# Close Binary Stars

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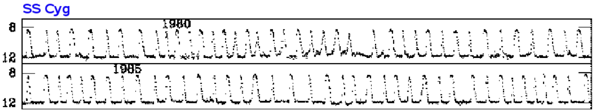
# Cataclysmic Variables Part 1 – Discs

# Long-term light curves




*original: AAVSO*

(Normal) Dwarf Novae, U Gem stars;

semi-regular brightenings (outbursts) with $\Delta m \sim 3 - 4$ mag, $\Delta t \sim 1 - 3$ d, $\Delta t_{\rm rec} \sim 20 - 100$ d

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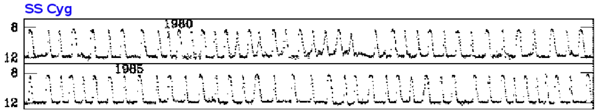


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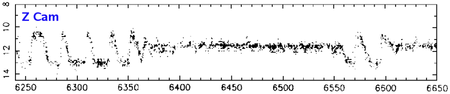


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Z Cam stars; irregular standstills after outbursts at ∼1 mag below maximum
$\Delta m \sim 2 - 3$ mag, $\Delta t \sim 1 - 3$ d, $\Delta t_{\rm rec} \sim 15 - 30$ d

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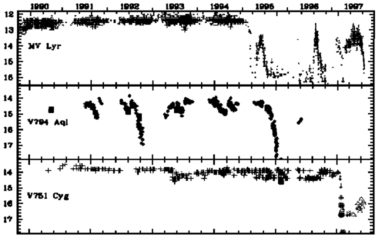


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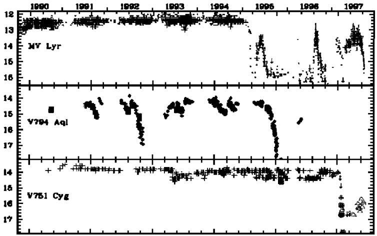


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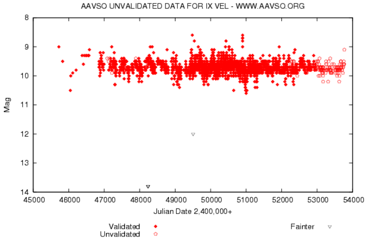


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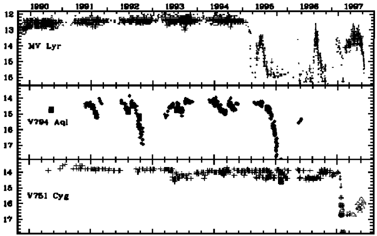


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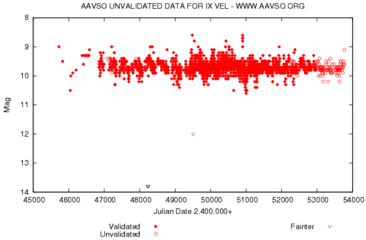


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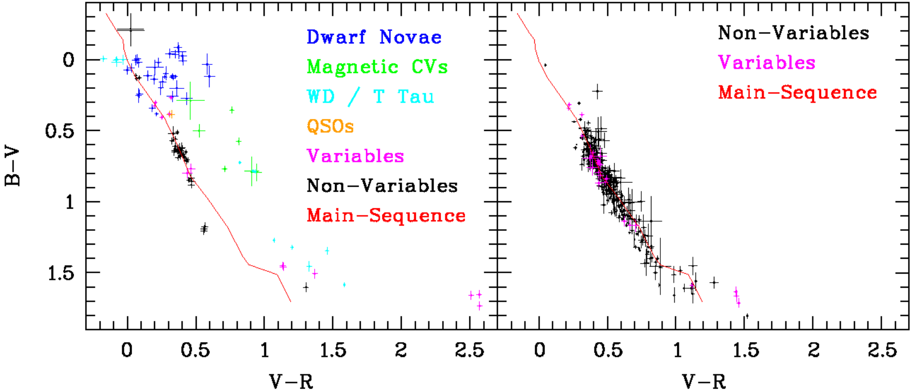
fun fact: the first four discovered CVs, U Gem, SS Cyg, T Leo and Z Cam, belong to three different CV subtypes

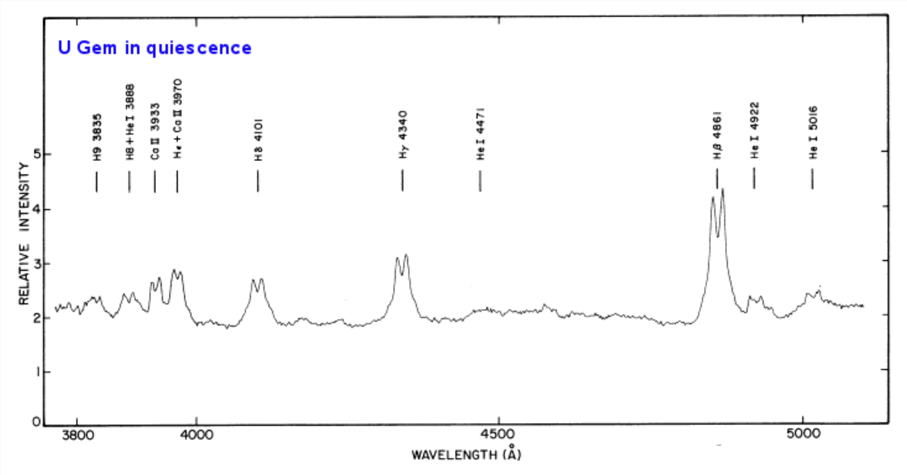
# Colours




*(data from the Calán-Tololo Survey; Tappert et al. 2004; Augusteijn et al. 2010)*

⇒ CVs are blue, but also red

# Spectroscopy: Dwarf Nova in quiescence




*(Stover 1981)*

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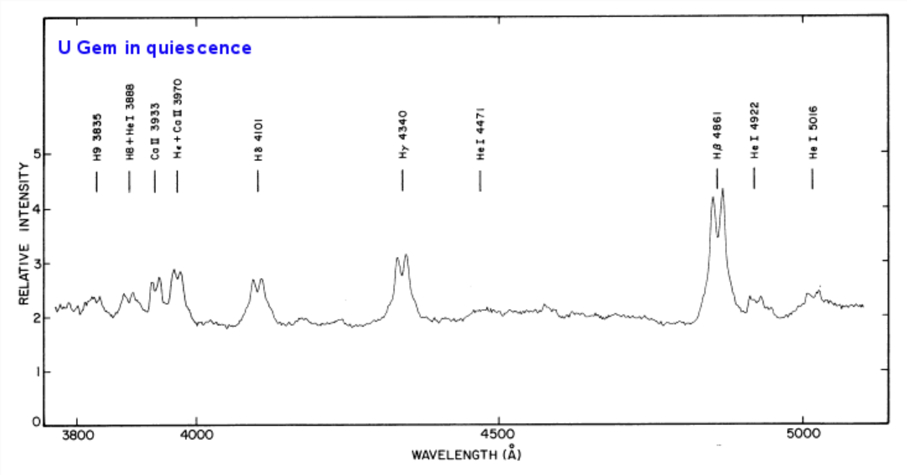


