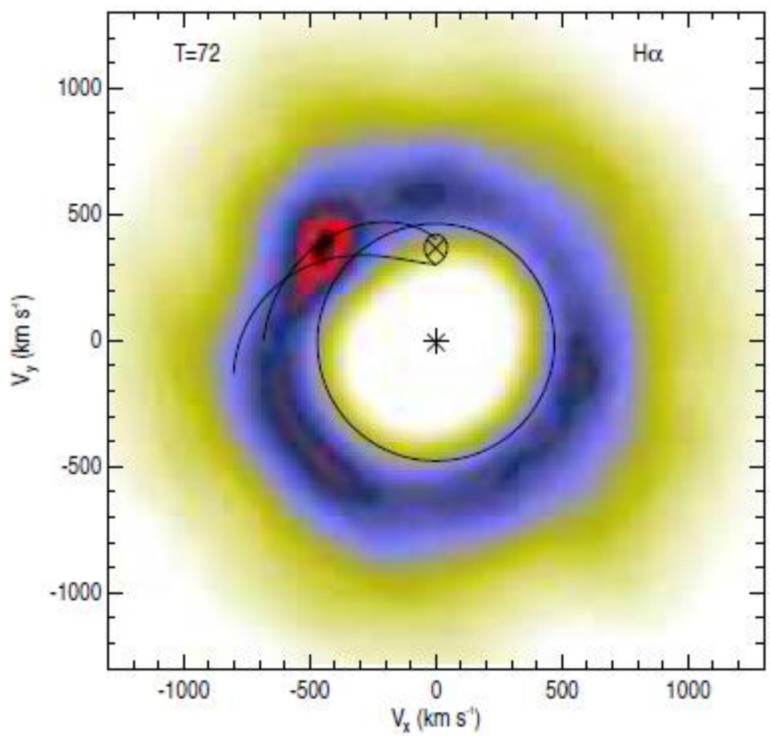
ASTROPHYSICS OF INTERACTING BINARY STARS

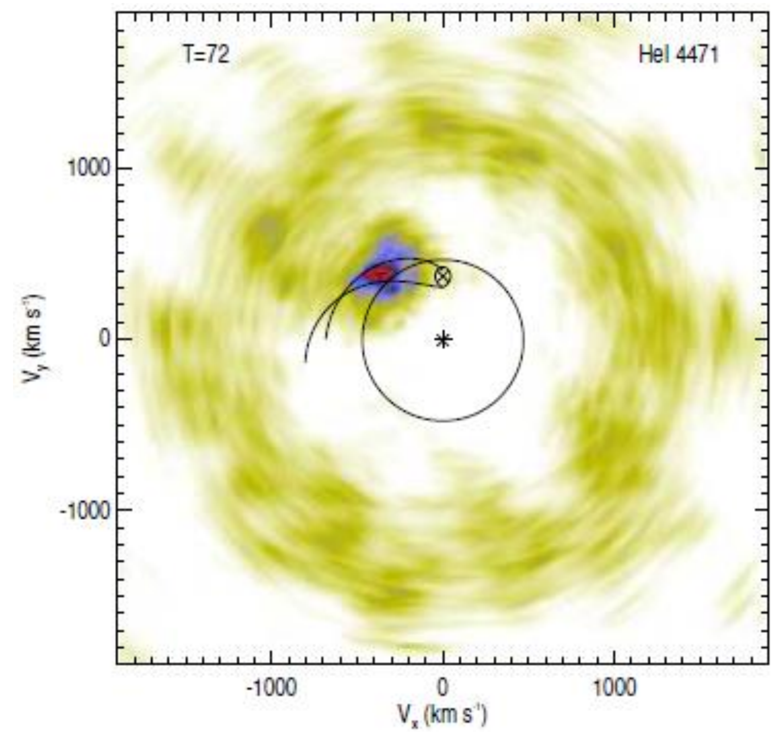
Lecture 11

Vitaly Neustroev

Tomography: Expected structures

Disk ring and a hot spot





Tomography: Expected structures

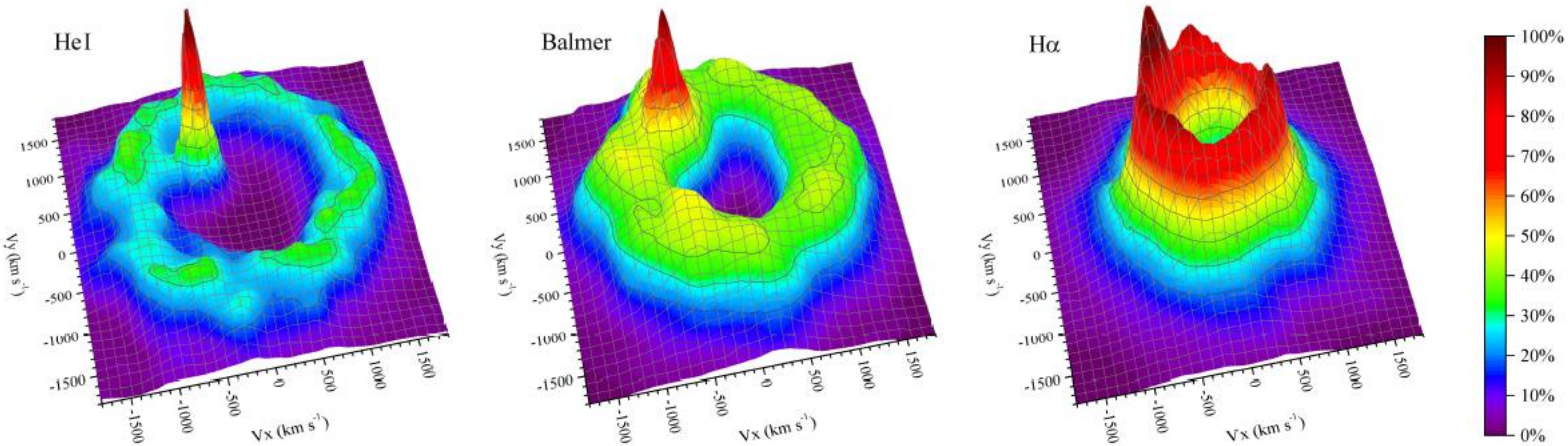
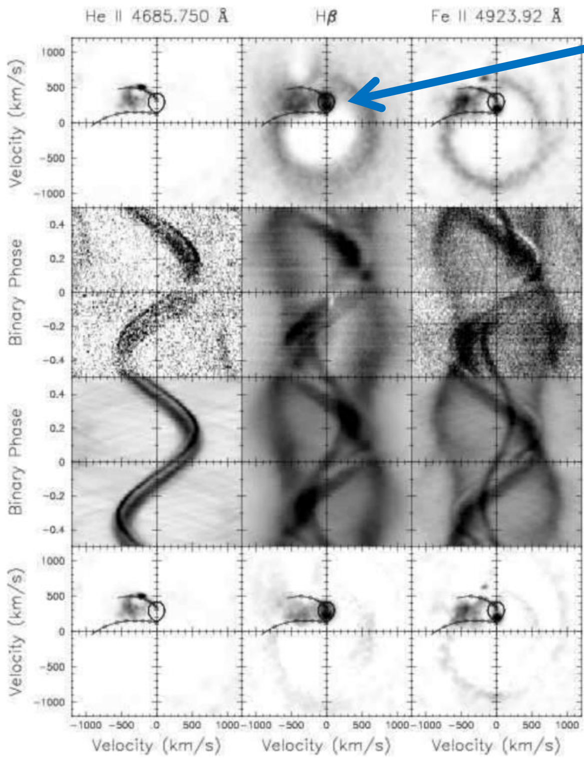


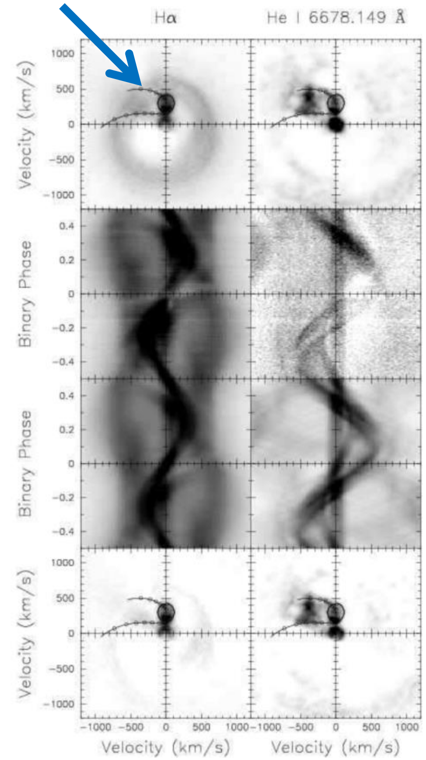
Figure 9. The Hα tomogram and the averaged higher order Balmer and He I maps from the T=72 data set in 3D representation (see text for detail).

Tomography: Expected structures

Disk ring and a hot spot

Donor star!



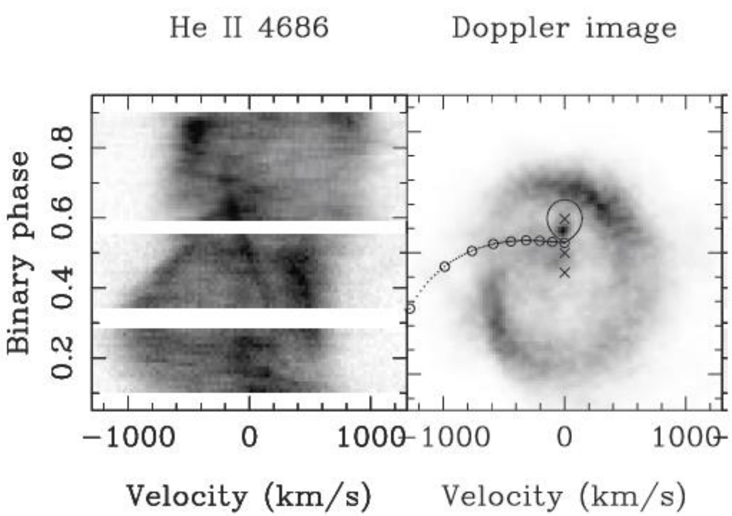


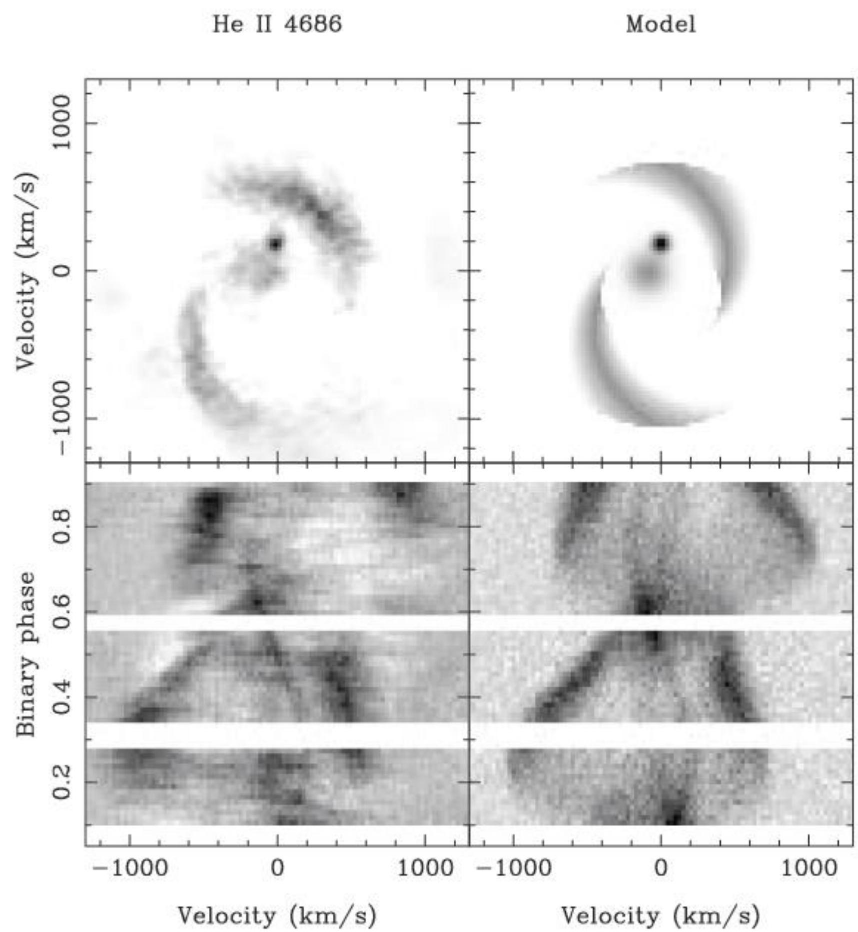
Unda-Sanzana et al. 2006, MNRAS, 369, 805

Tomography: Spiral Arms

IP Peg:

Outburst



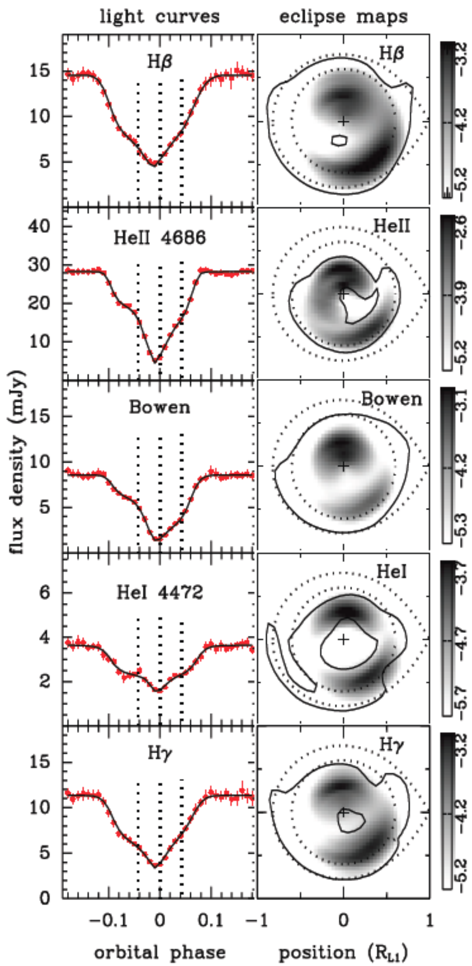


Harlaftis et al. 1999, MNRAS, 306, 348

Confirmation from eclipse mapping

Eclipse maps in selected emission lines of IP Peg in outburst

Detection of spiral structure



Baptista et al. 2005, A&A, 444, 201

What's a problem with spiral arms?

