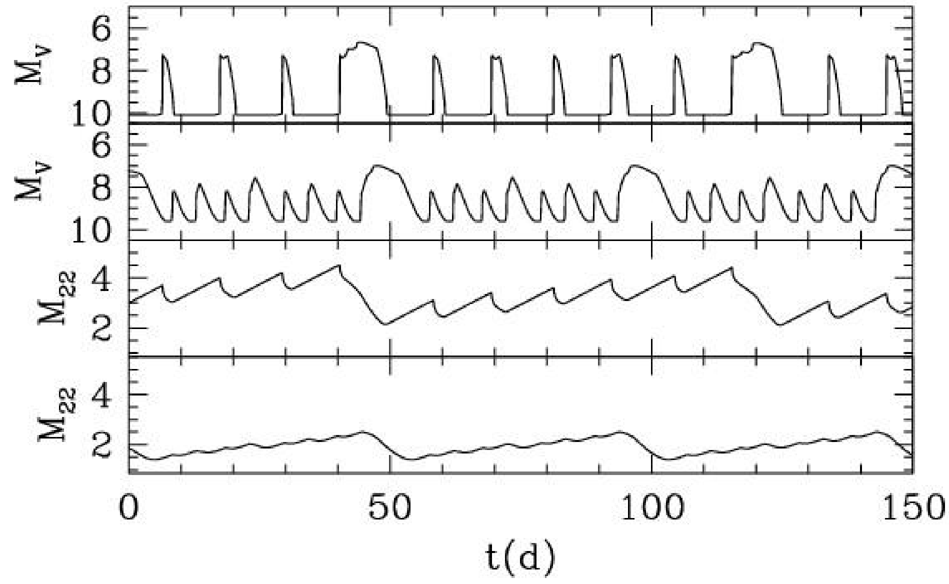
Hameury et al. (1998)

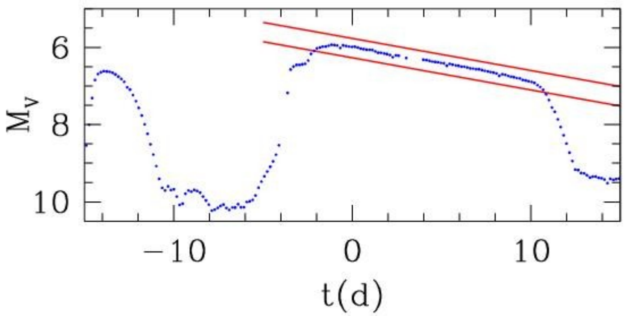
$$\alpha(r) = \alpha_{\rm cold} + \frac{T - T(\Sigma_{\rm max})}{T(\Sigma_{\rm min}) - T(\Sigma_{\rm max})}(\alpha_{\rm hot} - \alpha_{\rm cold})$$

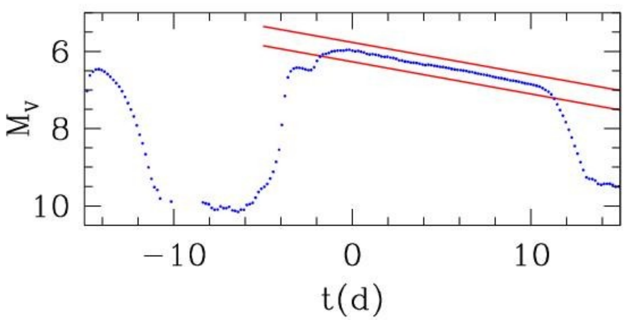
Systematics: Interpolation method

Logarithmic:

Linear:







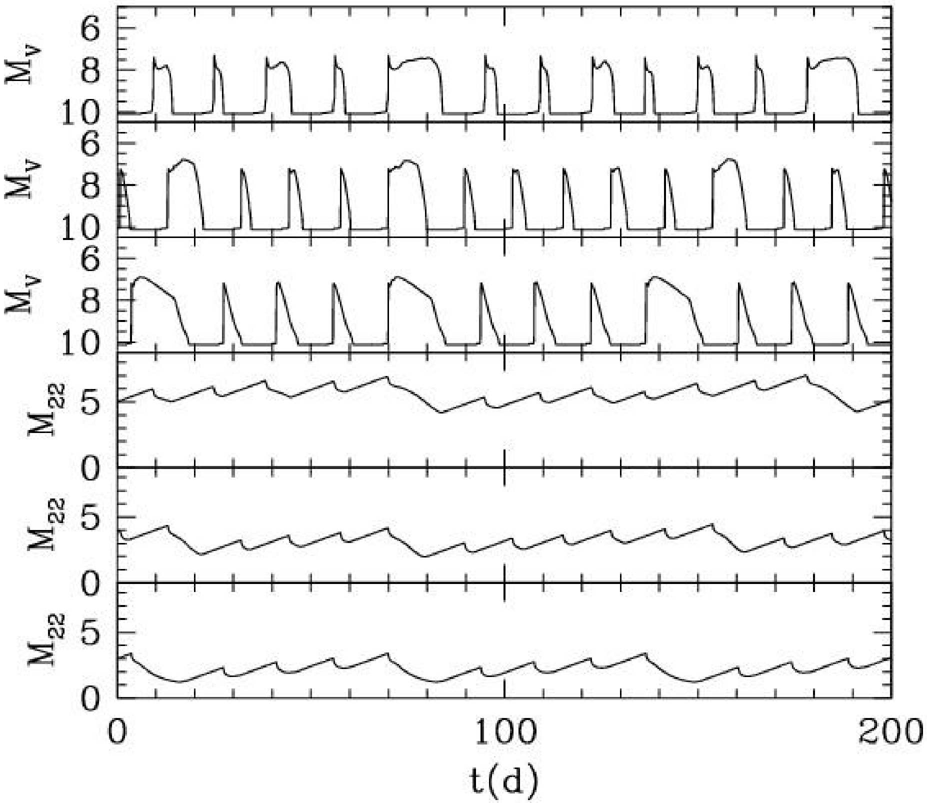
Systematics: Interpolation

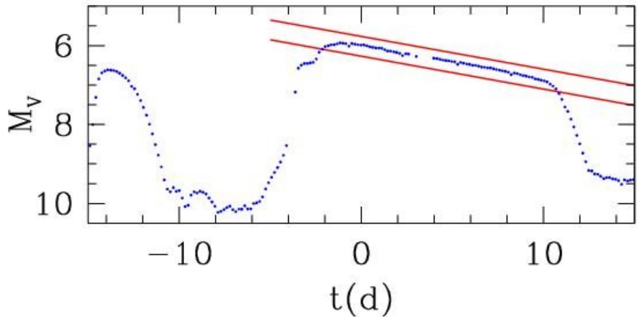
T0=25000 K

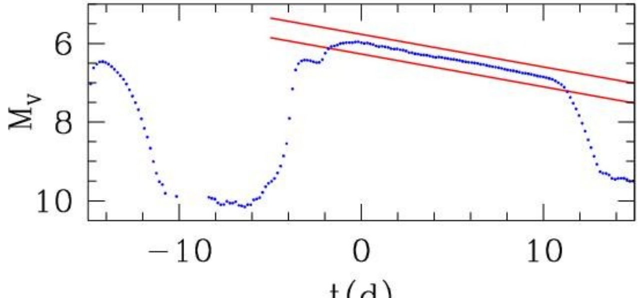
Hameury et al. (1998) 18750 K

prescription 12500 K

$$f = \left[1 + \left(\frac{T_0}{T}\right)^8\right]^{-1} (\log_{10}\alpha_{\rm hot} - \log_{10}\alpha_{\rm cold})$$