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# Line profiles from a disc

assume optically thin, axisymmetric, flat accretion disc with a Keplerian velocity distribution

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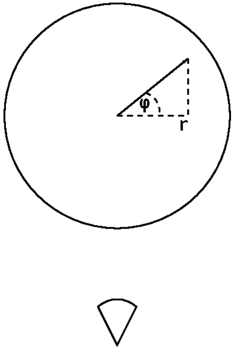

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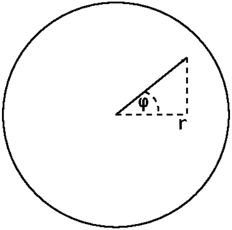
$\Rightarrow$ intensity distribution along the radial velocity $v_\mathrm{rad}$:

$I(v_\mathrm{rad}) \propto \int_{R_1}^{R_2} j(R)\ R\ \frac{d\varphi}{dv_\mathrm{rad}}\ dR$

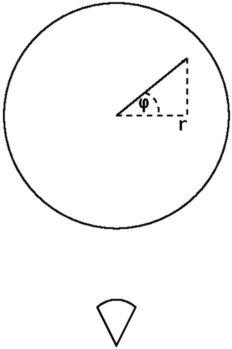
$j(R) \propto R^{-\alpha}$ is the local line emissivity ($\alpha = [1..2]$),
$R_1$ and $R_2$ are the limiting radii of the disc segment
minimum: inner disc radius $R_\mathrm{i}$, maximum: outer disc radius $R_\mathrm{D}$




# Line profiles from a disc

using $r = \frac{R}{R_{\mathrm{D}}}$, setting the origin of a cartesian coordinate system to the centre of the accretion disc, with the observer being at $(x, y) = (0, < 0)$, the Keplerian velocity law transforms to

$v_\varphi(r) = (\frac{GM}{R})^{1/2} = \frac{\mathrm{const}}{R^{1/2}} = \frac{\mathrm{const}}{\sqrt{r}}$



# Line profiles from a disc

$v_\varphi(r) = (\frac{GM}{R})^{1/2} = \frac{\mathrm{const}}{r^{1/2}}$; set const = 1

$v_\varphi(r) = \frac{1}{\sqrt{r}} = \frac{1}{\sqrt[4]{x^2+y^2}}$

component along the line-of-sight

$v_y = v_\varphi \cos\varphi = v_\varphi \frac{x}{\sqrt{x^2+y^2}} = \frac{x}{(x^2+y^2)^{3/4}}$

$\Rightarrow y = \pm\sqrt{\left(\frac{x}{v_y}\right)^{4/3} - x^2}$

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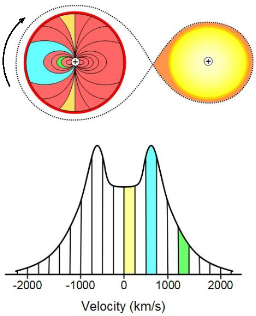
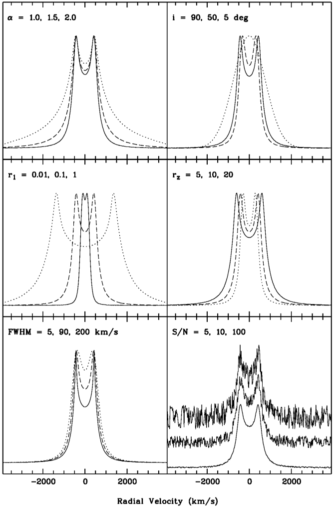