- Predicted by theory (Sawada et al. 1986)
- Angular momentum transport mechanism.
- Observed around peak of outburst:
  - IP Peg (DN) — Harlaftis et al. 1999
  - WZ Sge (DN) — Kuulkers et al. 2002
  - SS Cyg (DN) — Steeghs et al. 2001
  - U Gem (DN) — Groot et al. 2001

  - V 3885 Sgr (NL) — Hartley et al. 2005
  - UX UMa (NL) — Neustroev et al. 2011
- Sometimes observed in quiescence.

Tomography: unusual structures

Disk eccentricity:

- Tidal perturbation of the disk by the secondary star at $q < 0.25$
- Proposed to explain "superhumps" in CVs (Whitehurst 1988; Lubow 1991)

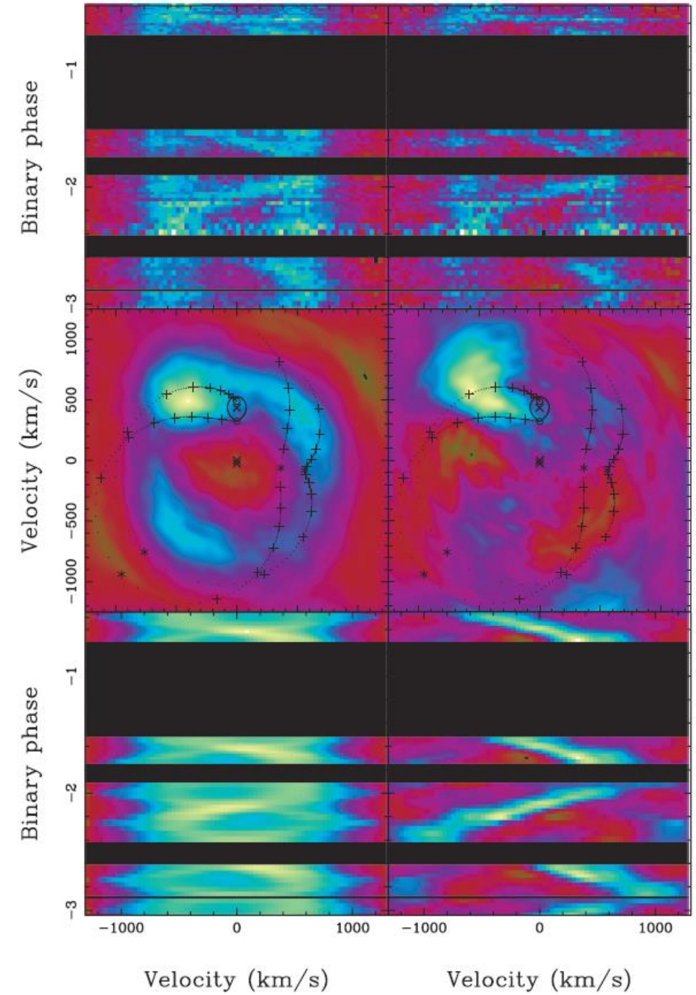
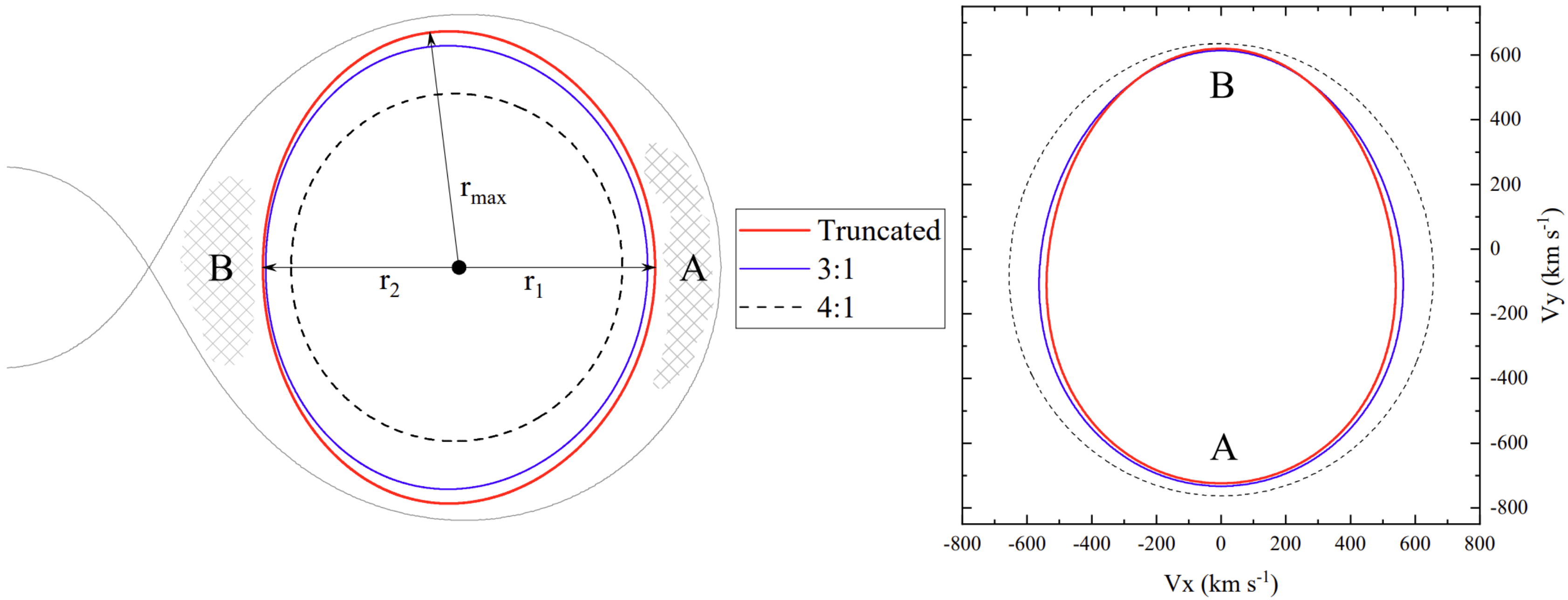


Figure from Nielsen et al. 2008, MNRAS, 384, 849

Tomography: unusual structures

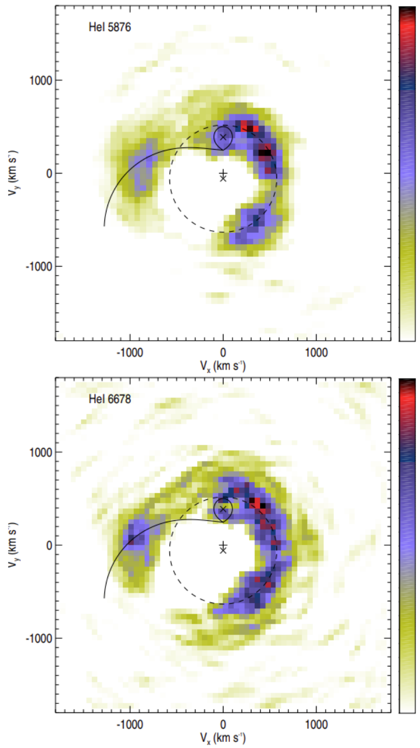


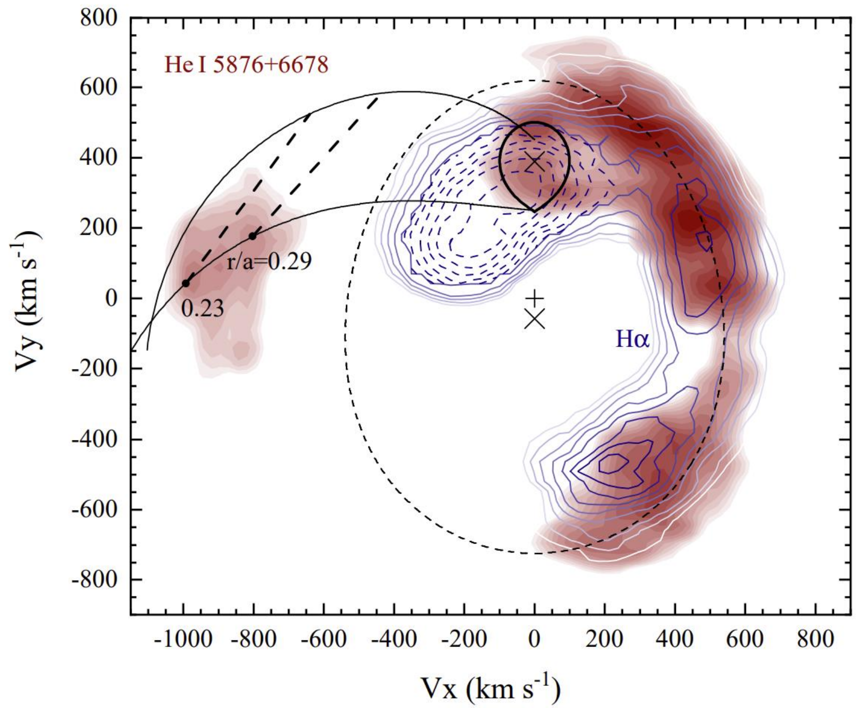
Unusual, but explained: disk elongation:

Tidal perturbation of the disk by the secondary star

Neustroev & Zharikov.: 2020, A&A, 642, A100

Tomography: unusual structures





Unusual, but explained: disk elongation:

Tidal perturbation of the disk by the secondary star

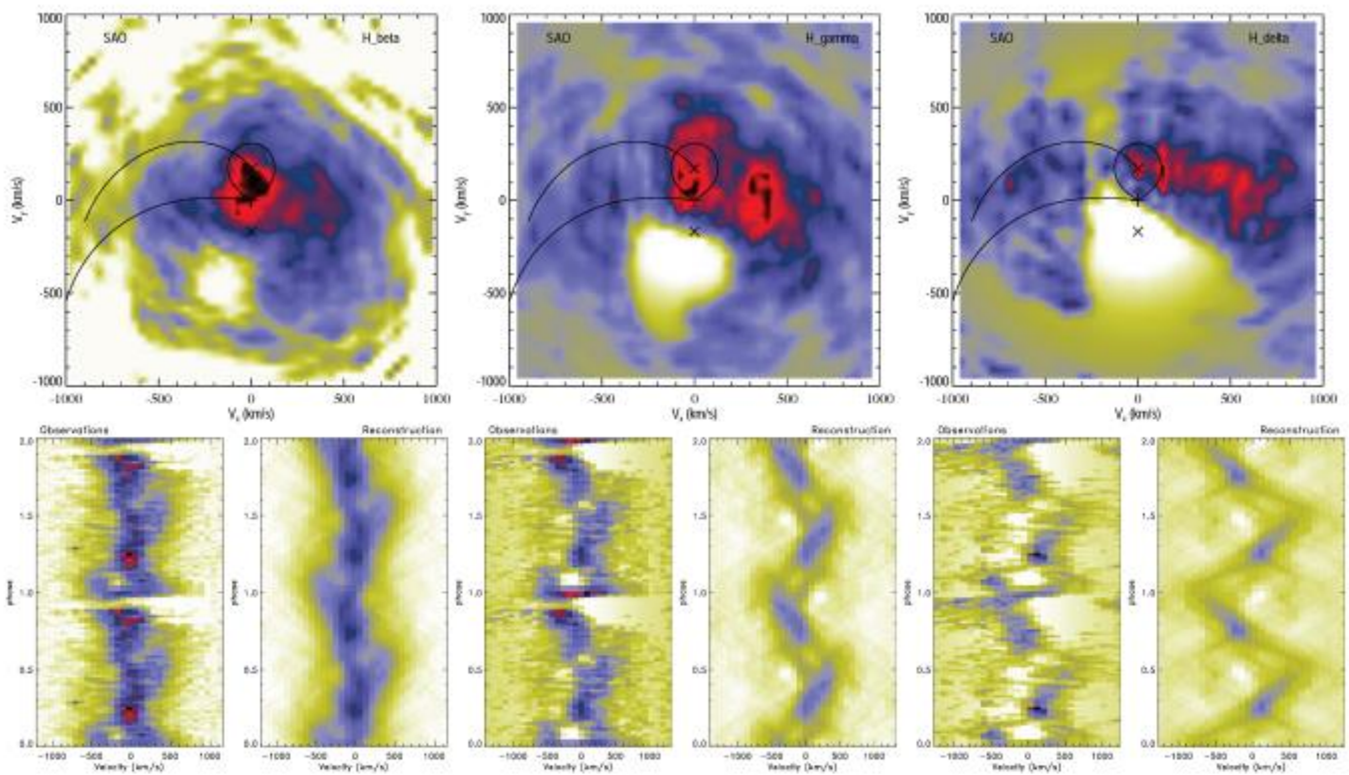
Neustroev & Zharikov.: 2020, A&A, 642, A100

Tomography: Unusual/Unexpected structures

Dark spot:

Disk overflow?