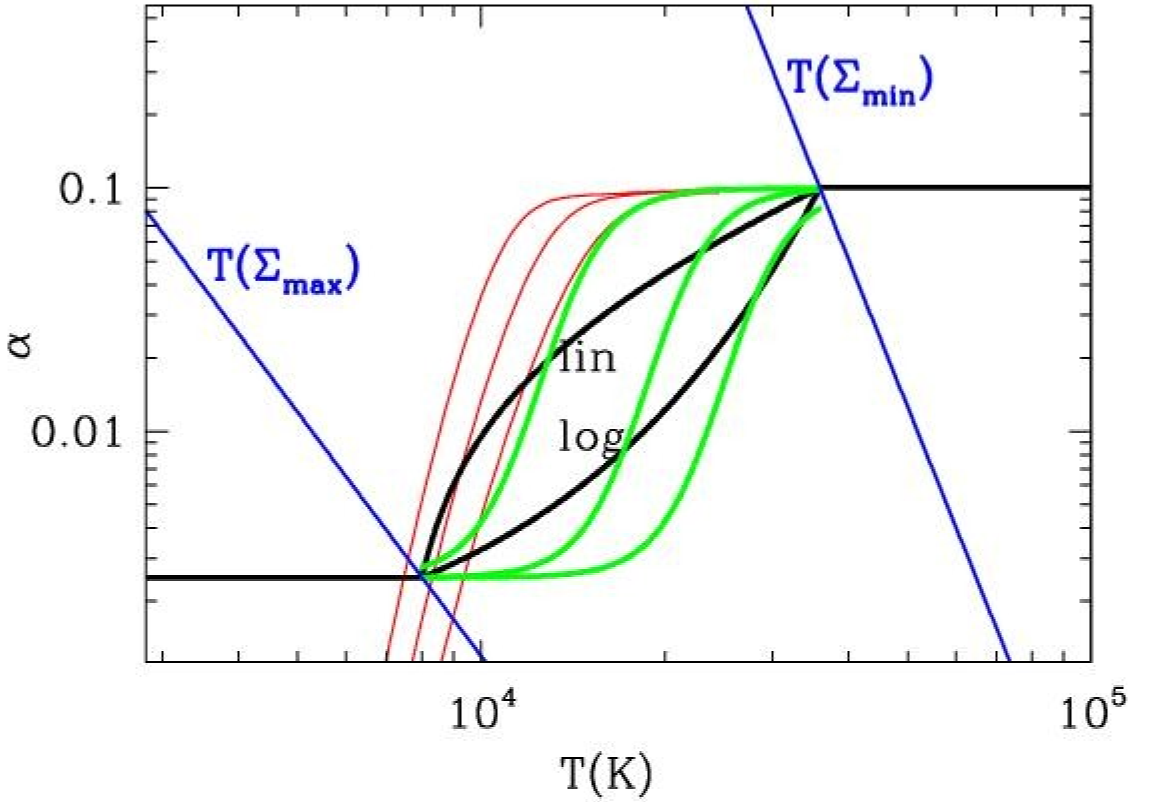


Green: H98

12500 K

18750 K

25000 K



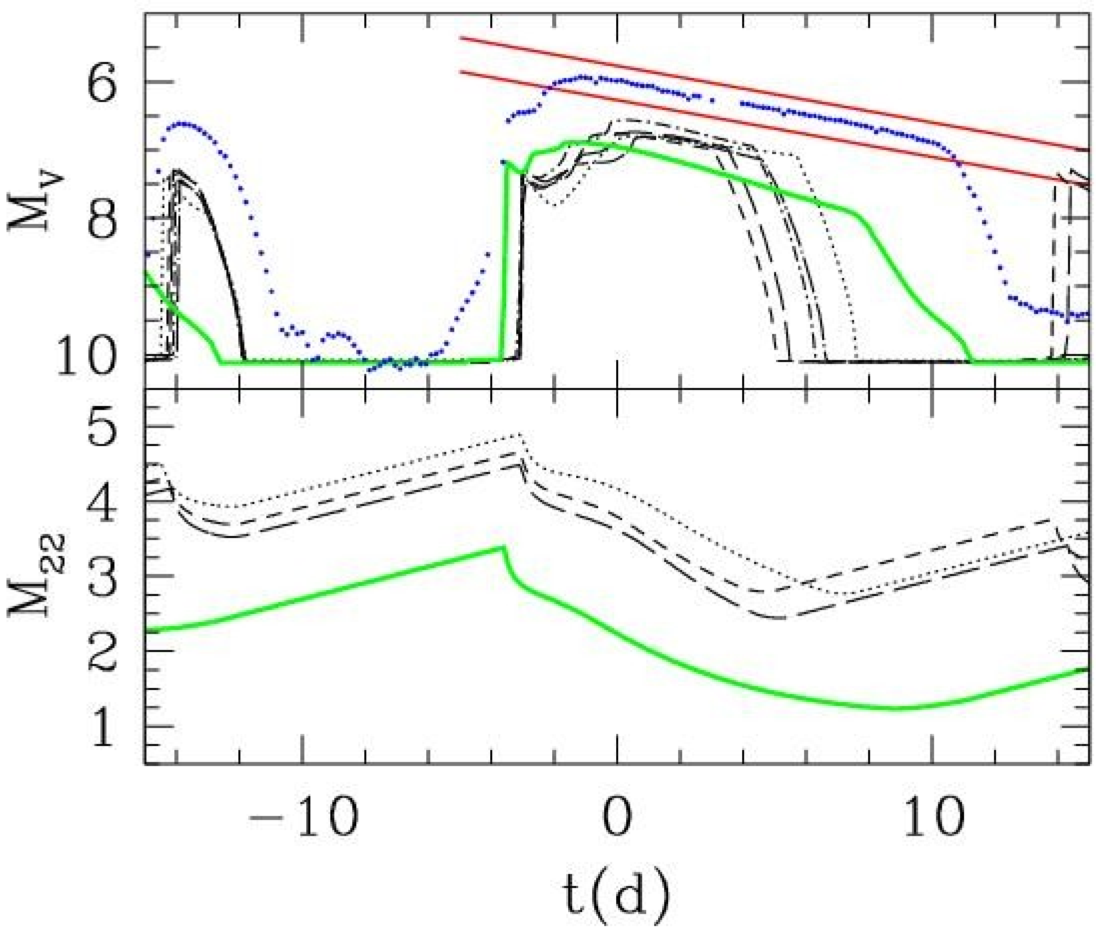
Red: Ionization fraction

$\rho=10^{-8}, 10^{-7}, 10^{-6}$ g cm^{-3}

MRI motivated prescription should also include local growth rate $[\Omega(r)]^{-1}$