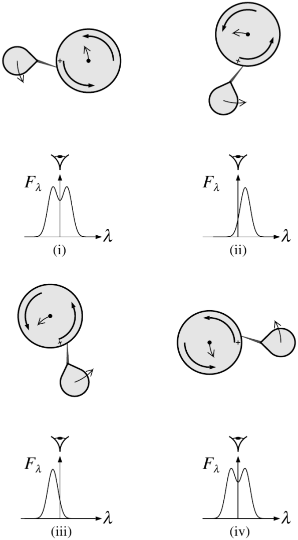

*(Horne & Marsh 1986)*

# The effect of different parameters on the line profile



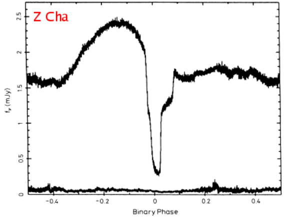

*Tappert (1999)*

# The effect of eclipses

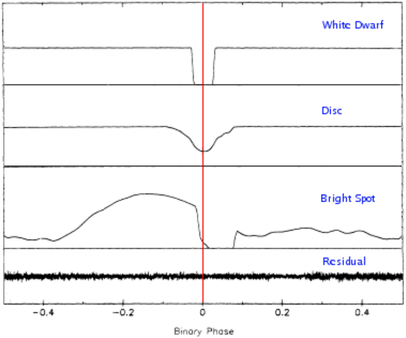



*Frank et al. (2002)*

# Eclipses

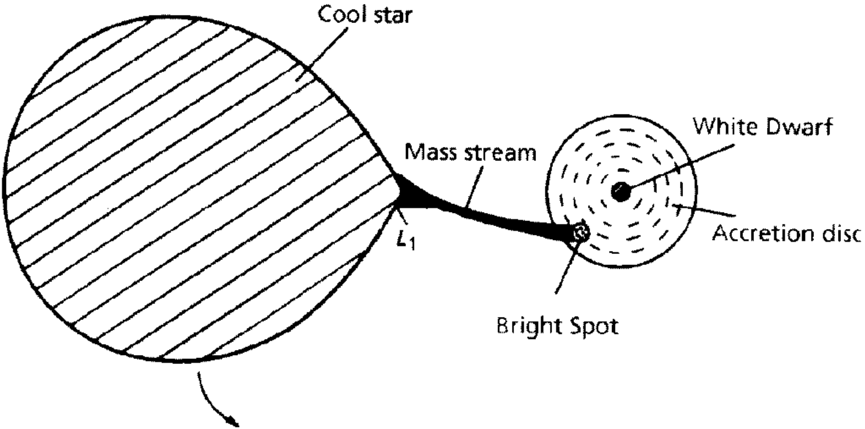



*Wood et al. (1986)*



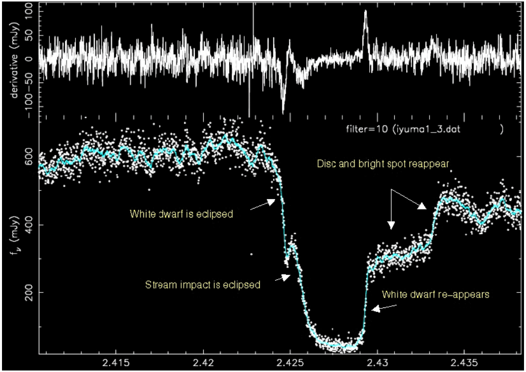

*Wood et al. (1986)*

# (Disc) CV components




*Warner (1995)*

# Eclipse structure




*(www.vikdhillon.staff.shef.ac.uk/seminars/exeter/eclipses.html)*

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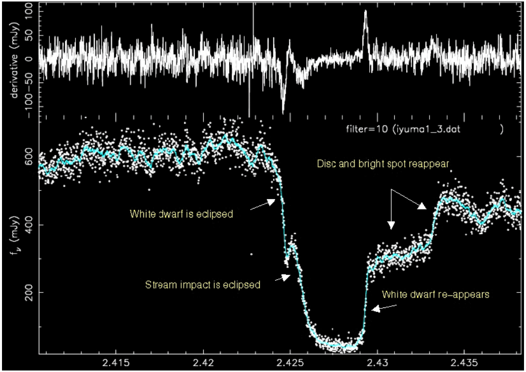


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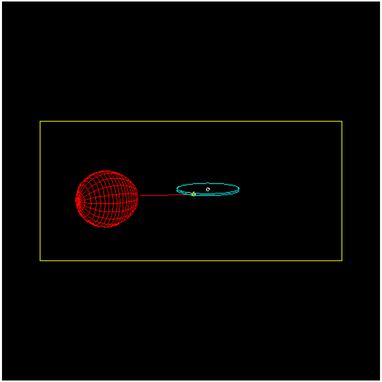

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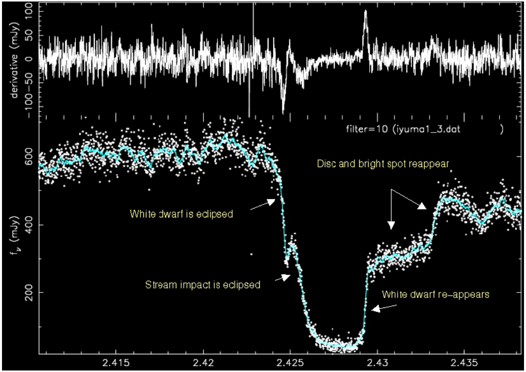


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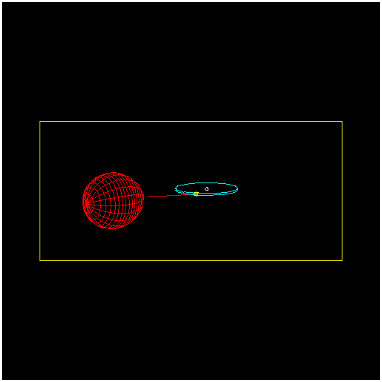

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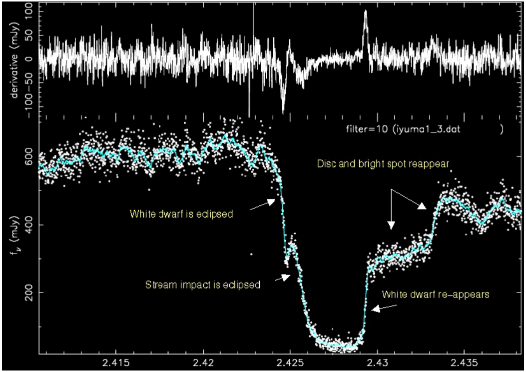


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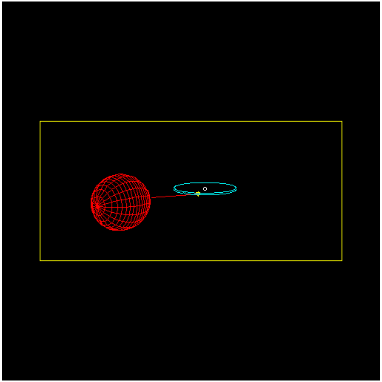

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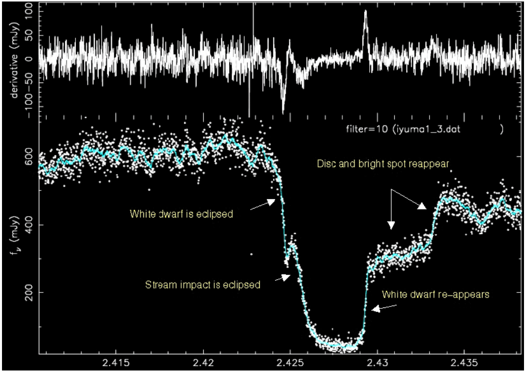


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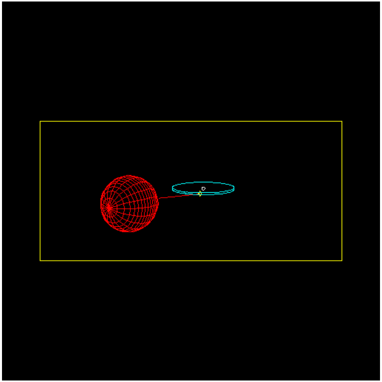

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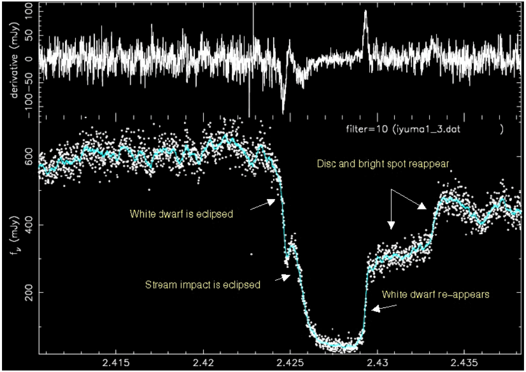


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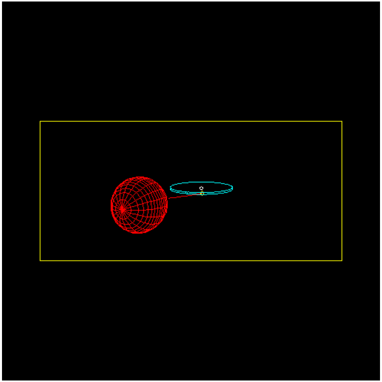