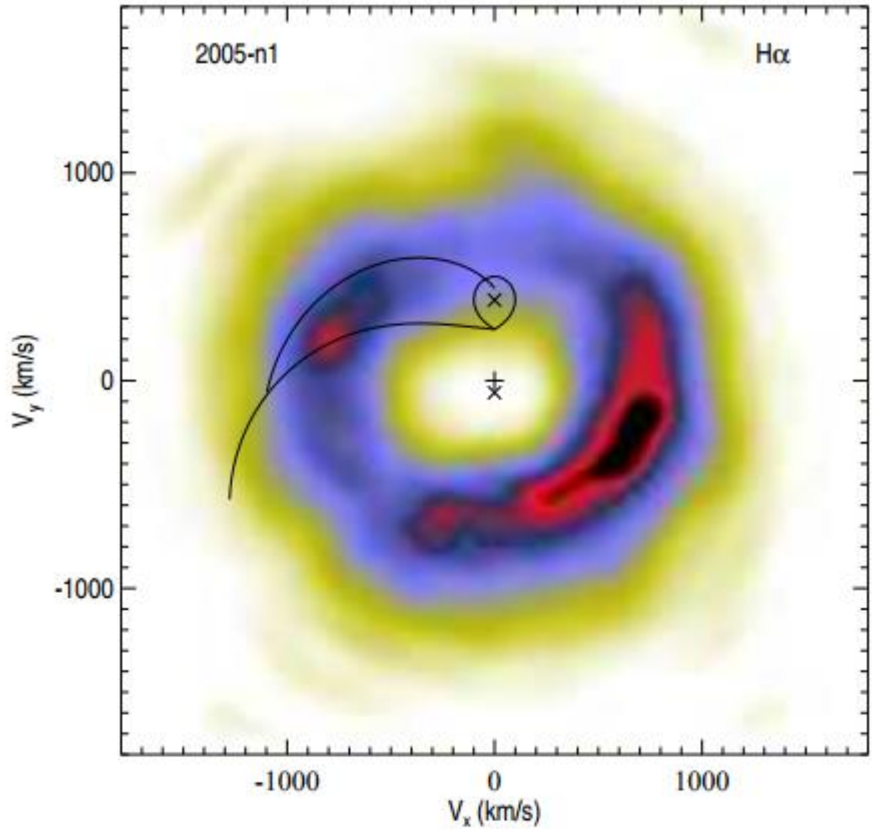
UX Uma:



Neustroev et al.: 2011, MNRAS, 410, 963

Tomography: Unusual/Unexpected structures

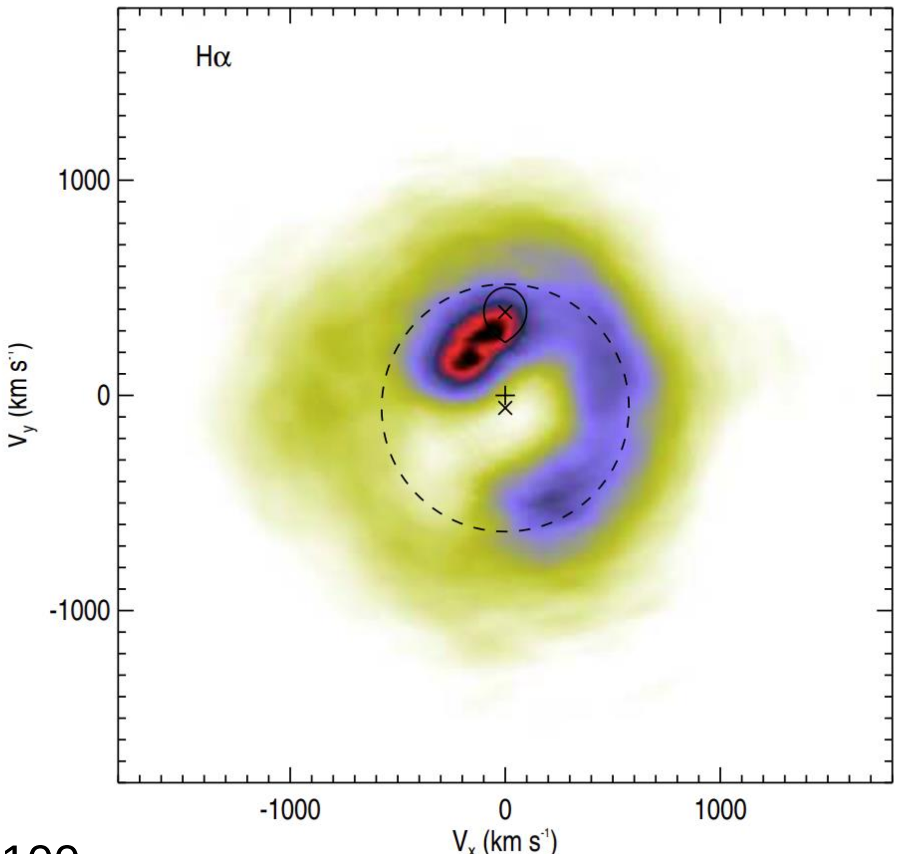
HT Cas:
Bright spot on the opposite side of the disk



Neustroev et al.: 2016, A&A, 586, A10

Tomography: Unusual/Unexpected structures

HT Cas:
a horseshoe structure
during
the superoutburst



Neustroev & Zharikov.: 2020, A&A, 642, A100

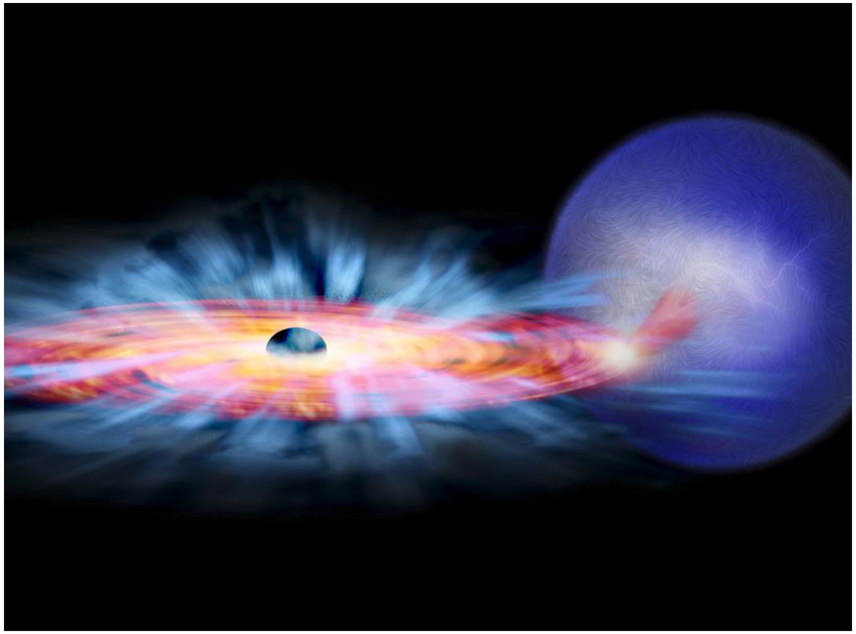
Single Peaked Lines?

- Why do the lines change from double-peaked to single-peaked during outburst?
- Why some eclipsing NLs show single-peaked profiles?
- Do single-peaked lines still come from the disk?

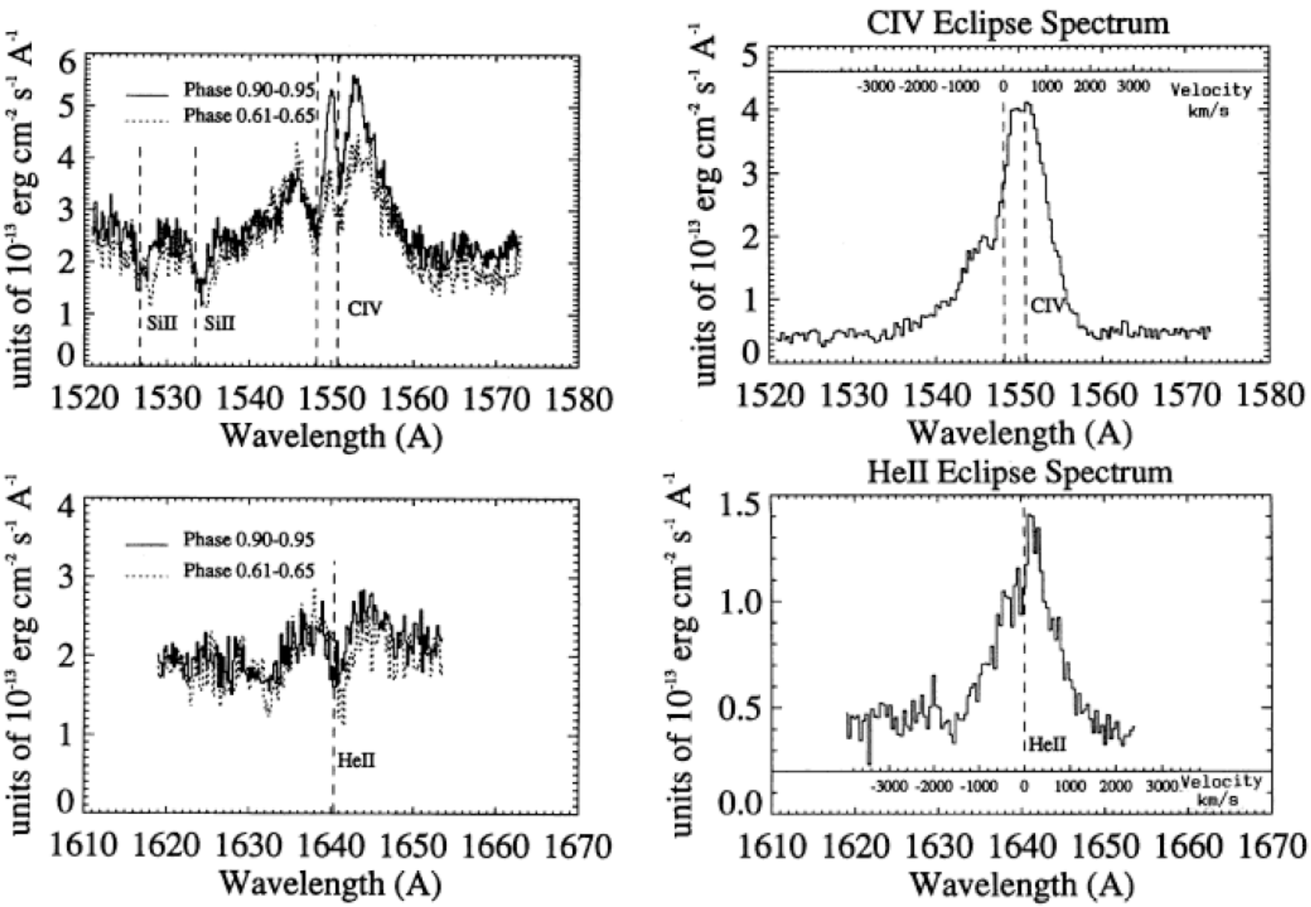
> "The answer is blowin' in the wind"
> — Dylan, B.1962, Special Rider Music

How do we know there are outflows?

- Blueshifted absorption lines in the UV spectra of CVs (P-Cygni profiles)
- Residual flux during eclipse (vertically extended gas)



The Wind of UX UMa



figures from Mason et al. 1995, MNRAS, 274, 271

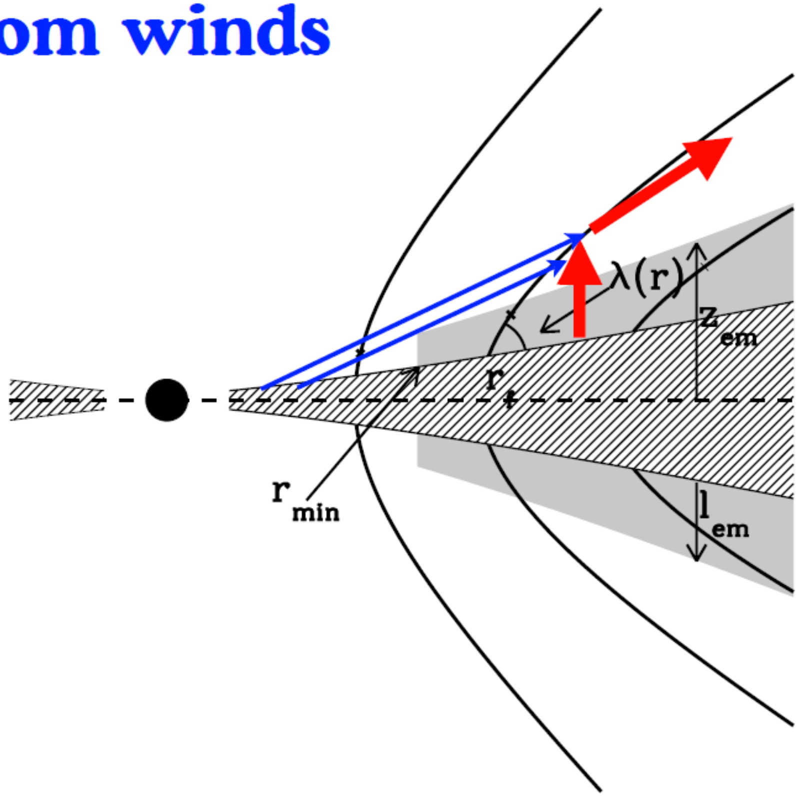
The Wind

Emission lines from winds

- Dense layer at the base emits the lines.
- Powered by photoionization
- $v_r \ll v_\varphi$