Green: H98

with T0=12500 K

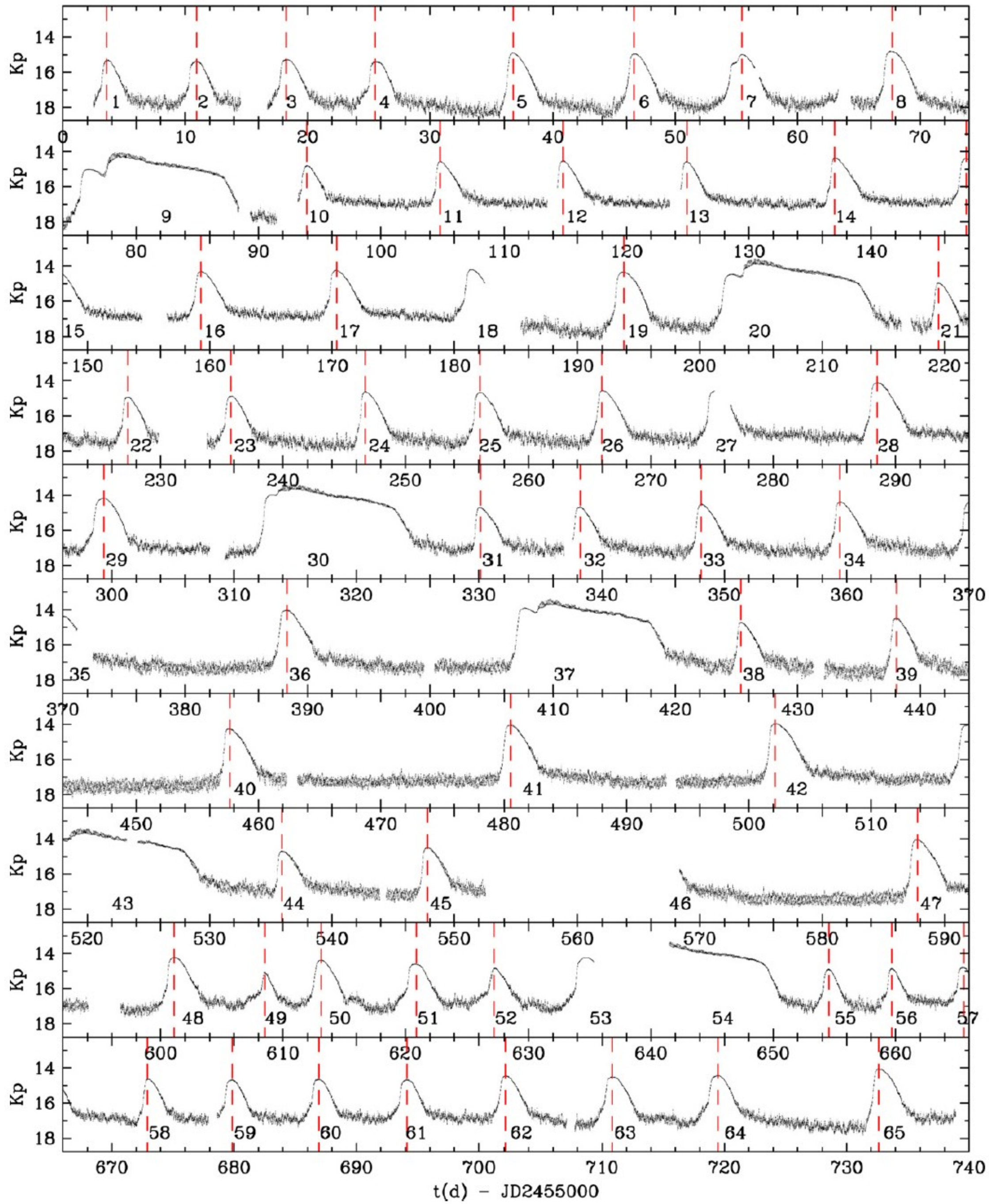


JKC et al. 2012

V1504 Cyg

-- 2 yr at

1 min. cadence

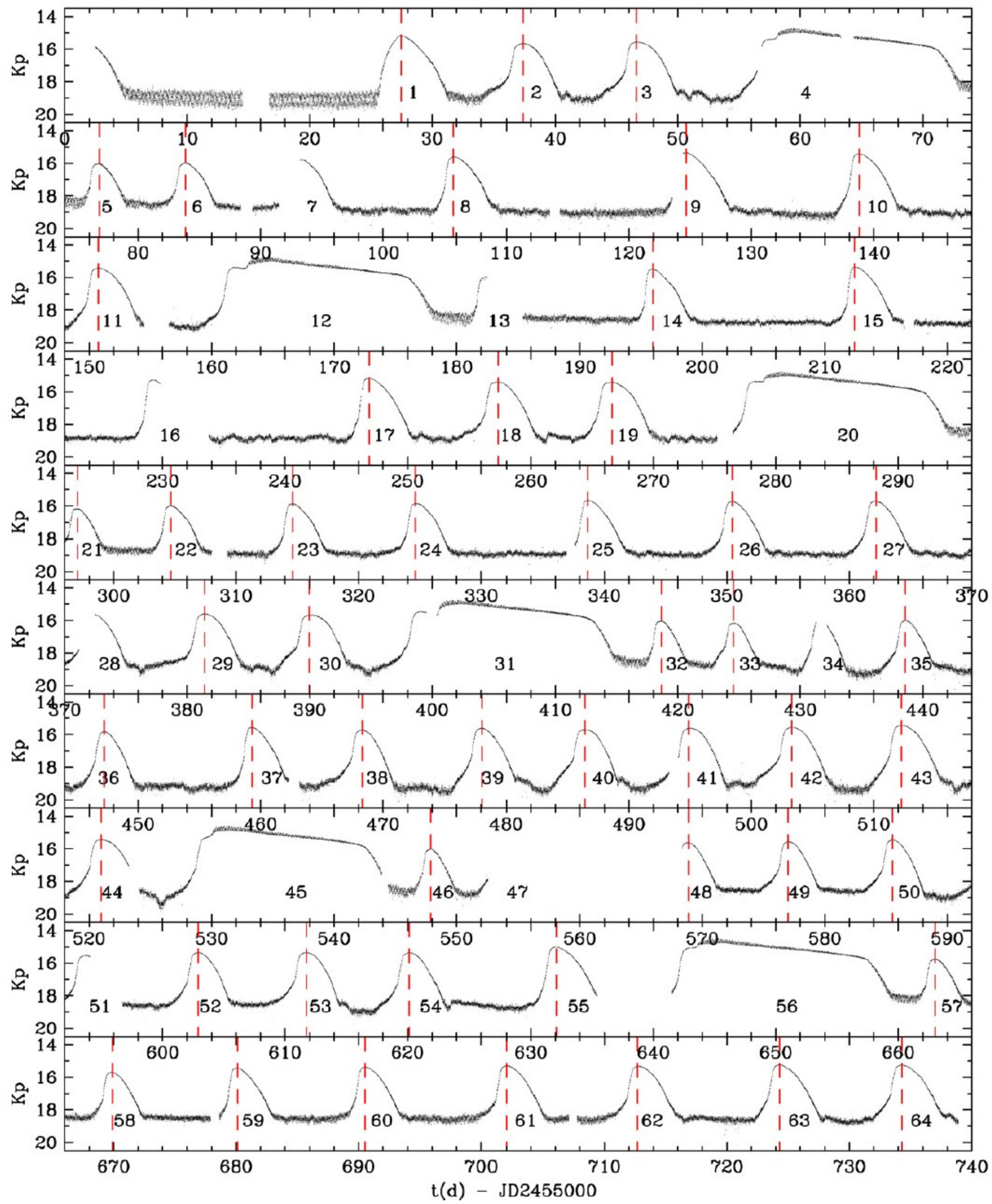


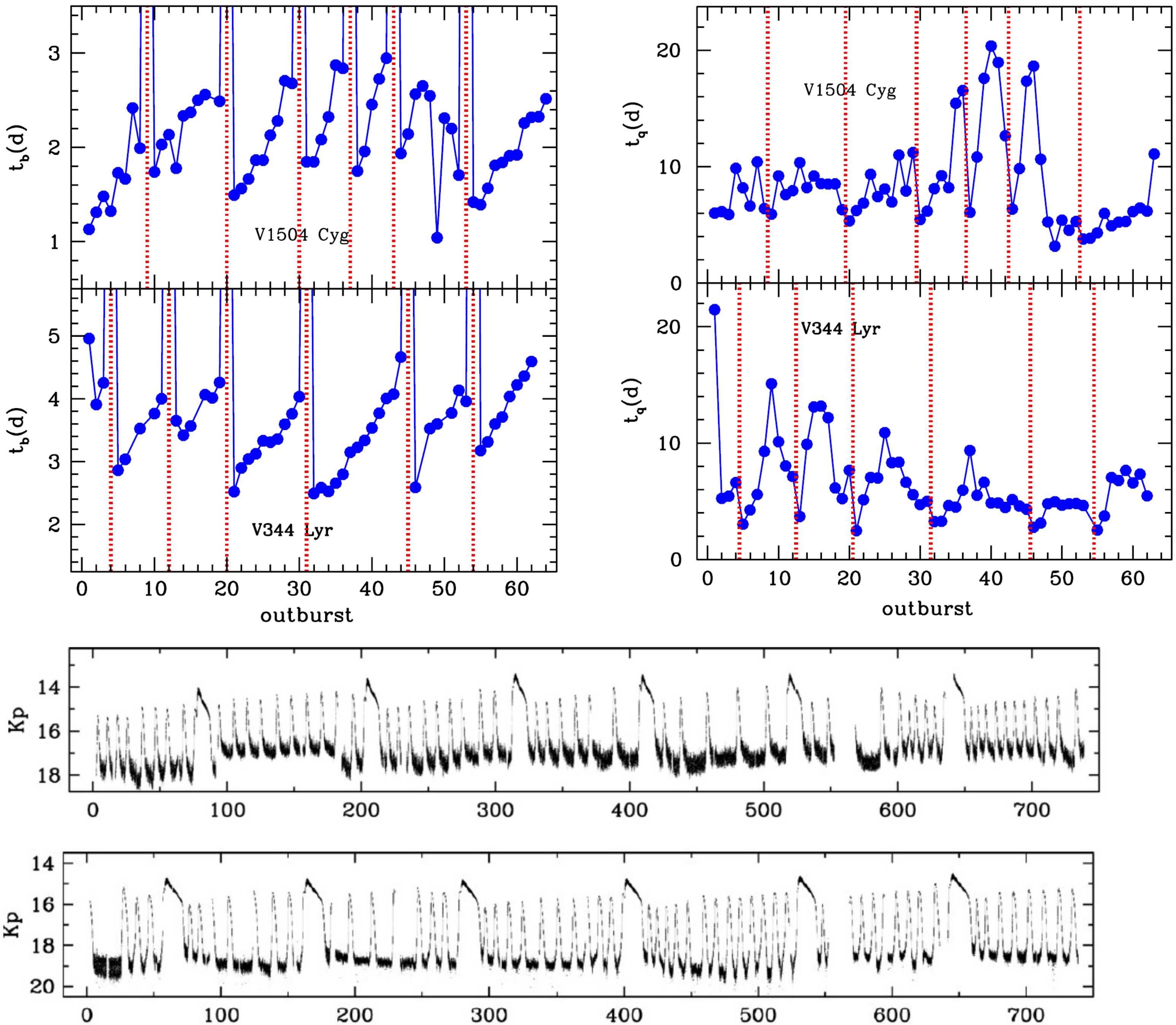