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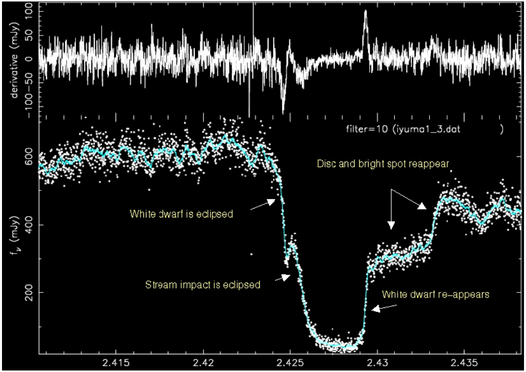


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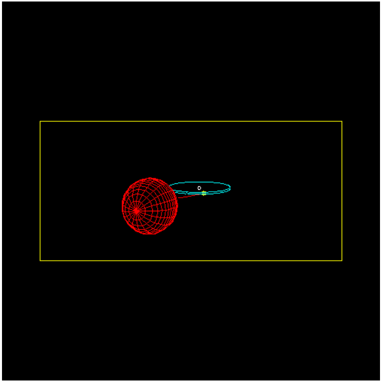

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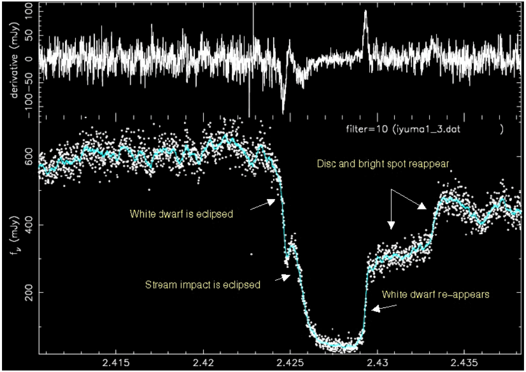


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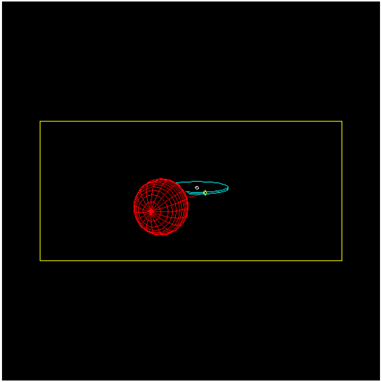

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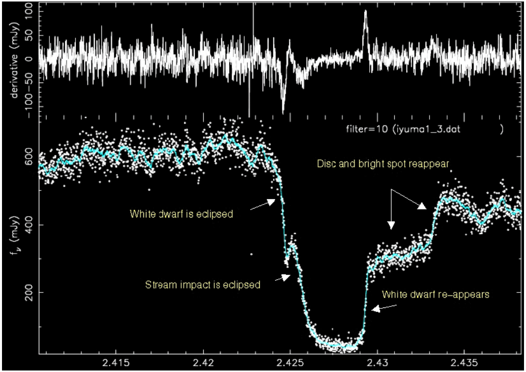


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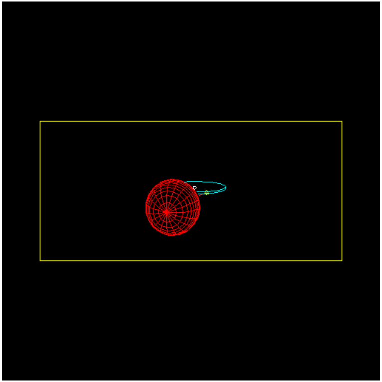

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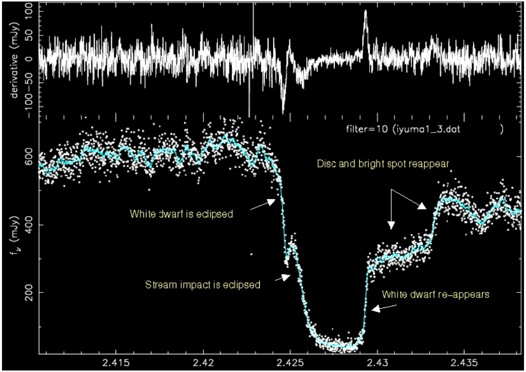


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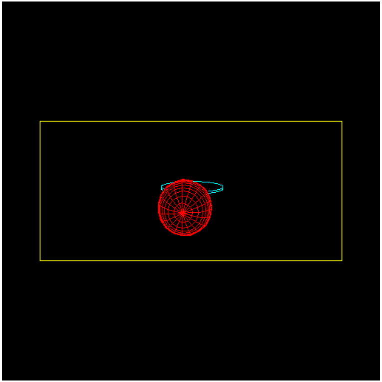

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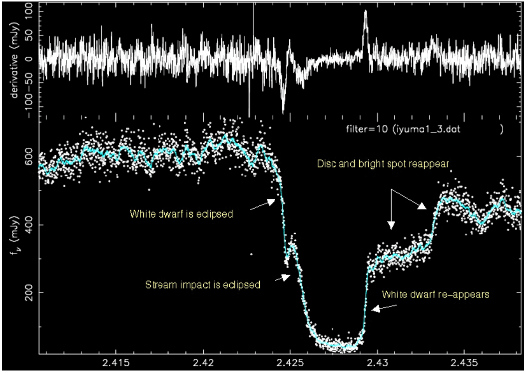


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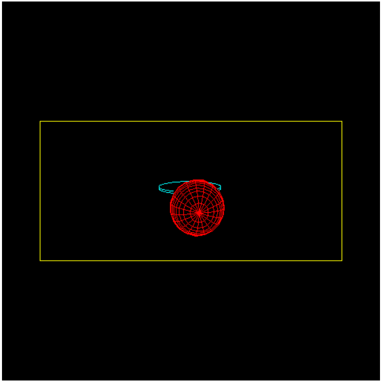

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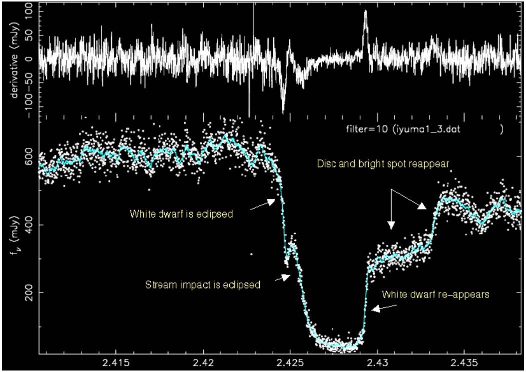