  but

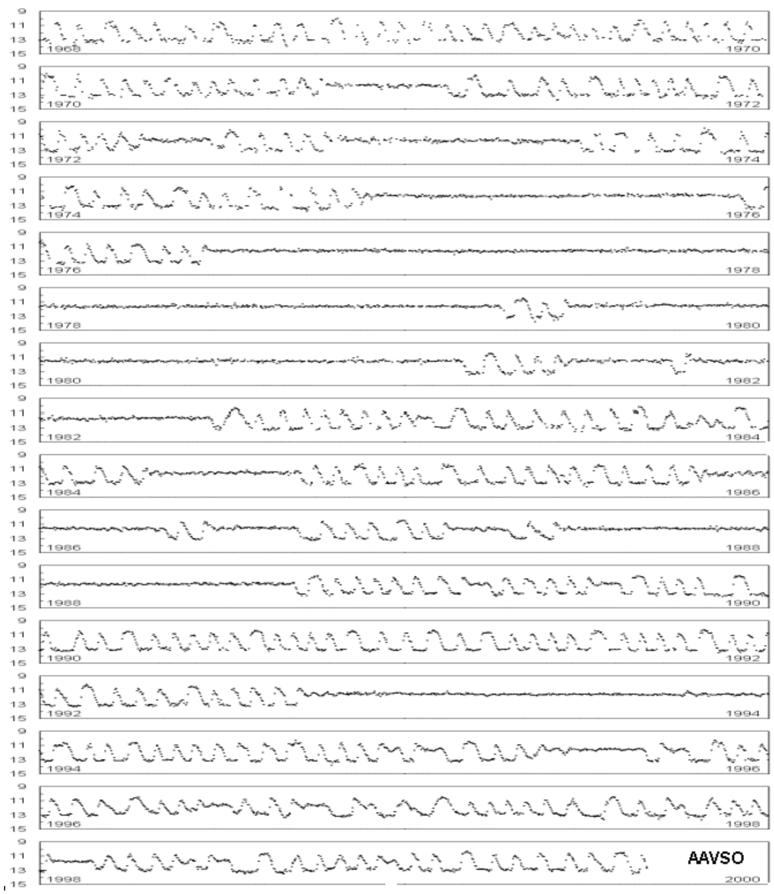
  $dv_r/dr \gg dv_\varphi/dr$



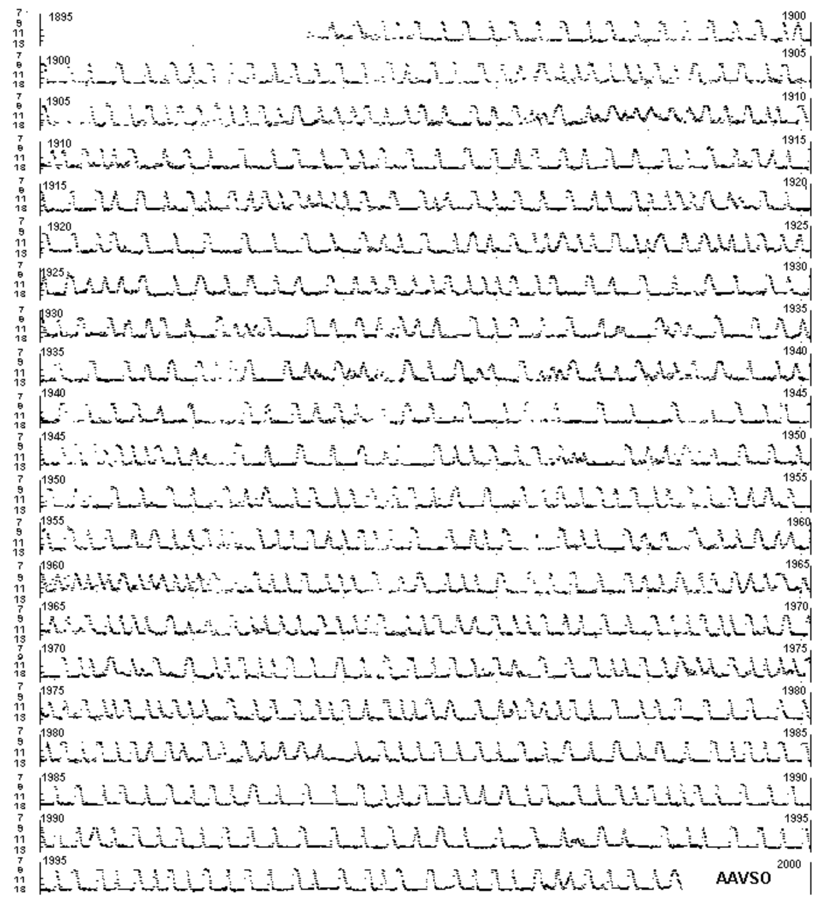
from Murray et al. 1995, ApJ, 451, 498

Dwarf Nova Outbursts

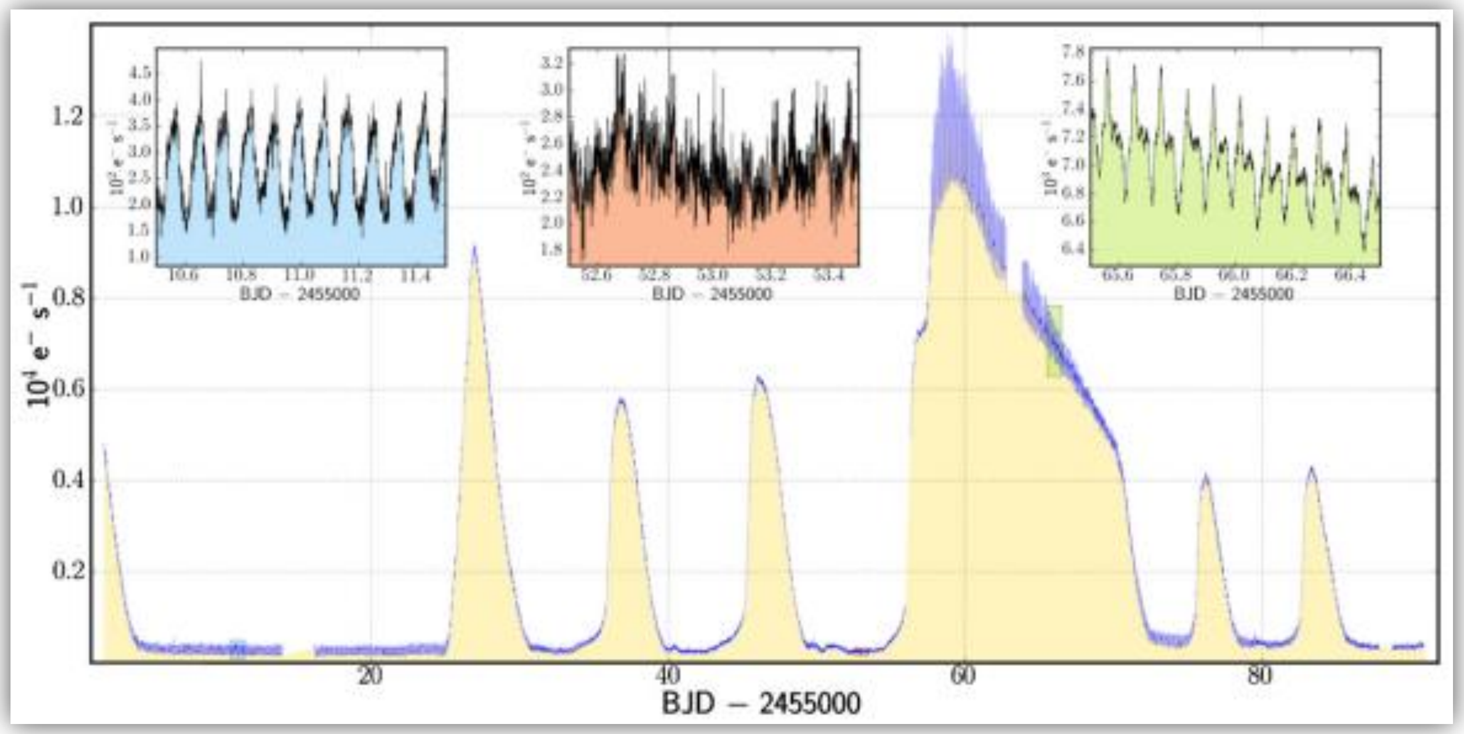
Z Camelopardalis



SS Cygni



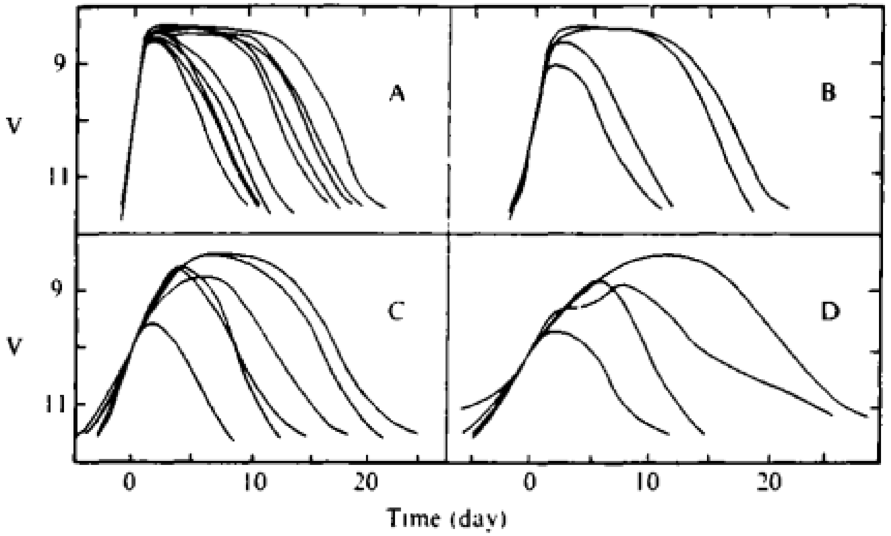
Dwarf Nova Superoutbursts

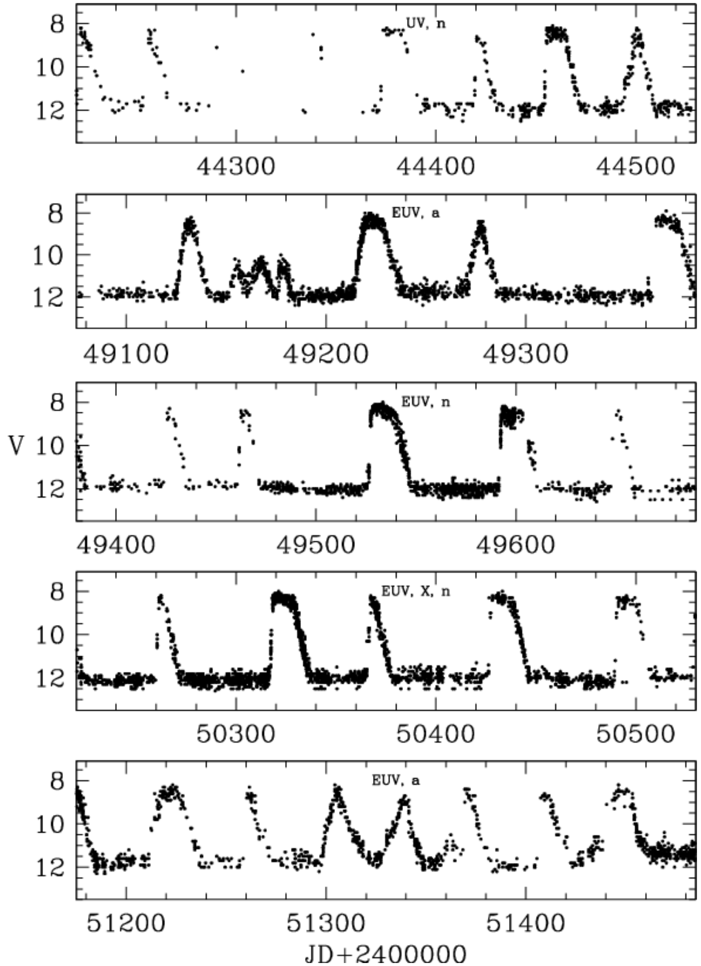


Kepler light curve of V344 Lyrae showing several normal outbursts and one superoutburst (from Still et al. 2010).

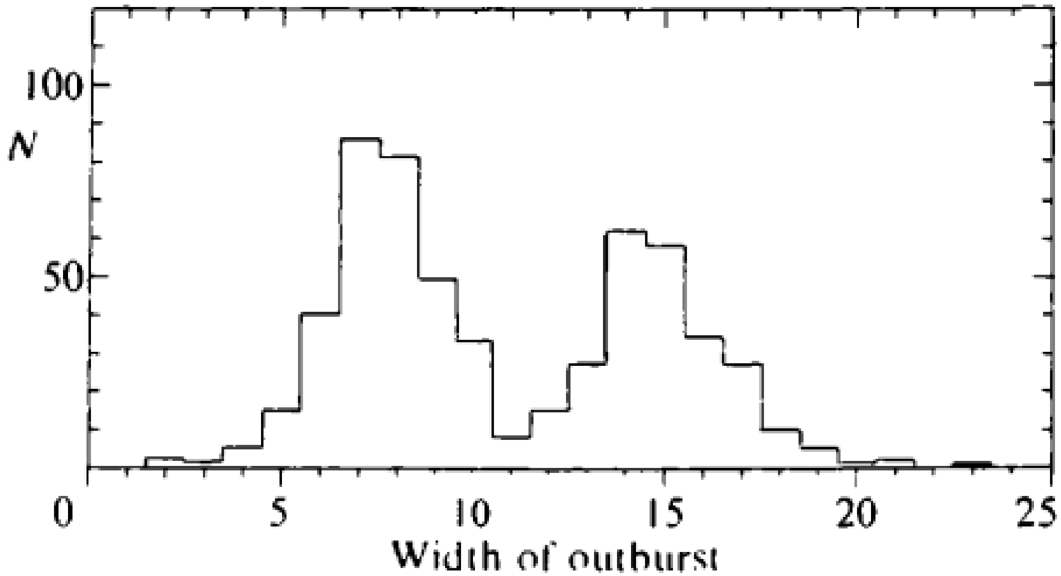
DN Outbursts: Properties and Correlations

- **Outbursts of SS Cyg:**
  Short, Long, and Slow-Rise





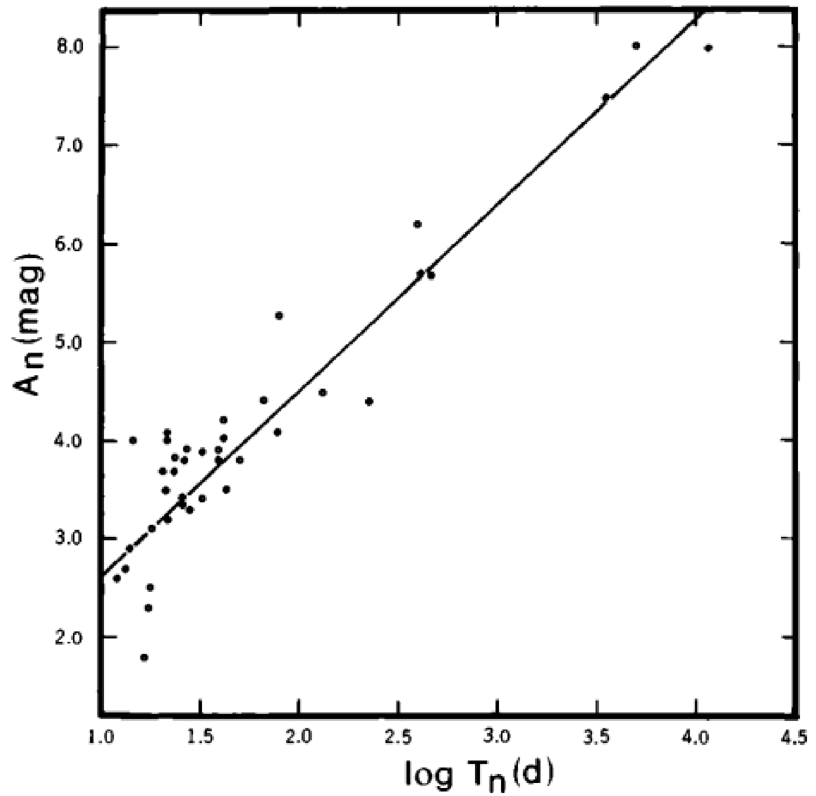
DN Outbursts: Properties and Correlations



Bimodal distribution of outburst widths of SS Cyg.
From Bath & van Paradijs (1983).