JKC et al. 2012

V344 Lyr

-- 2 yr at

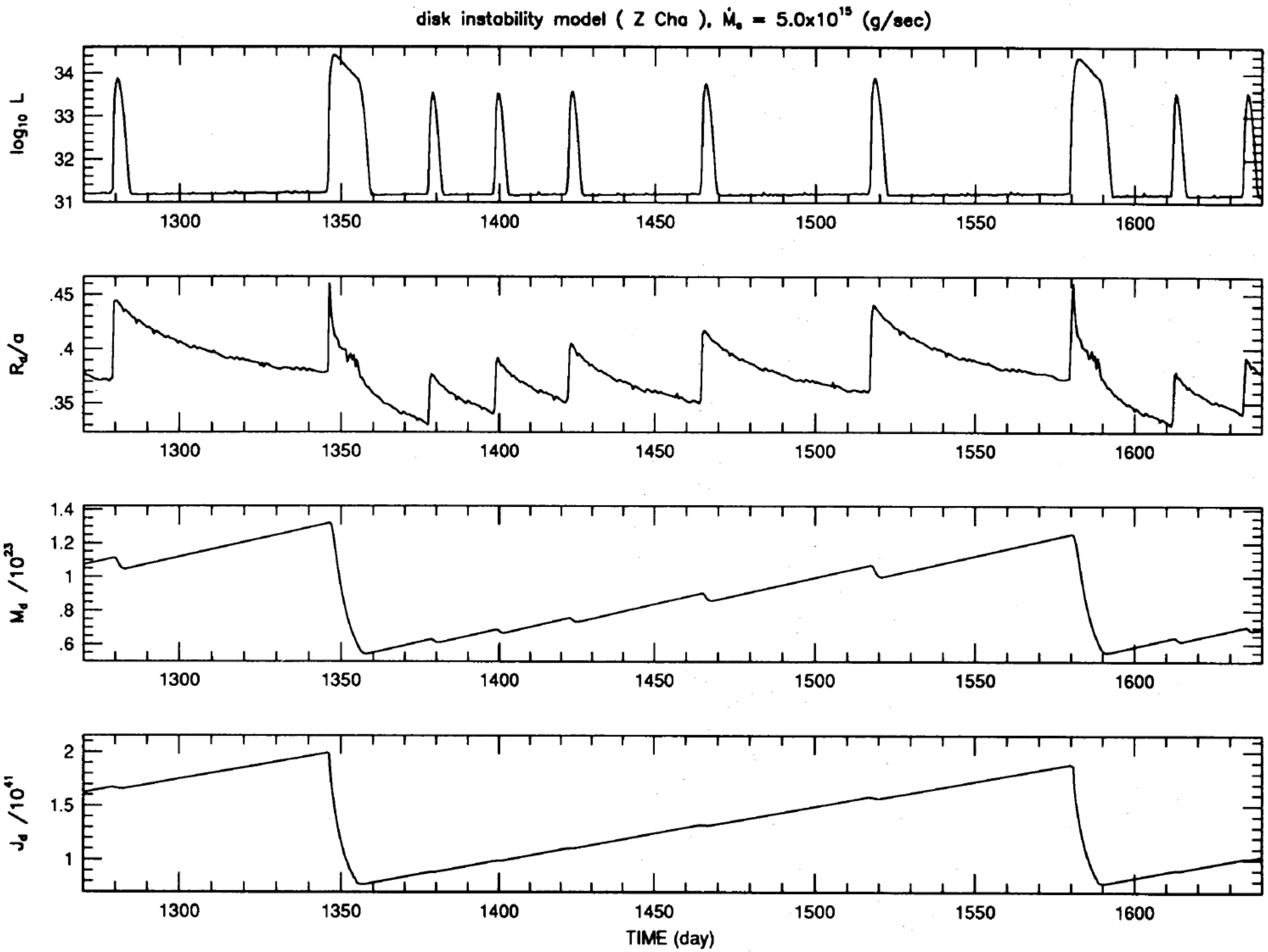
1 min. cadence



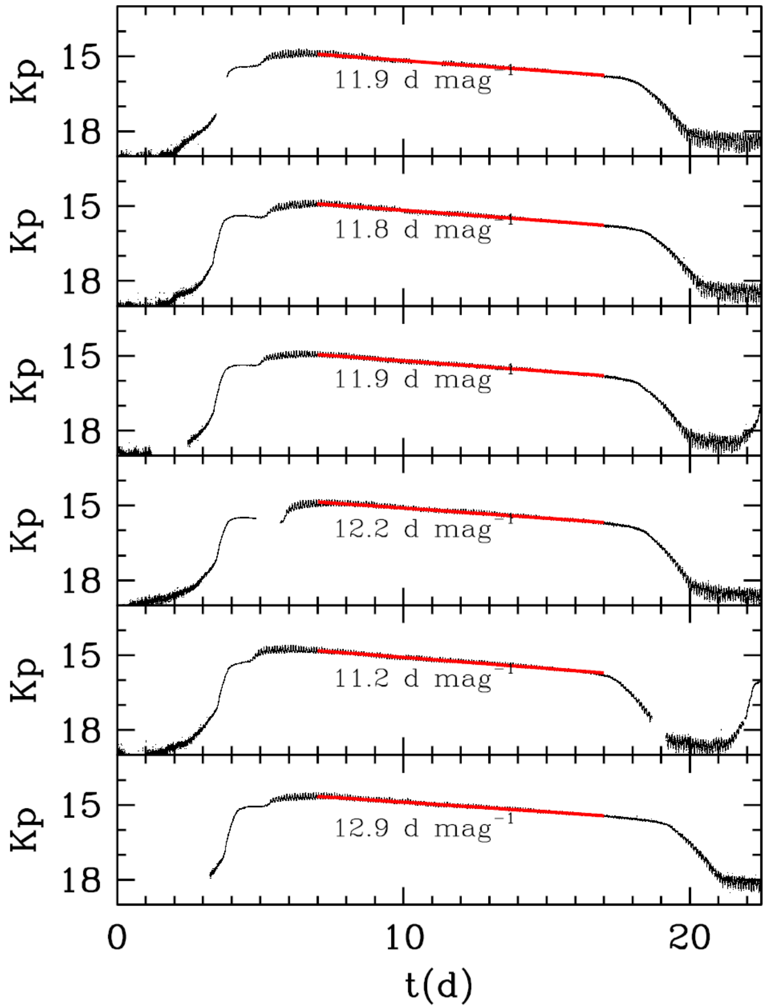


V1504 Cyg
V344 Lyr
V1504 Cyg
V344 Lyr
t_b(d)
t_b(d)
t_q(d)
t_q(d)
outburst
outburst