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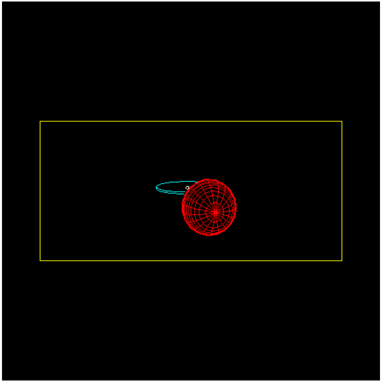

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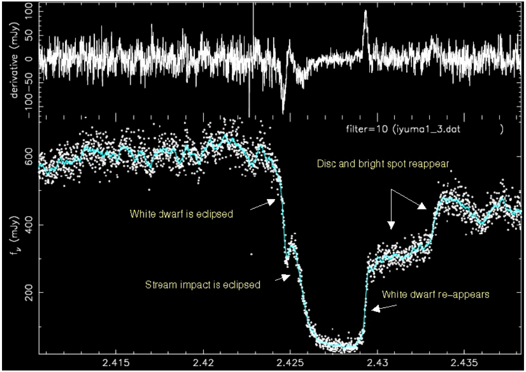


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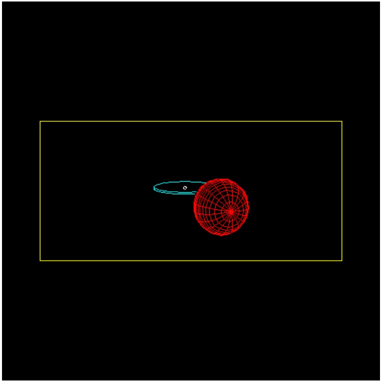

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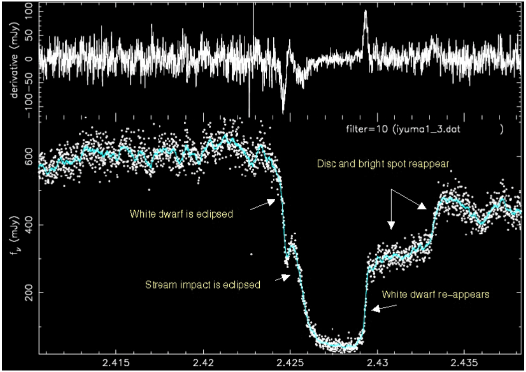


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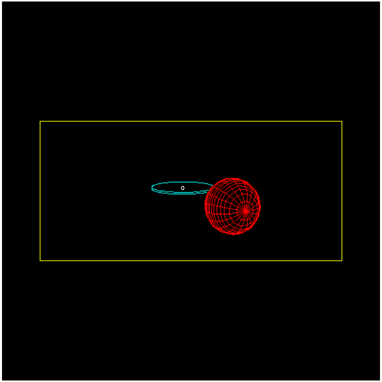

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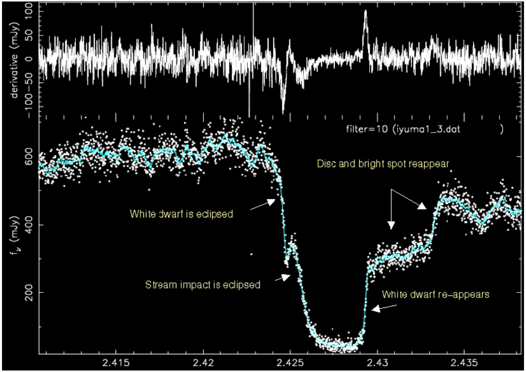


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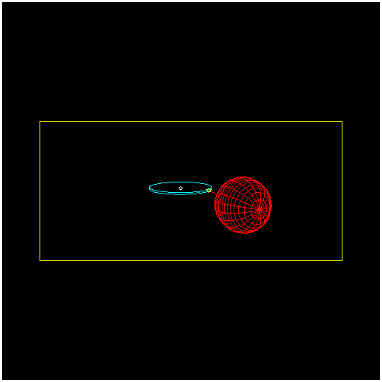

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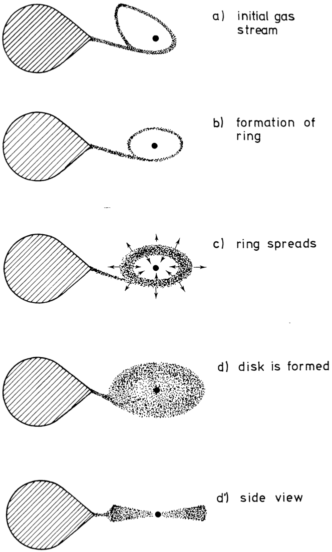
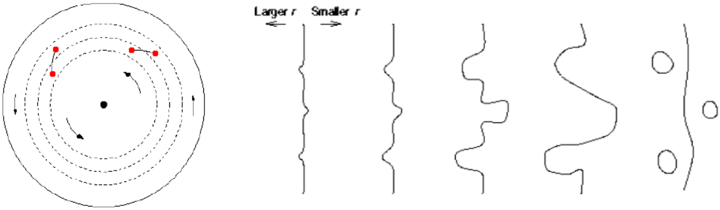
# Disc formation




*Verbunt (1982)*

Accretion discs transport matter inwards and angular momentum outwards

# Magnetic Turbulence




(Hellier 2001)

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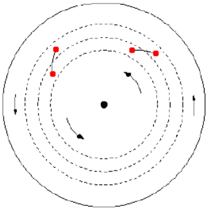

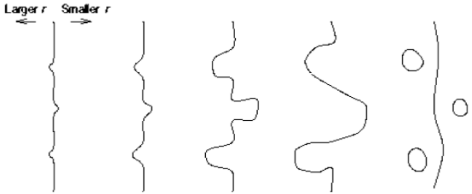


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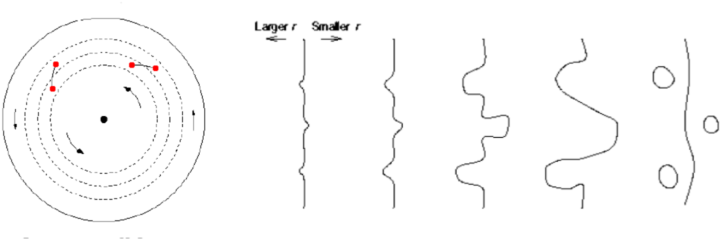


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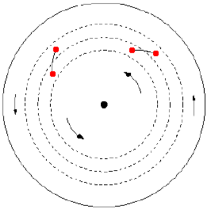

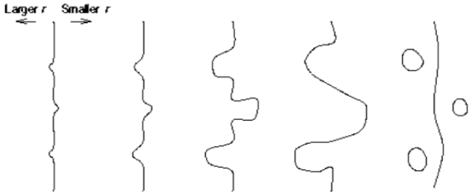


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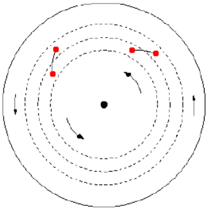