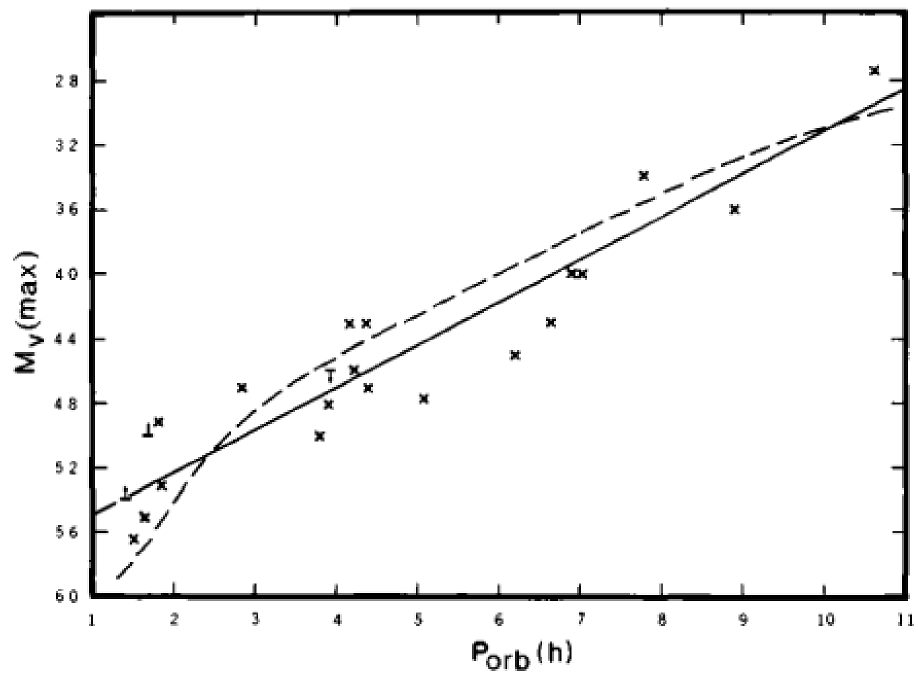
DN Outbursts: Properties and Correlations

- Corrected outburst amplitude versus outburst interval for dwarf novae.



DN Outbursts: Properties and Correlations

- Absolute visual magnitude of DN disks at maximum of normal outbursts - orbital period relation.
- The solid line represents equation

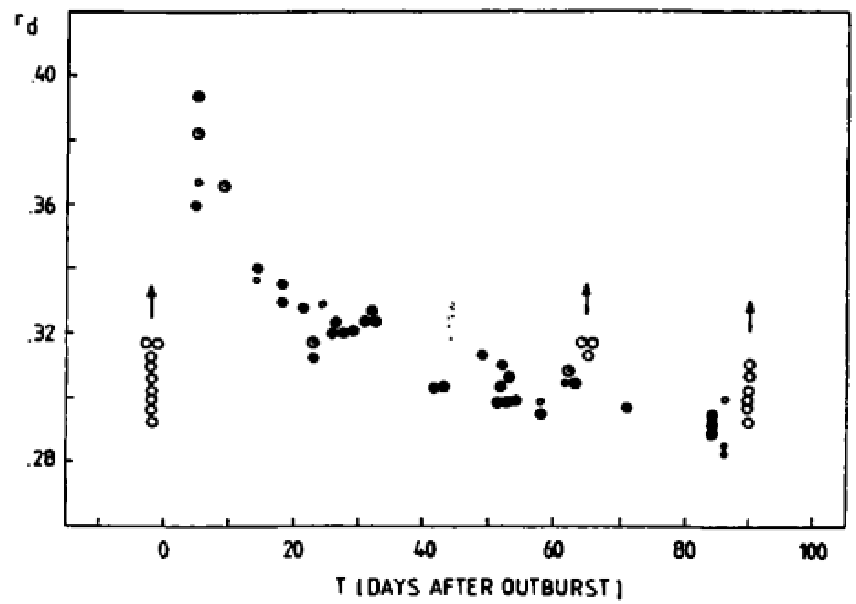


$$M_v(\max) = 5.74 - 0.259 P_{orb}(\mathrm{h}) \quad P_{orb} \lesssim 15 \text{ h}.$$

(Warner 1987)

DN Outbursts: Properties and Correlations

- Variation of disk radius r_d in U Gem, as a function of days after outburst.
  r_d is in units of the orbital separation a.

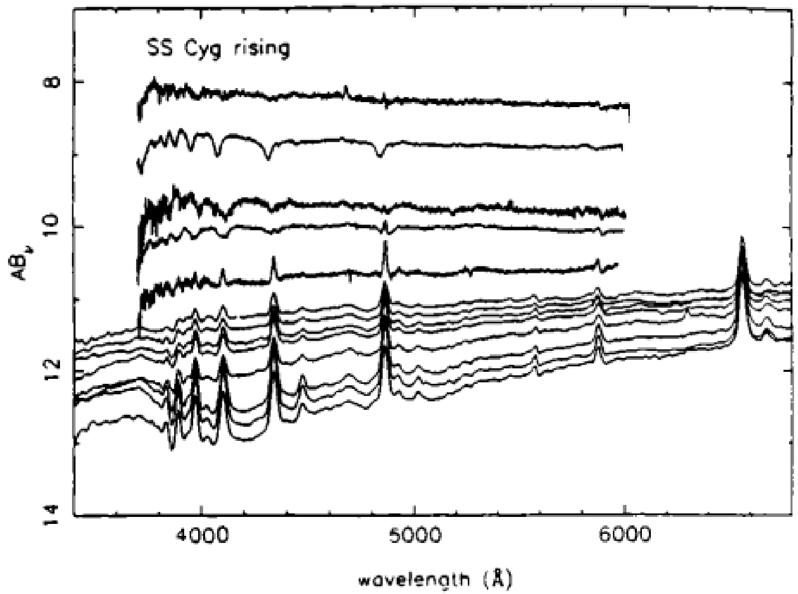


- **Warning!**
  r_d is measured from the position of the hot spot.

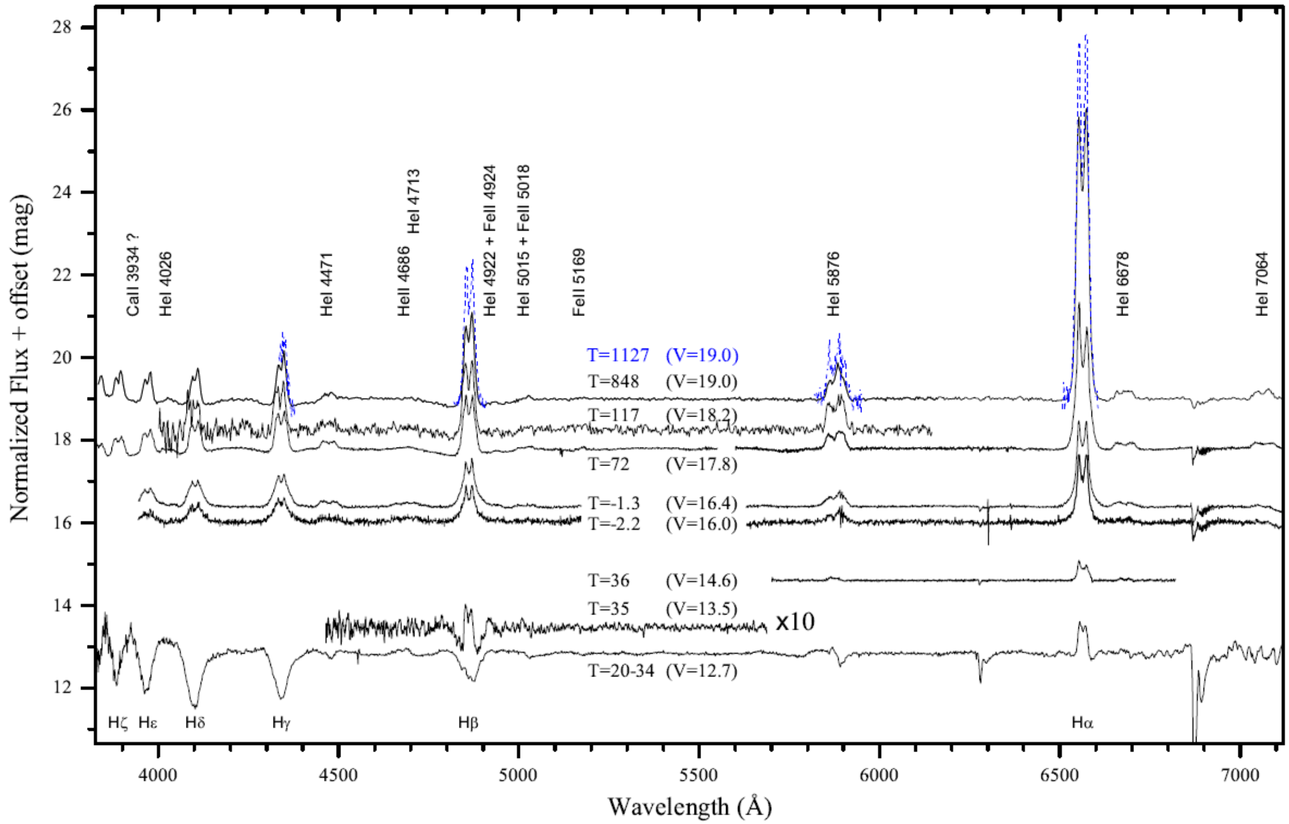
DN Outbursts: Properties and Correlations

- Spectral changes in SS Cyg from quiescence (lowest spectrum) to maximum of outburst (uppermost spectrum).

(From Horne 1991).



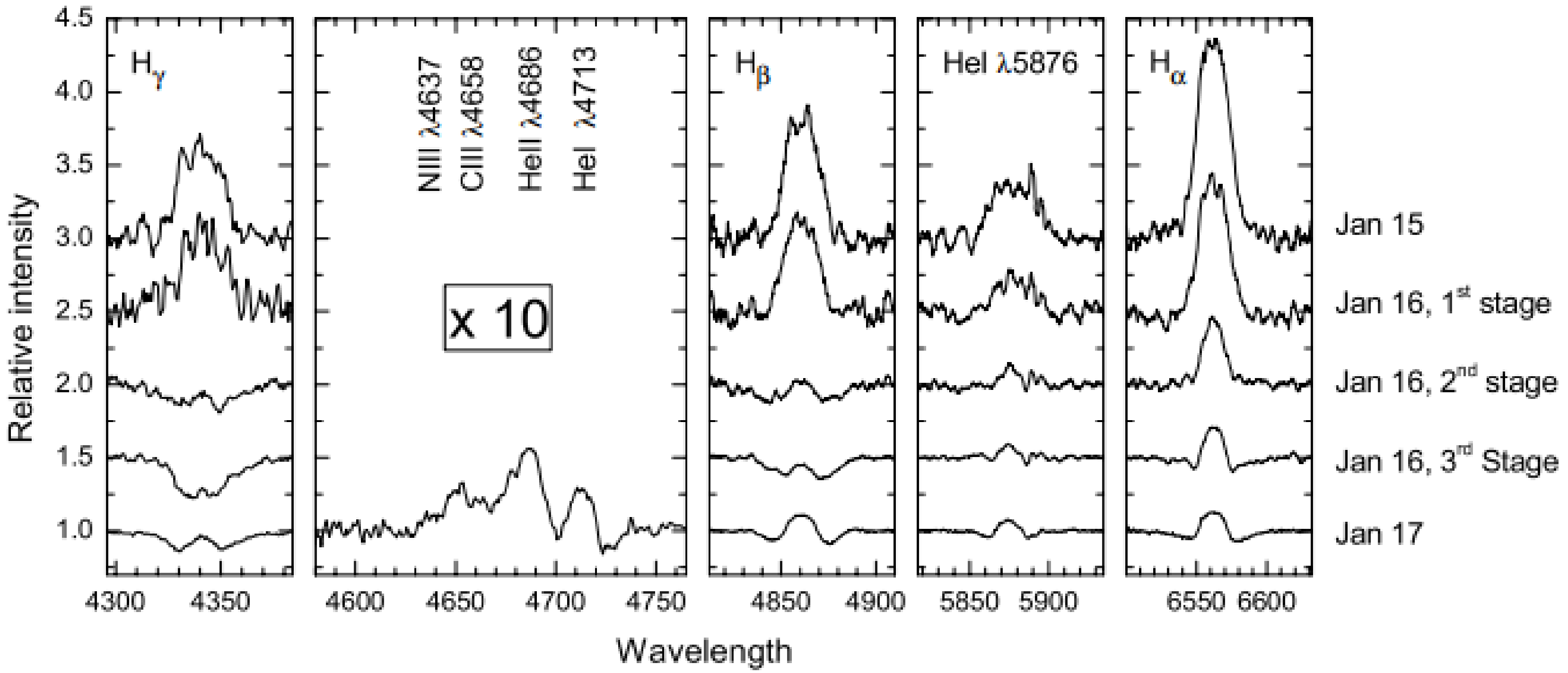
DN Outbursts: Properties and Correlations