Kp
Kp

Ichikawa, Hirose, & Osaki (1993)



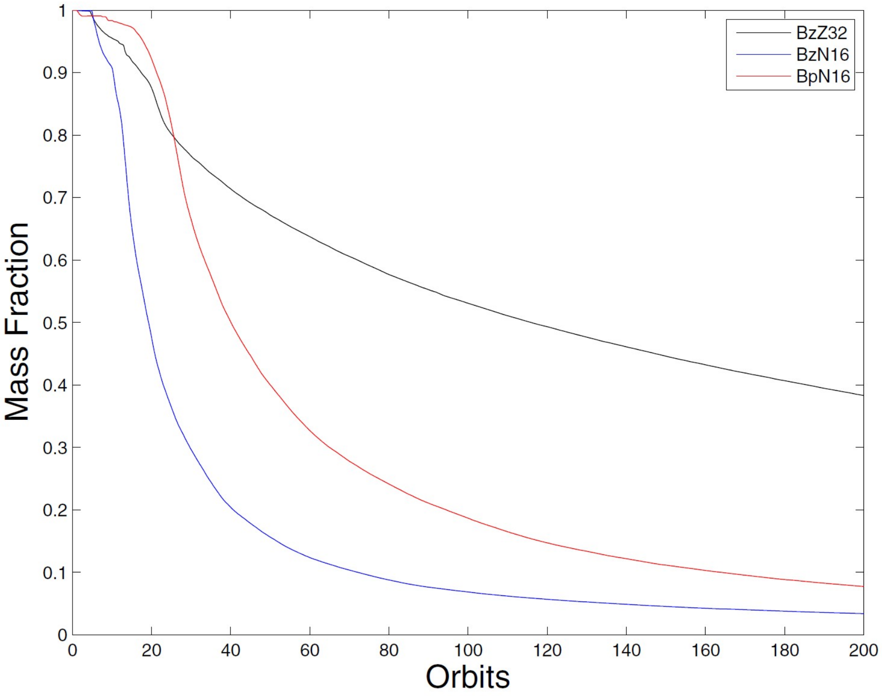
JKC et al. 2012



V344 Lyr: t(e)/t(orb) ~10^3

Sorathia et al. 2012

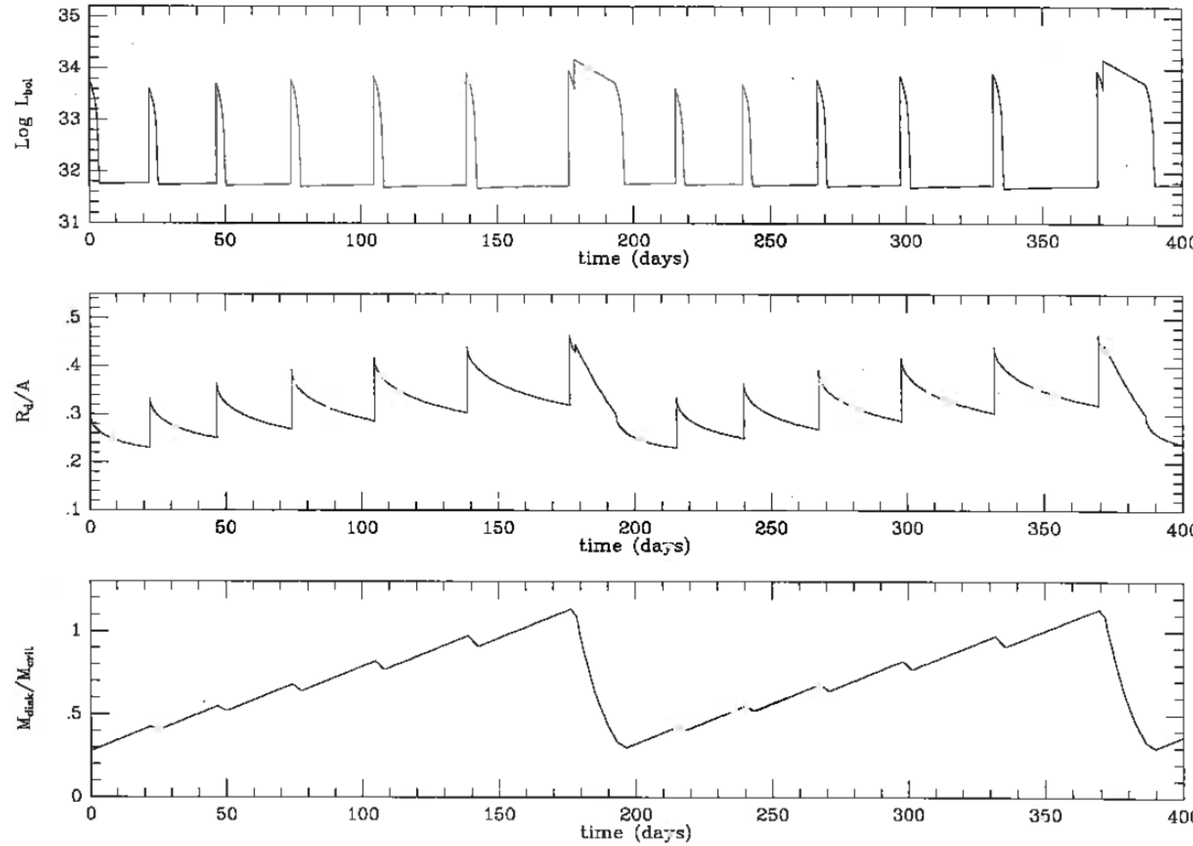
Global MRI simulations:

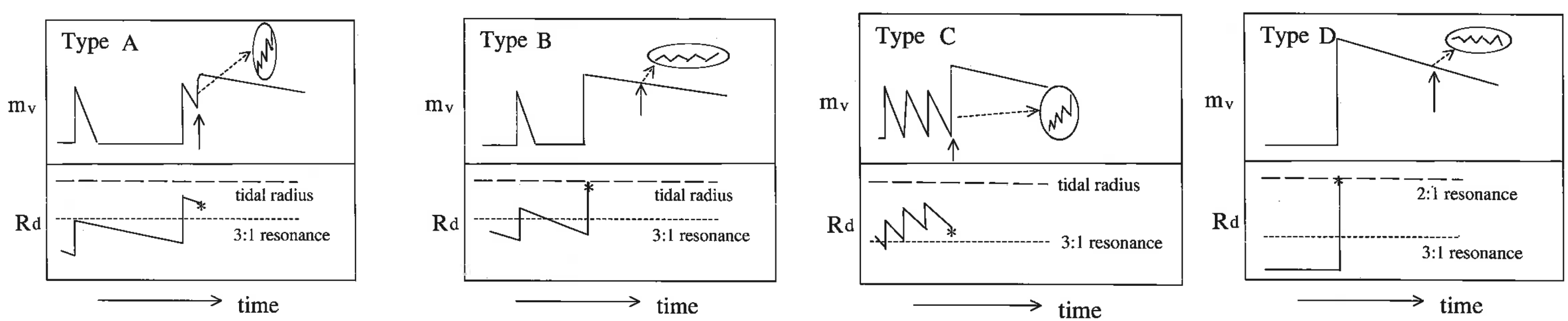


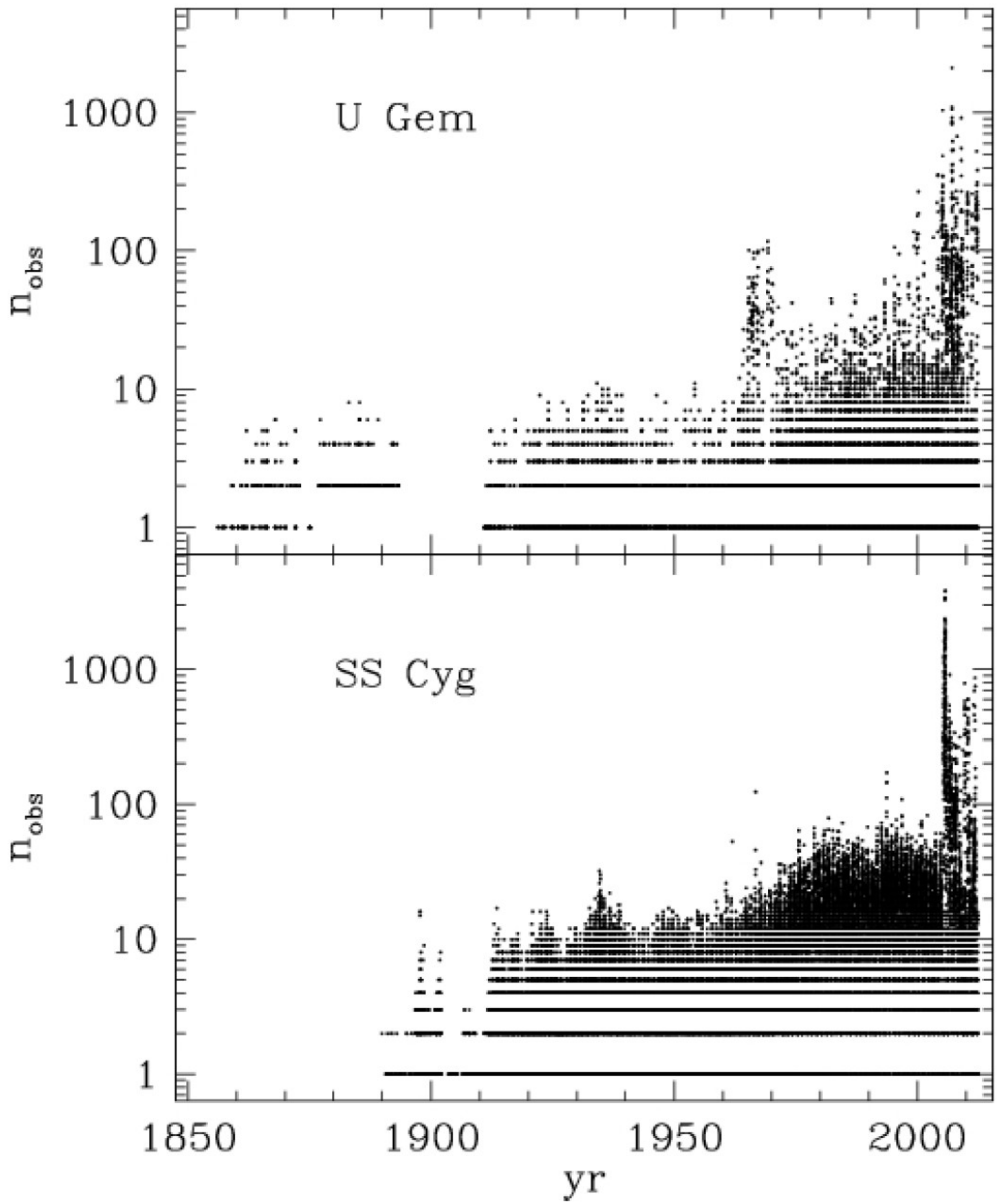
t(e)/t(orb) ~ 10^2

Osaki 2005

TTI:

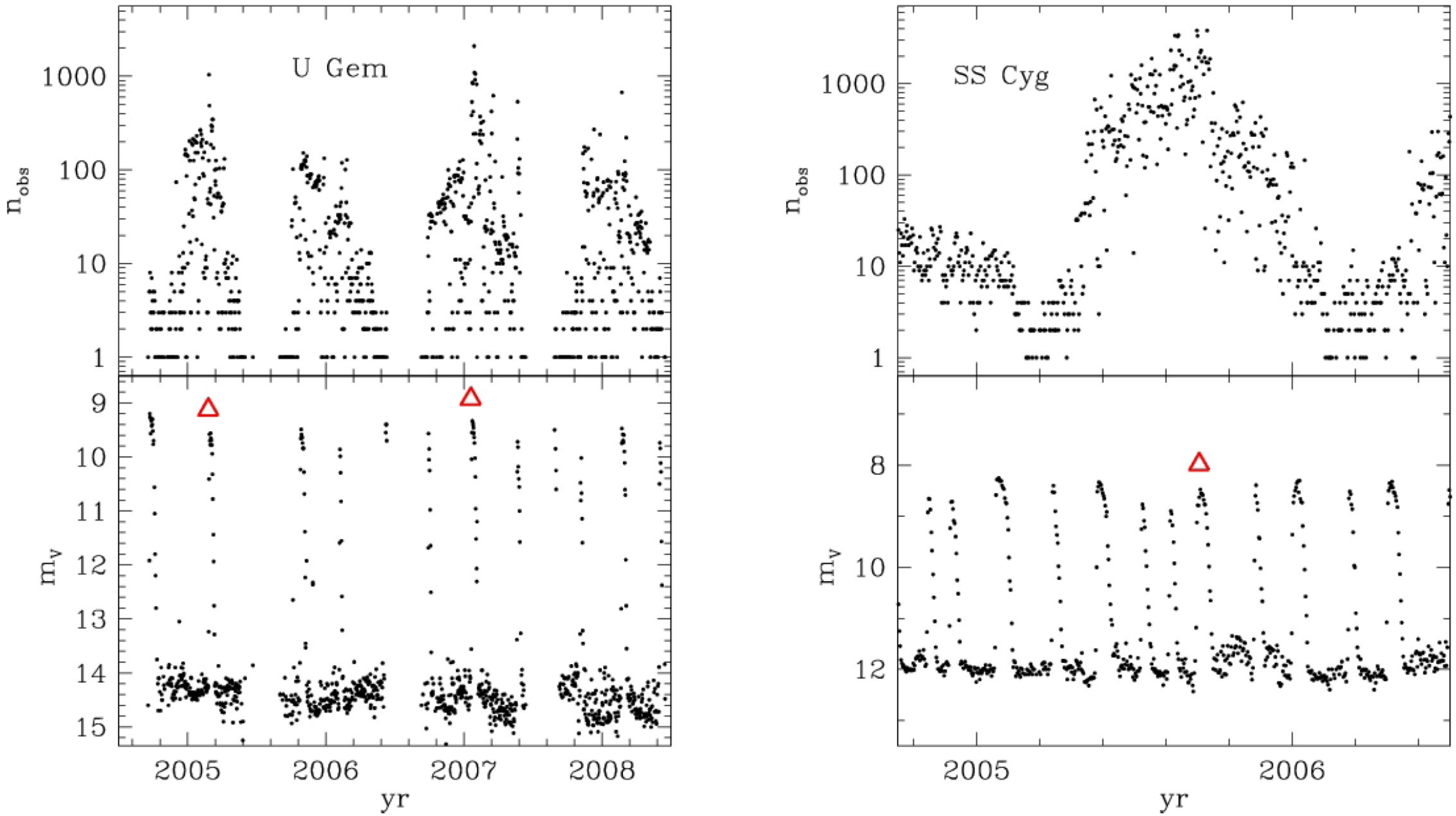


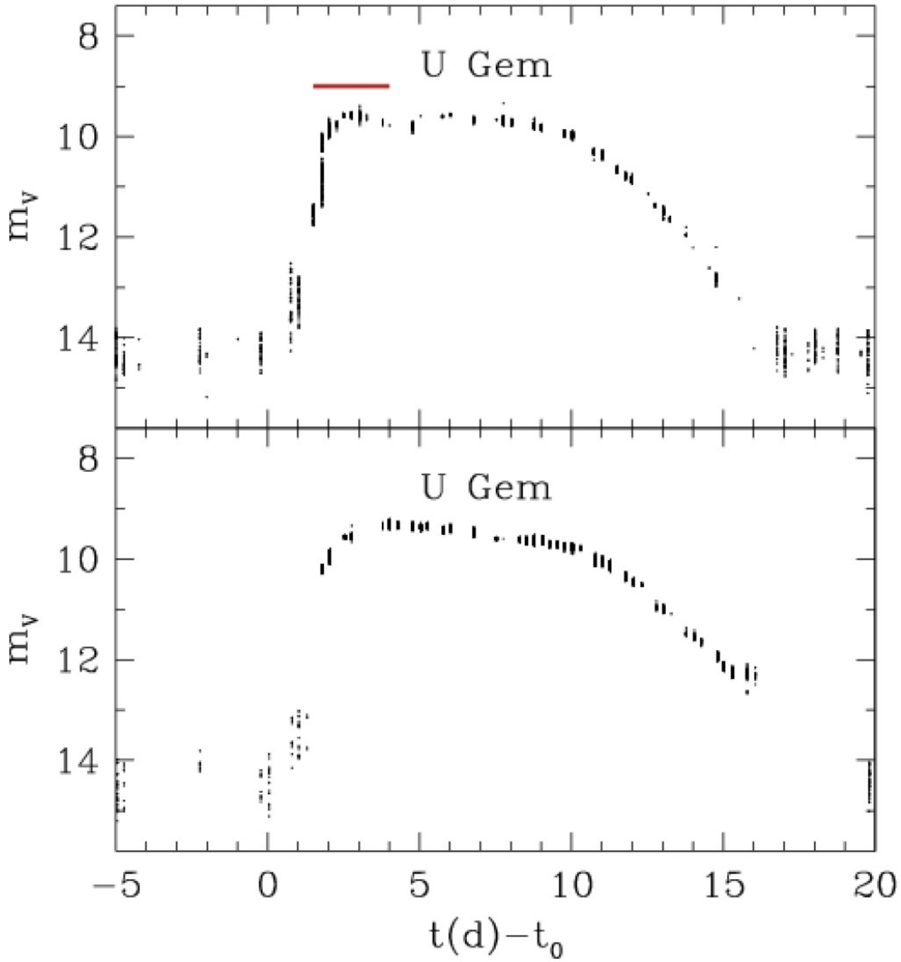


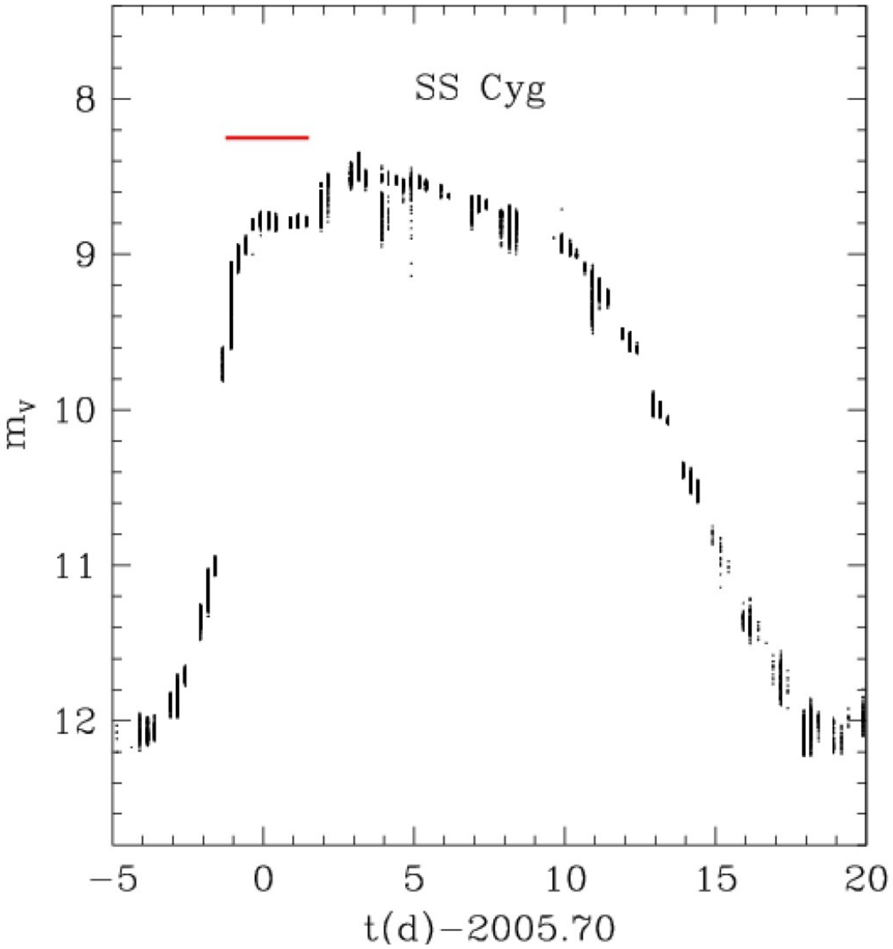


JKC 2012

Q: Is there any hope at being able to find embedded precursors in other data - e.g. AAVSO?


U Gem
SS Cyg
n_{obs}
m_V
yr
1000
100
10
1
9
10
11
12
13
14
15
8
2005
2006
2007
2008





P(h)=4.25 hr

P(h)=6.60 hr

Summary:

It's been a great 30+ yrs for accretion disk limit cycle model!!

α_{cold}~ 0.003-0.03; α_{hot} ~ 0.1; MRI studies are improving