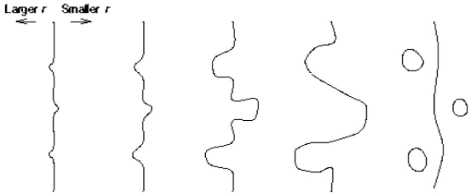


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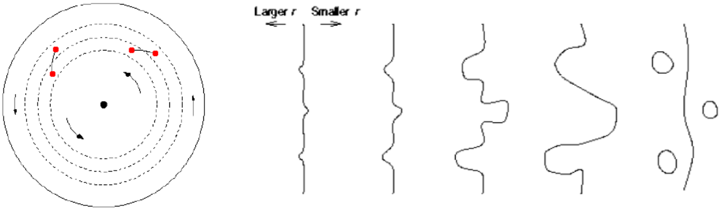


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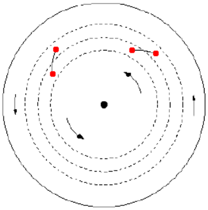

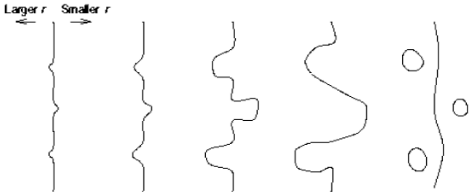


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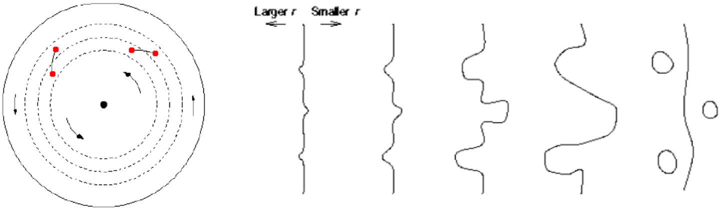


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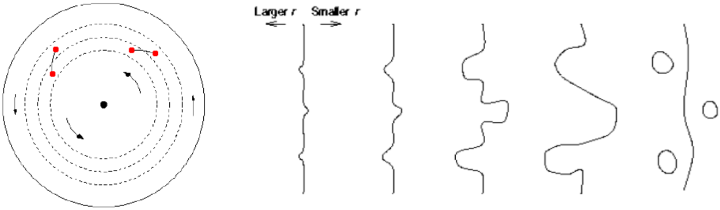


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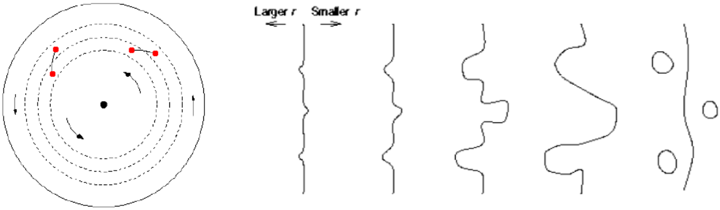


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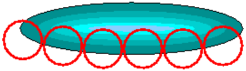
material follow field lines $\Rightarrow$ "intermediate" magnetic loops effectively transport matter and angular momentum $\Rightarrow$ feasible viscosity mechanism

# Disc Structure: Eclipse Mapping



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translate 1-D info to 2-D structure ⇒ maximum-entropy algorithm

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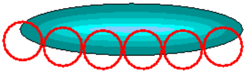

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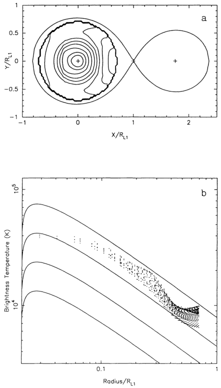
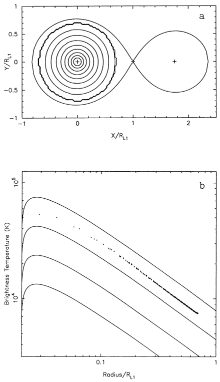



Wood (1994)

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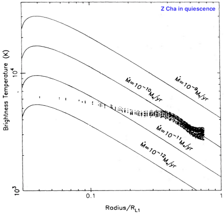
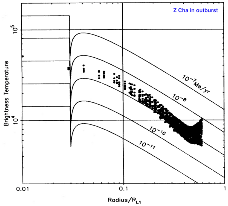
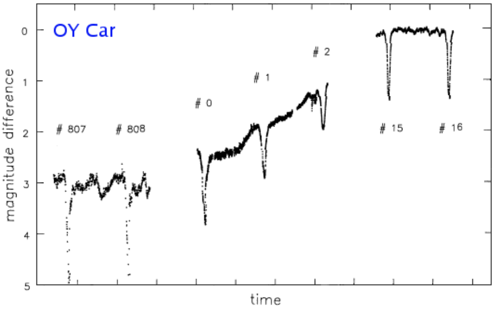



*original: Wood et al. (1986)*

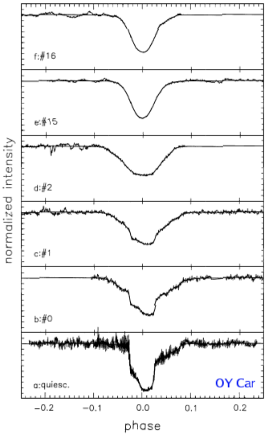



*original: Horne & Cook (1985)*

# Outburst observations




*Rutten et al. (1992)*

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during outburst, hump disappears, eclipse becomes symmetric (disc eclipse)

$\Rightarrow$ dwarf-nova outbursts = increase of disc luminosity

# Disc-Radius Variation

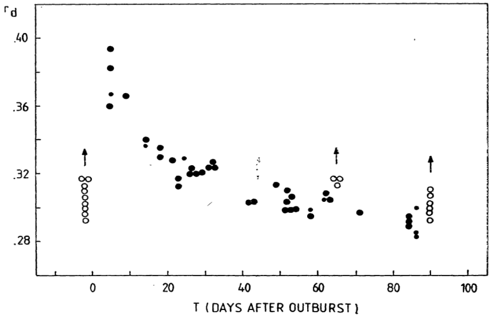
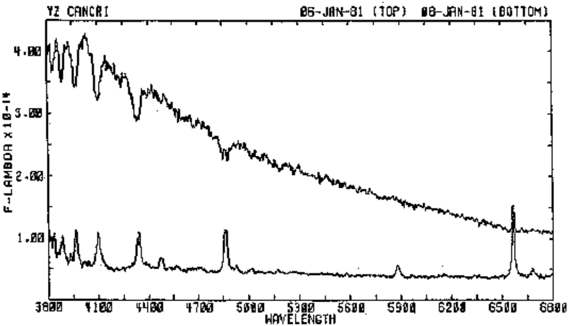



Fig. 1. Variations of the disk-radius. Small symbols are of lower weight. Open circles are from eclipses observed at the onset of an outburst.