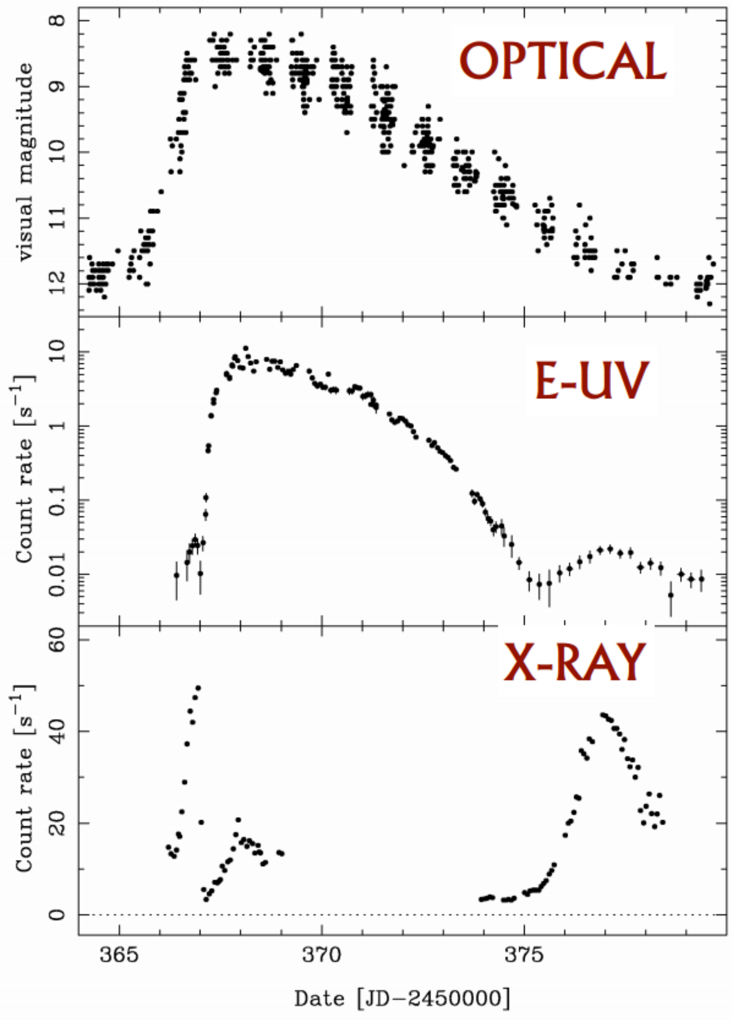
Spectral changes in SSS122222 from quiescence (uppermost spectrum) to maximum of superoutburst (lowest spectrum). (From Neustroev 2017).

DN Outbursts: Properties and Correlations

BZ Uma from the quiscent to outburst state (Neustroev et al., 2005)



DN Outbursts: Properties and Correlations



- Observations of SS Cyg through a dwarf nova outburst
- Change in density of boundary layer opt. thin ←→ opt. thick

(from Wheatley et al. 2003)

Dwarf Nova Outbursts (1)

- **Two models were proposed in the 1970s:**

1. The mass-transfer instability model (MTI model) → Bath (1973).

The mass-transfer rate from the secondary star is thought to be unstable and the mass-accretion rate onto the white dwarf is variable accordingly.

Dwarf Nova Outbursts (2)

- **Two models were proposed in the 1970s:**

2. The disk-instability model (DI model)
   → Osaki (1974).

The mass-transfer rate from the secondary star is thought to be constant but the alternation of outburst/quiescence is caused by (some unknown at that time) instabilities within accretion disks; mass is stored within the disk during quiescence and, when it reaches some critical amount, it is suddenly accreted onto the white dwarf due to some instability, which explains an outburst.

Dwarf Nova Outbursts (3)

- The models fiercely competed in the 1970s.

- However, a very promising instability mechanism in accretion disks was discovered around 1980.
- On the other hand, there are several reasons to be dissatisfied with the MTI model.

Now the MTI model is <u>out</u> of favour

Dwarf Nova Outbursts (4)

- There are several reasons to be dissatisfied with the MTI model:
  - There is the fact that no high mass-transfer rate systems show DN outbursts.
  - There is no evidence from bright spot luminosities for increased mass-transfer rate during or before outbursts.
  - Polars do not have disks, and do not show DN outbursts.

Dwarf Nova Outbursts (5)

- A thermal instability of accretion disks based on the **bi-stable** nature of accretion disks with the disk temperature around 10^4 K where the hydrogen changes from an ionized state to a neutral state, and it is called the "thermal instability" or the "thermal limit cycle instability."

- The DI model is now widely accepted by both theoreticians and observers

Thermal limit cycle instability (1)

- The key property is viscosity.
- An accretion disk acts as a mass transfer channel between the mass-losing star and the white dwarf.
- The rate of mass flow through the disk, $\dot{M}_d$, is set by the viscosity, and will in general not be equal to the rate of mass transfer from the secondary, $\dot{M}$.
- If $\dot{M}_d < \dot{M}$, then mass will build up in the disk.
- If $\dot{M}_d > \dot{M}$ mass will drain out of the disk.

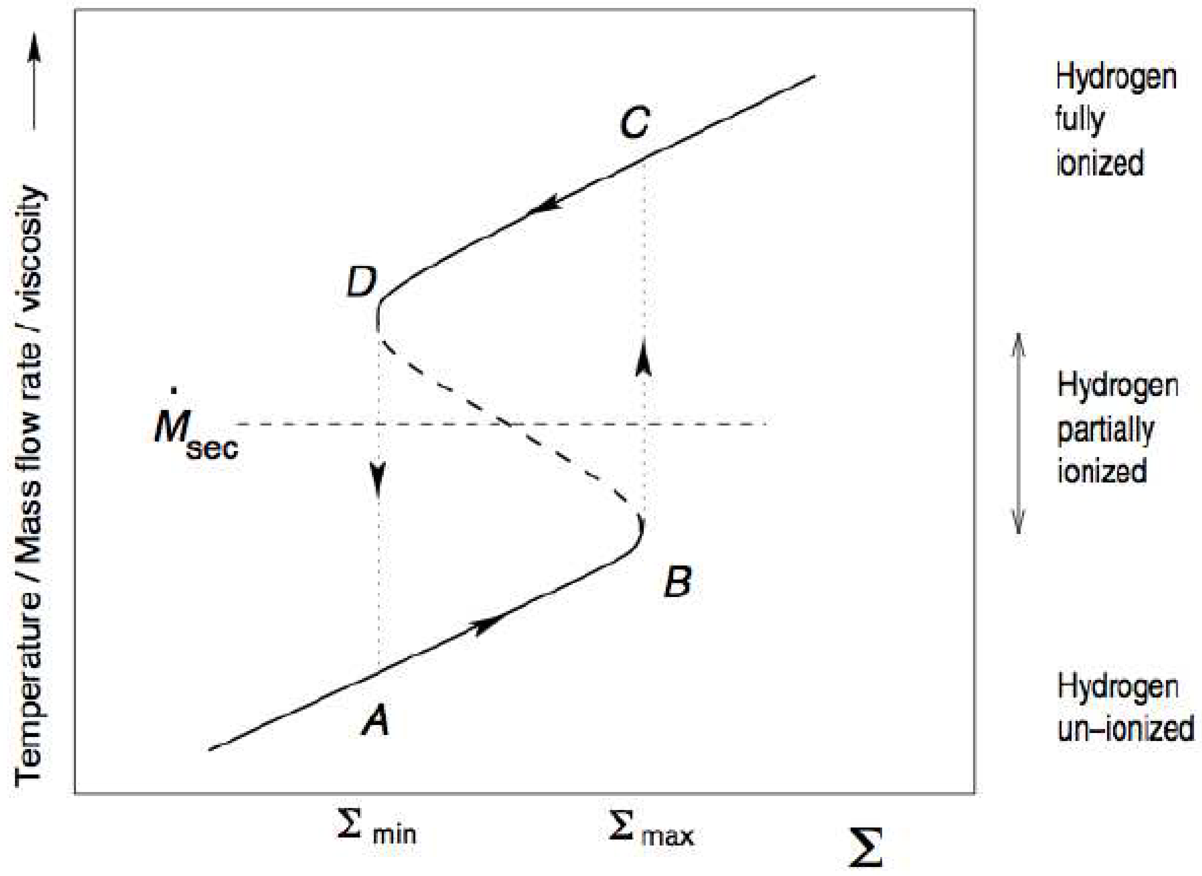
Thermal limit cycle instability (2)

- From calculations of the vertical structure of the accretion disk we can obtain the surface density Σ for given radius *r* and $\dot{M}_d$ (or equivalently averaged viscosity $\Sigma\bar{\nu}$ or T_{eff}).
- The vertical structure of accretion disks depends on whether energy transport is largely by radiation or largely by convection, and at temperatures around 10^4 K two solutions are possible – a convective solution with a low mass flow rate and a radiative solution with a high mass flow rate.

Thermal limit cycle instability (3)

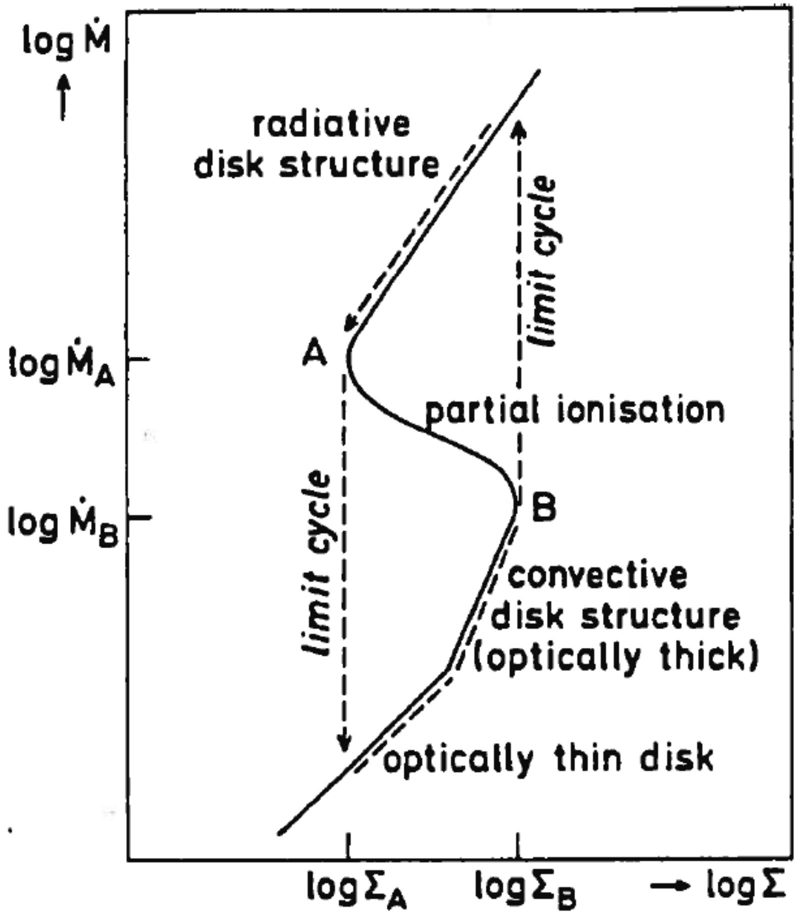
- In the range of temperatures at which hydrogen recombines, the resulting dramatic reduction of opacities makes the disk thermally and viscously unstable:
  a surface density – (averaged) viscosity relation
  $\Sigma - \Sigma\overline{\nu}$ is double-valued for a range of density.
- At a given radius, the disk thermal equilibria form an S – shaped curve, the middle branch of which represents unstable solutions.

Thermal limit cycle instability (4)



Thermal limit cycle instability (5)

- Outburst triggers at small R (inside-out front propagation) / large R (outside-in) for small / large $\dot{M}_d$
- Heating wave switches disk to outburst state
- Cooling wave switches disk to quiescent state



Thermal limit cycle instability (6)

Outburst properties:

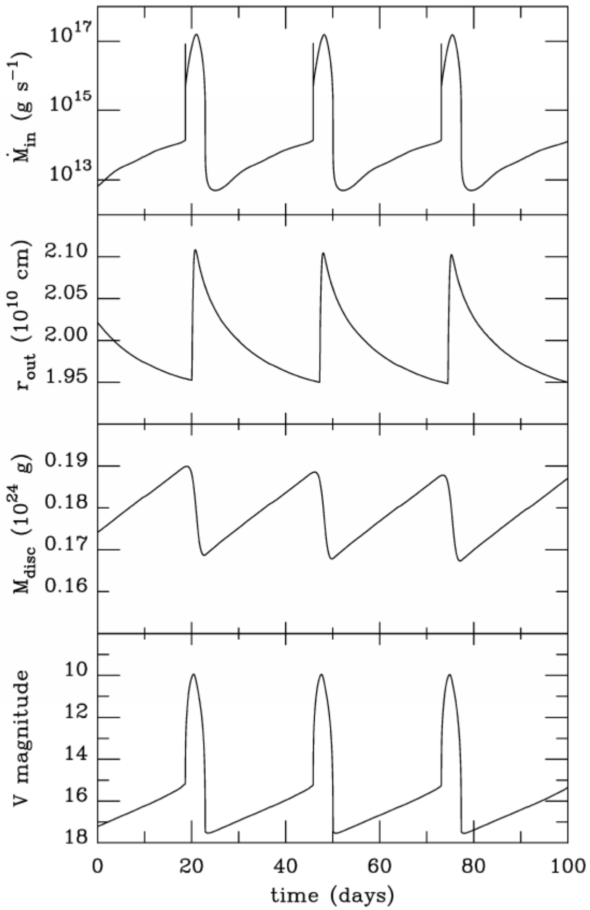
$M_1 = 0.6\ M_{sun}$

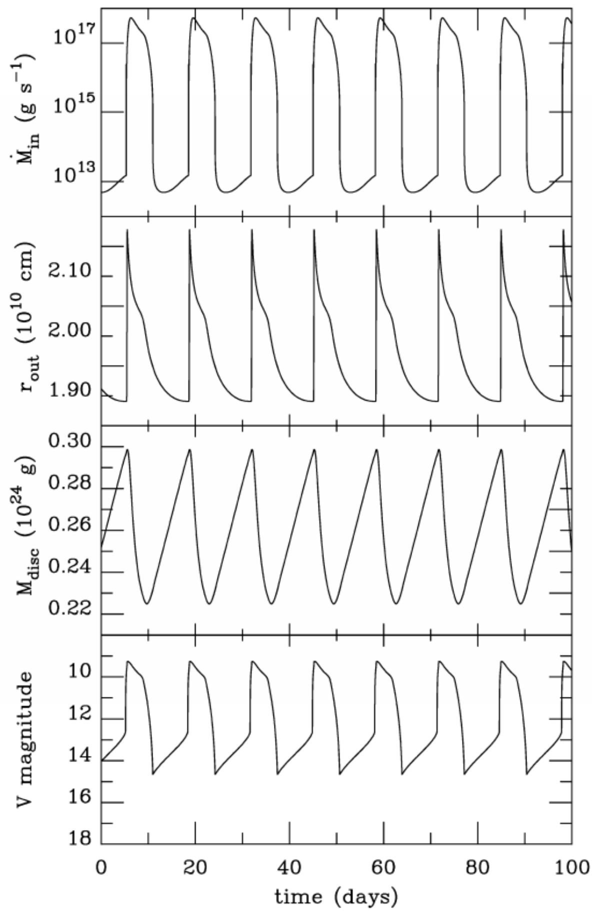
$\alpha_{cold}=0.04$, $\alpha_{hot}=0.20$