For SU UMa (Kepler data), Hameury et al. (1998) scaling with T0=12500 produces the best superoutbursts, & also seems to be the most physically motivated scaling.

Q: Is the thermal-tidal instability needed, or can the plain vanilla version of the limit cycle explain dwarf nova outbursts?

van Paradijs (1983)

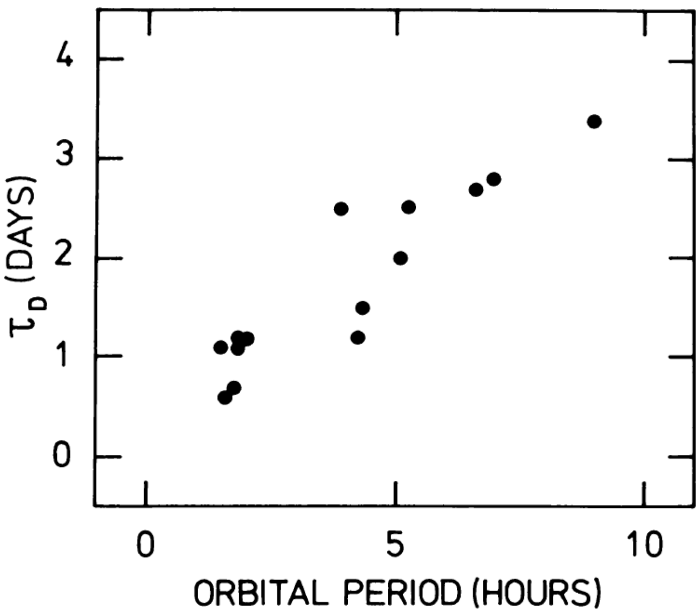


Fig. 1. *Relation between decay time and orbital period.*

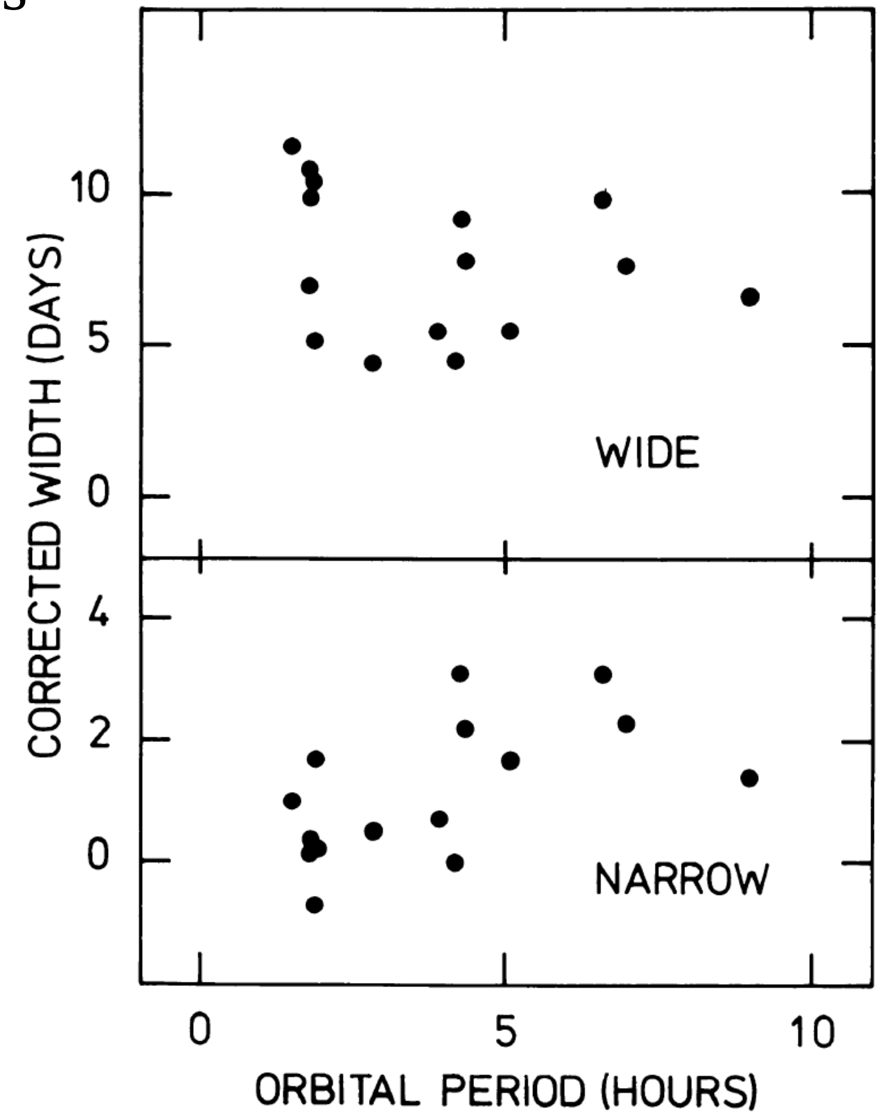


Fig. 3. *Relation between the "corrected" outburst widths (W'in text) and orbital period.*