*(Smak 1984)*

during outburst, the radius of the accretion disc increases rapidly, and afterwards slowly decreases to its quiescence value

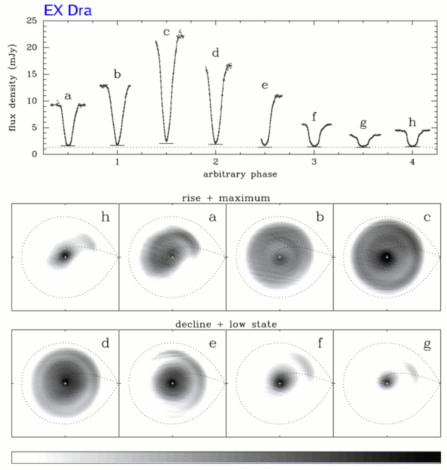
# Spectroscopy in quiescence and outburst




*Shafter (1983)*

accretion disc becomes bluer (= hotter) and optically thick during outburst

# Temperature evolution in outburst




*Baptista & Catalán (2001)*

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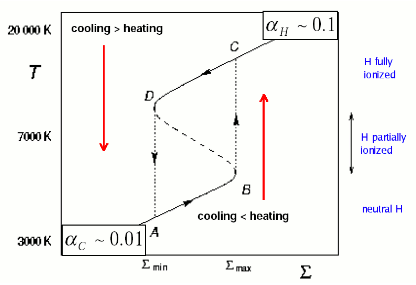
now, mass transfer from secondary $\dot{M}_2$ is smaller than mass transport through the disc $\dot{M}_d$
$\Rightarrow$ disc eventually returns to its quiescent state

# S-curve




*(Hellier 2001)*

consider one annulus in the disc with given Σ, *T* (surface density, temperature)

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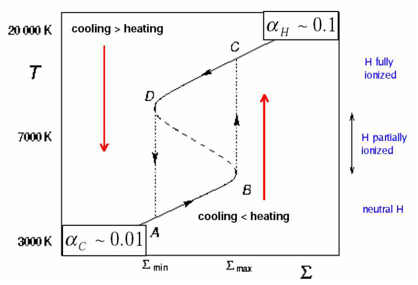


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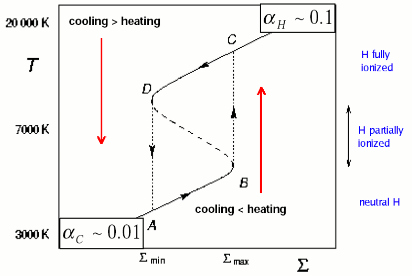


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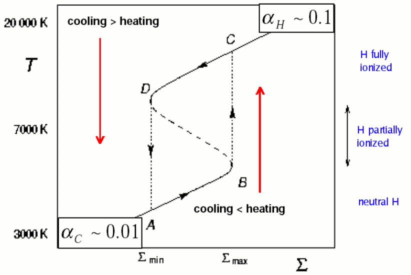


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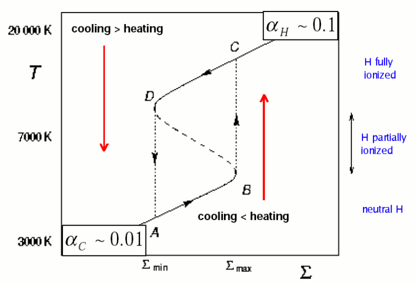


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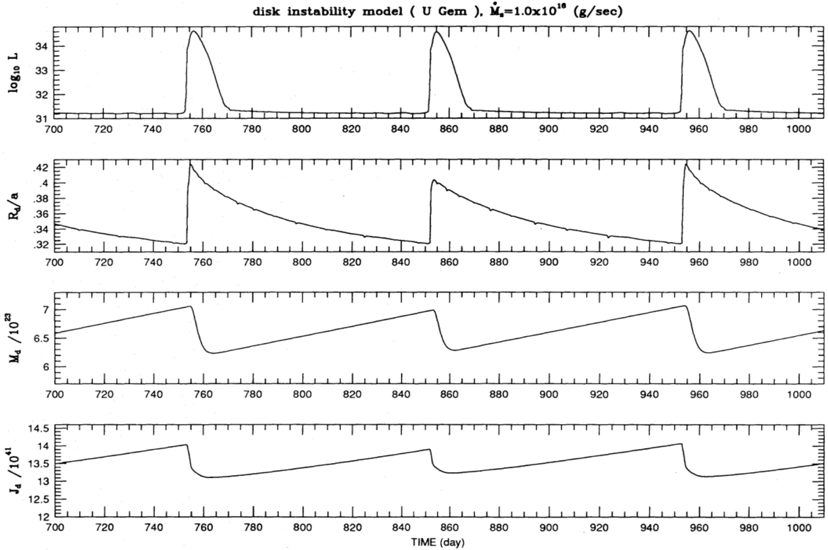
$D$: H recombines, disc cools down to $A$

Disc-Instability Model (DIM) (Osaki 1974)

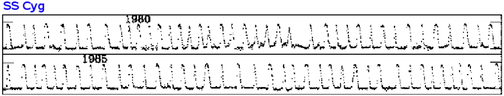
alternative: Mass-Transfer Instability (Bath 1975)

# Outburst Cycle

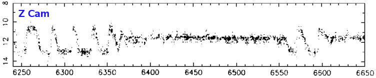



*(Ichikawa & Osaki 1992)*

# Interpretation of long-term light curves




original: AAVSO

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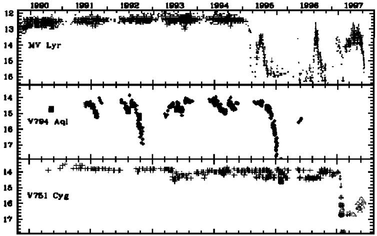
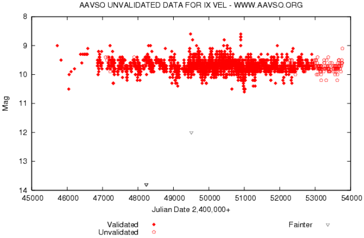



original: Greiner (1998)




data: AAVSO

U Gem dwarf novae continuously follow the S-curve

Z Cam dwarf novae follow the S-curve, but sometimes get "stuck" in a stable configuration

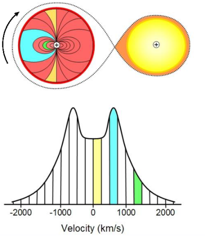
VY Scl NLs have stable discs, but sometimes slip into an unstable configuration