$\dot{M} = 10^{16}$ g/s (left)

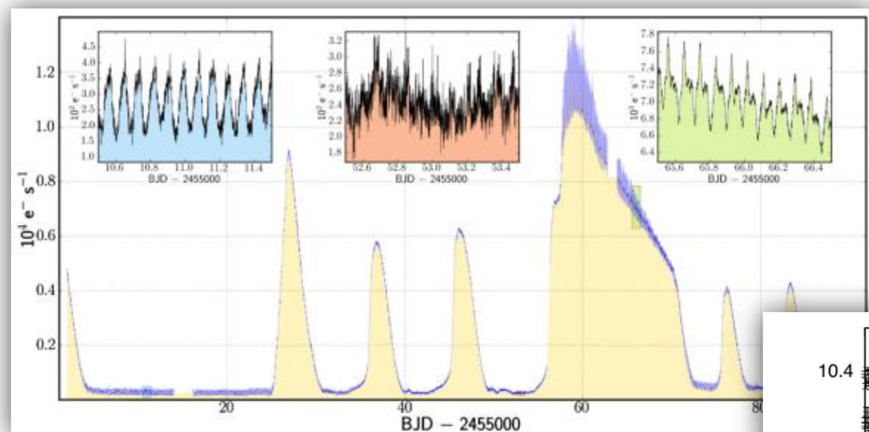
$\dot{M} = 10^{17}$ g/s (right)

(Hameury et al., 1998).



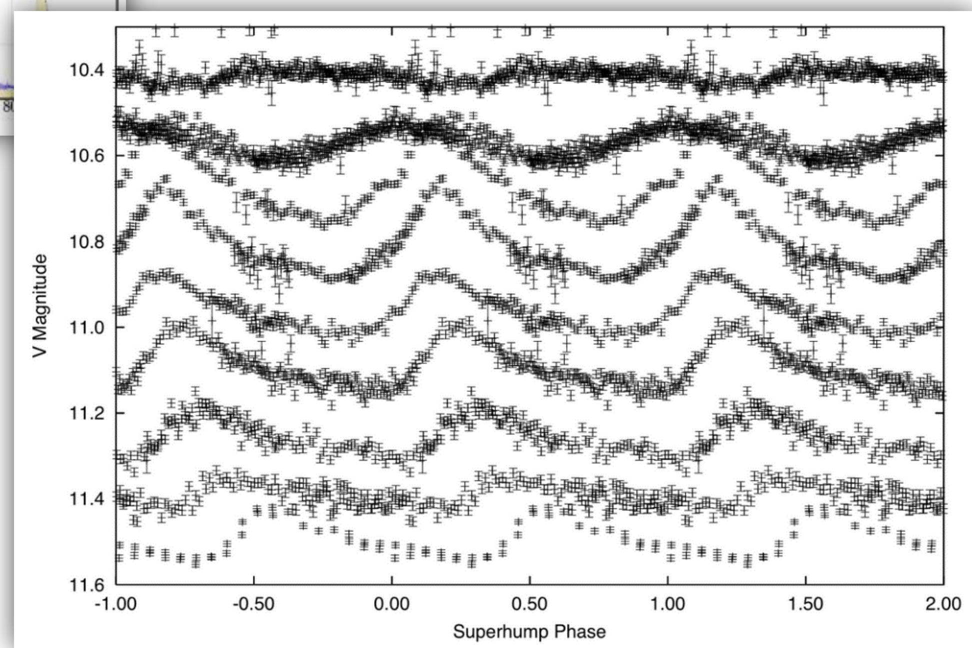


Superoutbursts and Superhumps (1)



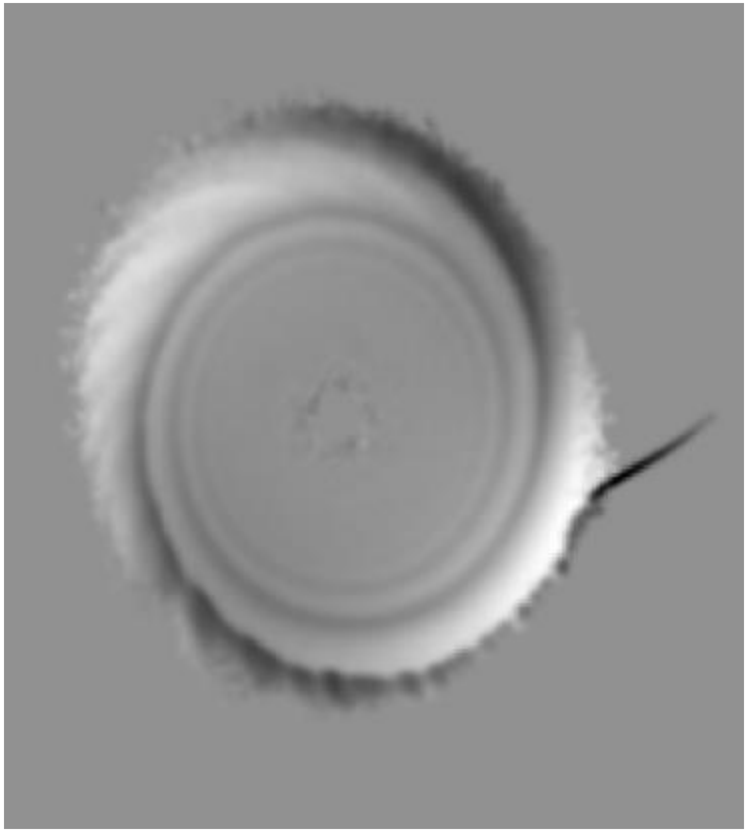
The duration of a superoutburst is several times longer than those of normal outbursts. The maximal brightness is about 1 mag brighter than those of normal outbursts.

Superhumps resembles in shape orbital humps in quiescence, but have a much larger (~100 times) luminosity (a few tenths of magnitude during superoutbursts). The period of light variation is a few per cent longer than the orbital period.



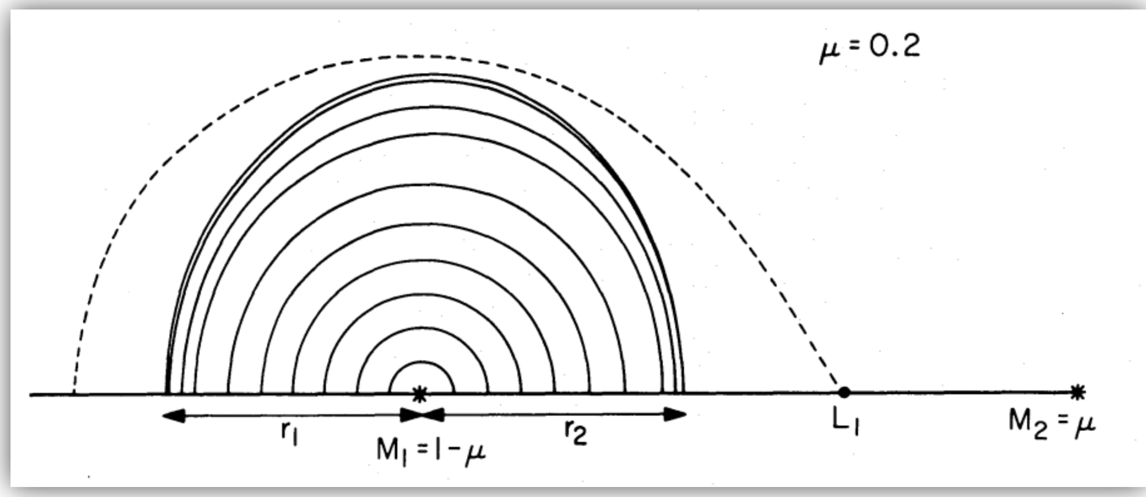
Superoutbursts and Superhumps (2)

- Mass is transported inwards through a disk, so angular momentum must be transported outwards.
- So what happens to the angular momentum at the outer edge?



Superoutbursts and Superhumps (3)

- For disks that approach R_{L1} in radius the outer parts will be significantly distorted by the gravitational influence of the secondary star. Tidal interaction with the secondary keeps the disk from overflowing the Roche lobe.



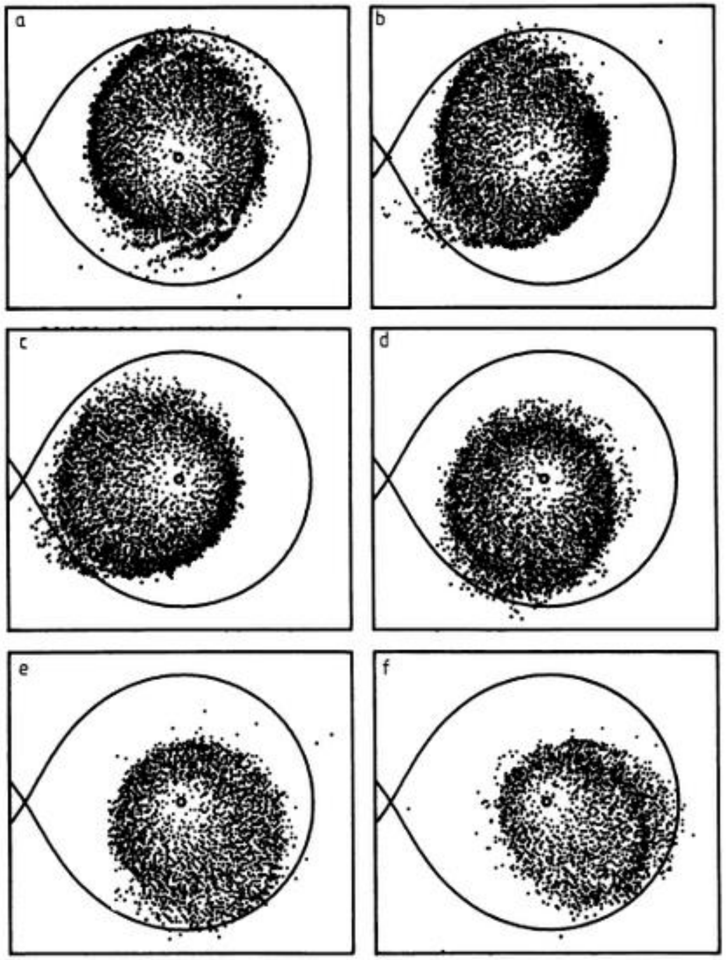
Paczynski (1977)

Superoutbursts and Superhumps (4)

- The outburst does not leave the disk in exactly the same state as it was at the beginning of the outburst cycle:
  not all the material stored in the disk has been lost to the white dwarf, so the disk is slightly more massive and larger at the beginning of the next cycle.
- The disk radius grows slowly from one cycle to the next, until the disk is large enough for tidal forces from the secondary to start distorting it.
- The disk becomes tidally unstable to a 3:1 resonance, in which the particle orbits have frequency $\Omega = 3\Omega_{orb}$

Superoutbursts and Superhumps (5)

- The resonant radius is within the disk if the mass ratio $q < 0.33$.
- The disk becomes elliptical, and its long axis precesses.
- Each snapshot is precisely 3 orbital period apart (Whitehurst 1988)

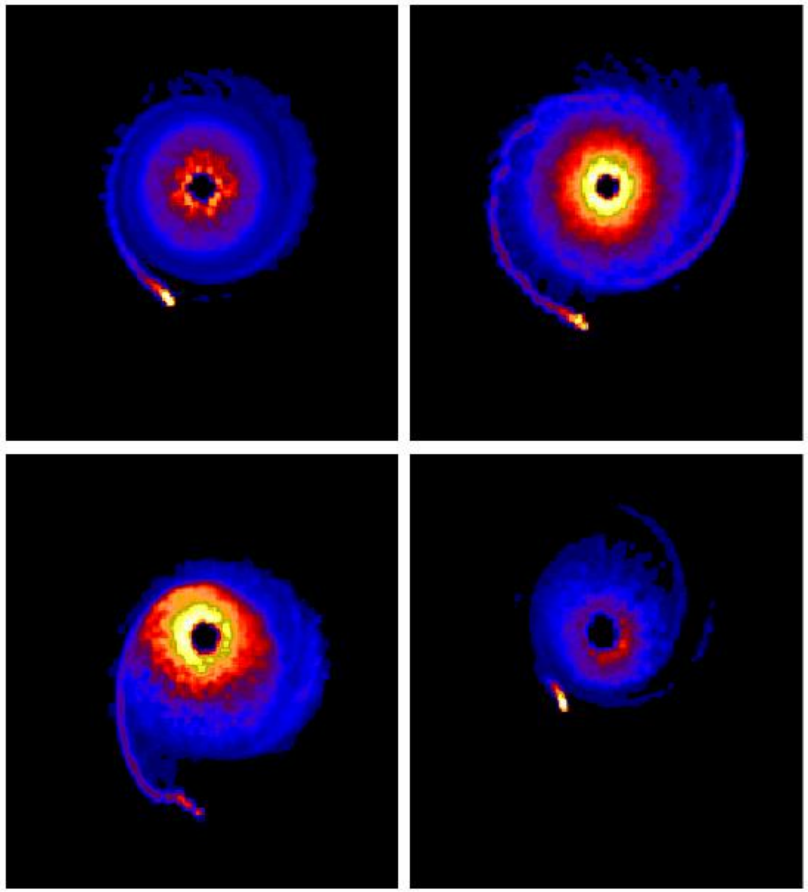


Superoutbursts and Superhumps (6)

- Osaki (1989) proposed that the superoutburst phenomenon of SU UMa stars may be explained by the basic frame work of the DI model in which the two intrinsic instabilities within accretion disks (i.e., the thermal and the tidal instabilities) are properly combined, and this DI model for SU UMa stars is called the "thermal-tidal instability" model.

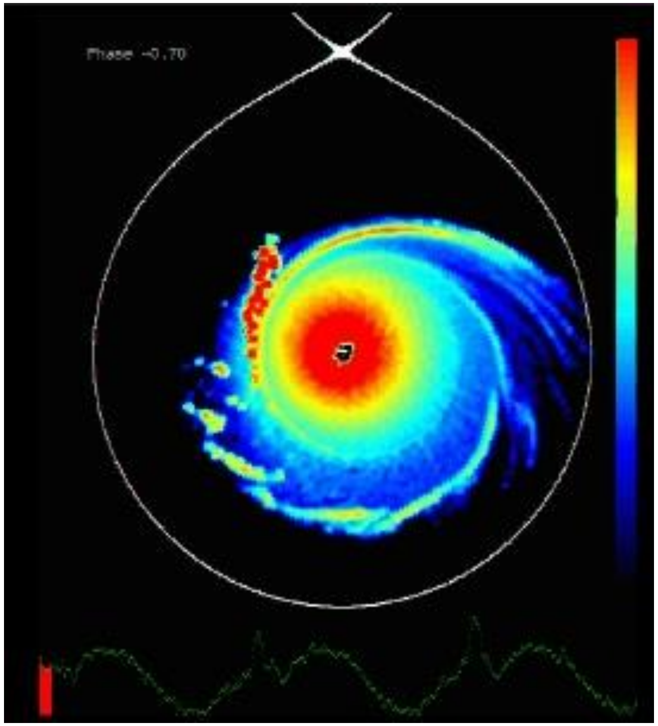
Superoutbursts and Superhumps (7)

- Outburst starts in normal way;
- Disk expands past 3:1 radius;
- Eccentricity: superhumps appear;
- Enhanced tidal heating drives more gas in and prolongs the outburst.



Superhumps: Video (1)

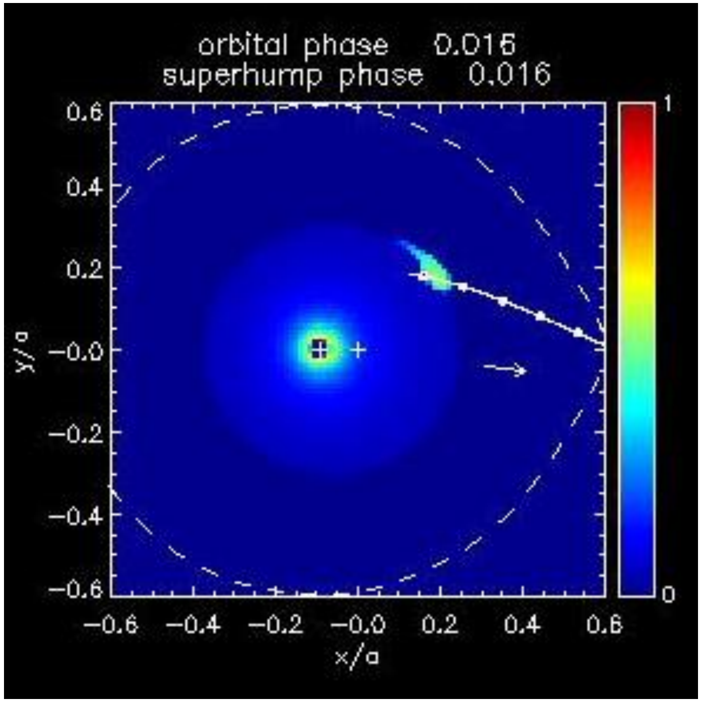
- 2D accretion disk surface dissipation animation using a logarithmic colour scale. The secondary rotates anti-clockwise with respect to the inertial binary frame. The curve at the bottom of the movie shows the simulated dissipation light curve.



Simulation & visualisation by Steve Foulkes et al. The Open University.
http://www.physics.open.ac.uk/FHMR/dudt.html (dudt.avi)

Superhumps: Video (2)

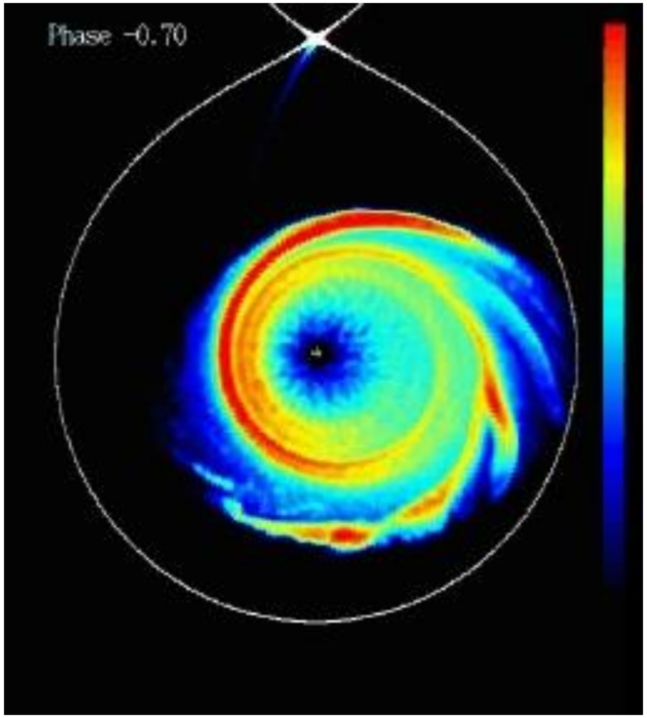
- 3D analytical accretion disk surface dissipation animation using a linear colour scale. The secondary rotates anticlockwise with respect to the inertial binary frame. The arrow indicates a fixed direction to an observer.



Simulation & visualisation by Steve Foulkes et al. The Open University.
http://www.physics.open.ac.uk/FHMR/analytical.html (dan7.avi)

Superhumps: Video (3)

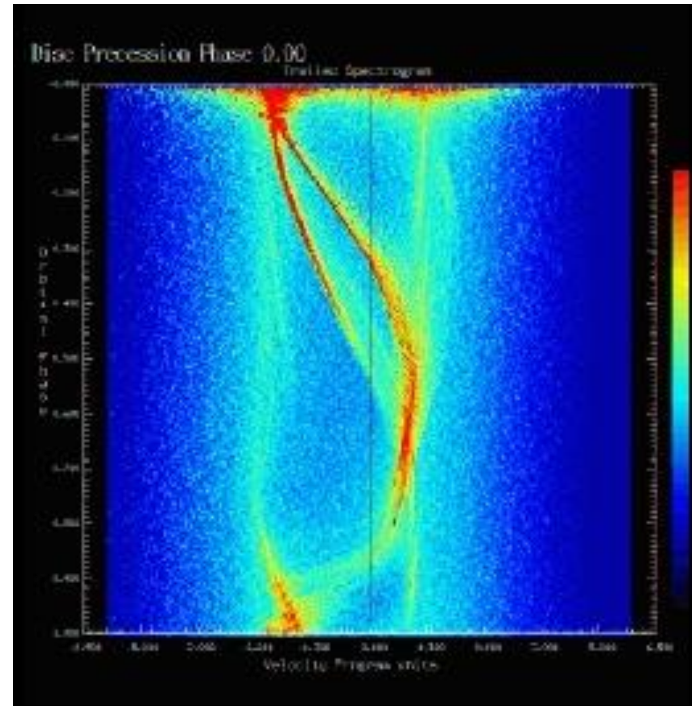
- 2D accretion disk surface density animation using a logarithmic colour scale. The secondary rotates anticlockwise with respect to the inertial binary frame.



Simulation & visualisation by Steve Foulkes et al. The Open University.
http://www.physics.open.ac.uk/FHMR/density.html (dens1.avi)

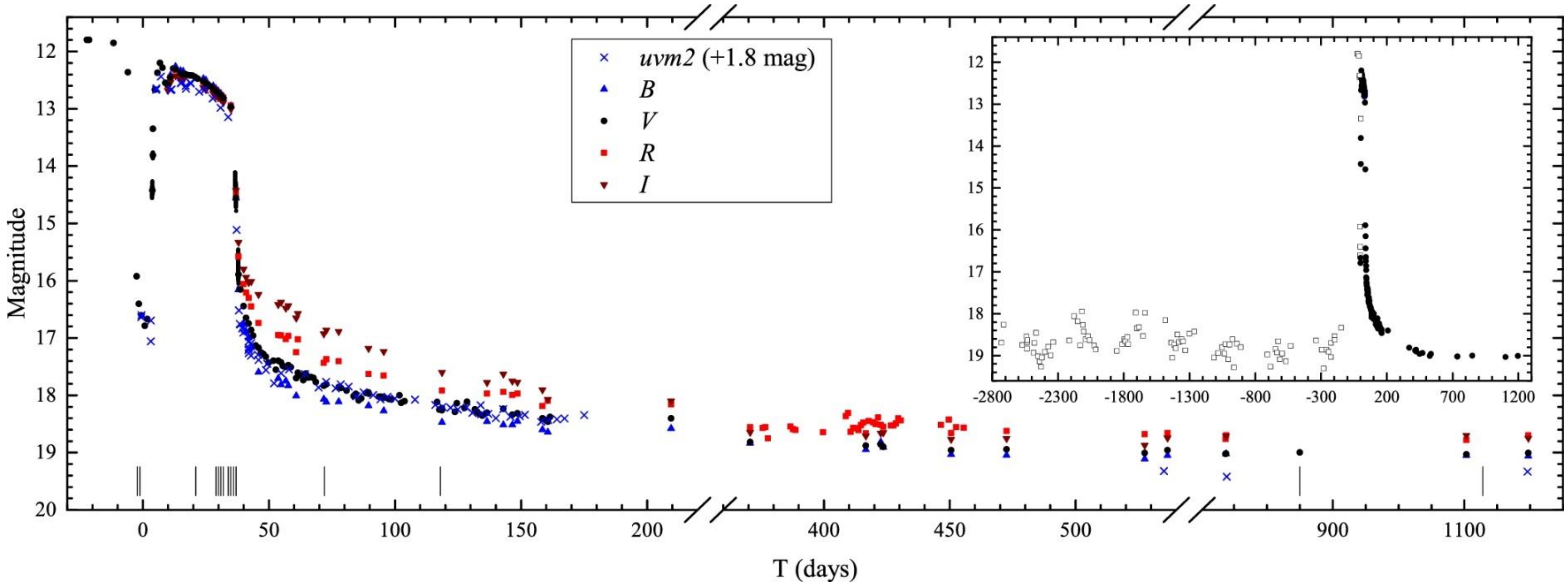
Superhumps: Video (4)

- Trailed spectrogram animation for two complete disk precessions from a SPH simulation. The spectrograms use a linear colour scale and the number in the upper left-hand corner indicates the disk precession phase.



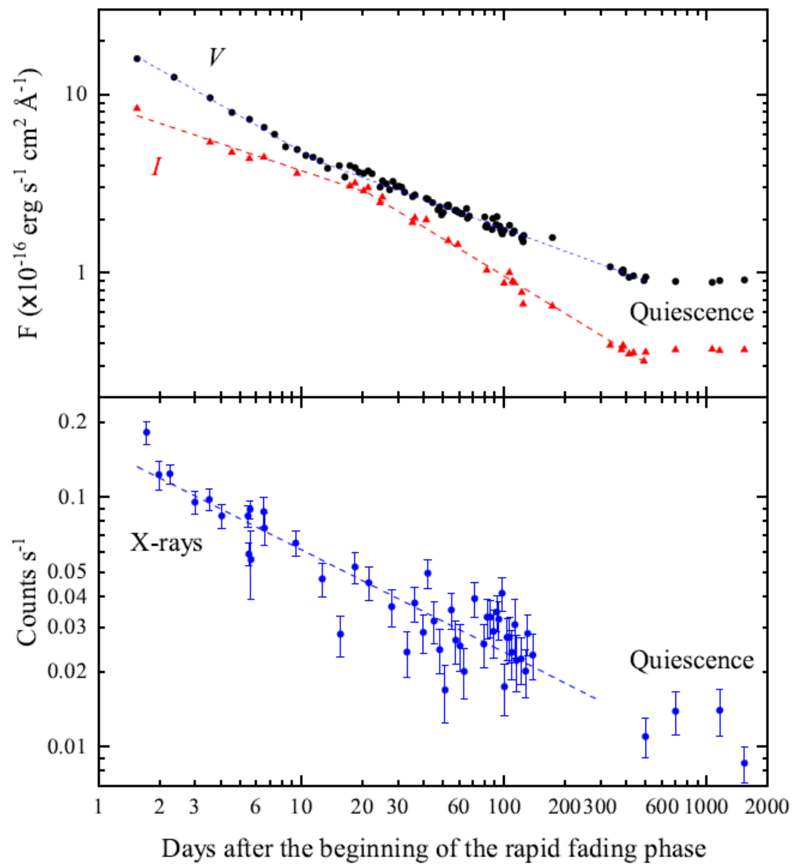
Simulation & visualisation by Steve Foulkes et al. The Open University.
http://www.physics.open.ac.uk/FHMR/spectra.html (spectrogram.avi)

Superoutbursts of WZ Sge-type stars: unexplained features (1)



Superoutbursts of WZ Sge-type stars: unexplained features (2)

- A very extended optical and X-ray decline



Dwarf Nova Outbursts

- P_{orb}-$\dot{M}$ diagram showing different outburst behaviours of non-magnetic CVs.