UX UMa NLs have stable discs

$\rightarrow \dot{M}_2$ vs $\dot{M}_{\rm disc}$

# Additional emission sources

Theory:




*(Horne & Marsh 1986)*

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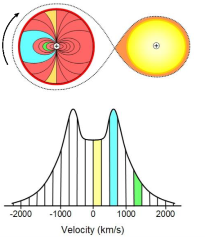
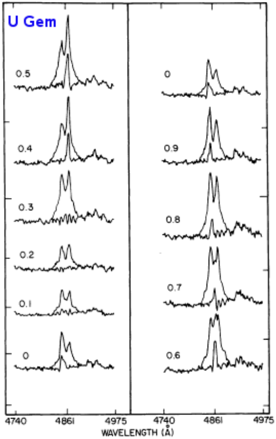



*(Horne & Marsh 1986)*

Observation:




*(Stover 1981)*

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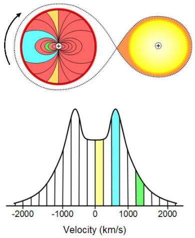


(Horne & Marsh 1986)

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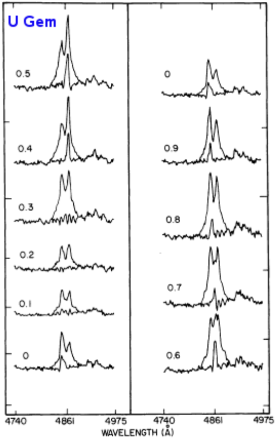
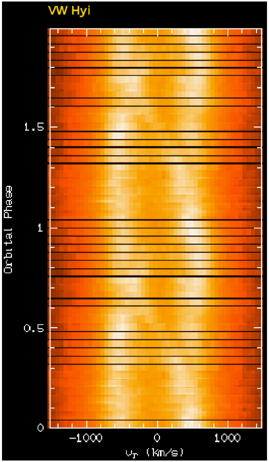
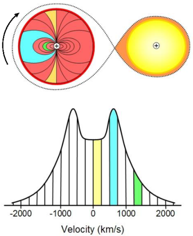



(Stover 1981)



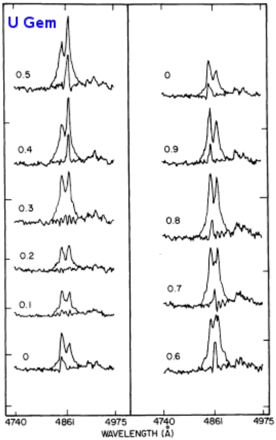
# Additional emission sources

Theory:

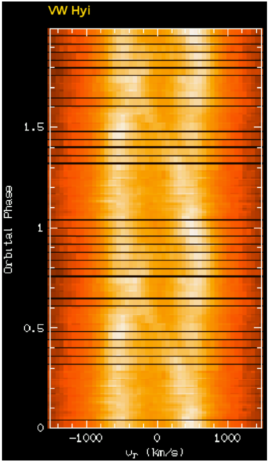



(Horne & Marsh 1986)

Observation:

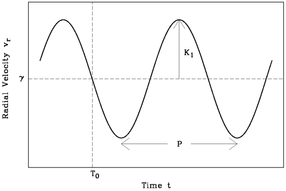



(Stover 1981)




possible emission sources:
bright spot, secondary, ...

# Consequences for radial velocity measurements




$$v_r(\varphi) = \gamma - K_1 \sin(2\pi\varphi), \quad \varphi = (t - T_0) \pmod P$$

Kepler III: $\frac{P^2}{a^3} = \frac{4\pi^2}{G(M_1+M_2)}$; $\quad K_1 = 2\pi \frac{a_1}{P} \sin i$; $\quad a = a_1 + a_2$

$$\Rightarrow q = \frac{M_2}{M_1} = \frac{K_1}{K_2}$$

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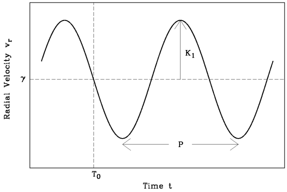


$v_r(\varphi) = \gamma - K_1 \sin(2\pi\varphi), \quad \varphi = (t - T_0) \pmod{P}$

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assuming a constant line profile that is Doppler-shifted according to the orbital motion of the WD

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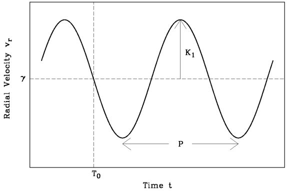


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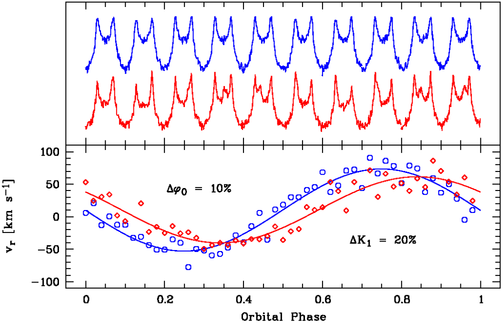


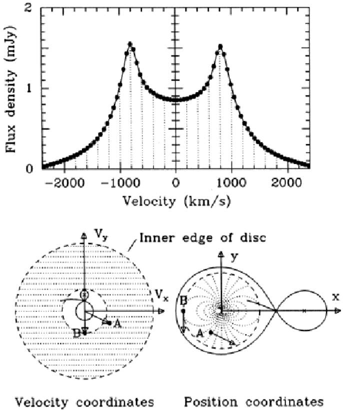

using a single broad Gaussian to measure the central wavelength of the emission line

$\Rightarrow$ the measured semi-amplitude does not reflect the motion of the WD and thus yields erroneous parameters

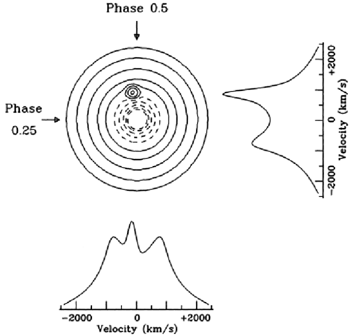
additional emission is confined to the central part $\Rightarrow$ solution: measure line wings (but: lower S/N)

# Doppler Tomography

images of the emission distribution in velocity space




Marsh & Horne (1988)

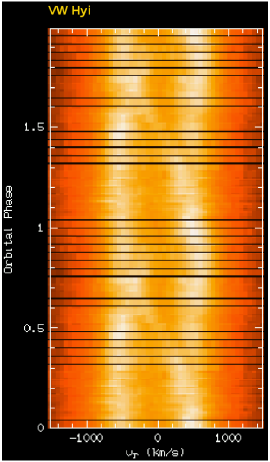


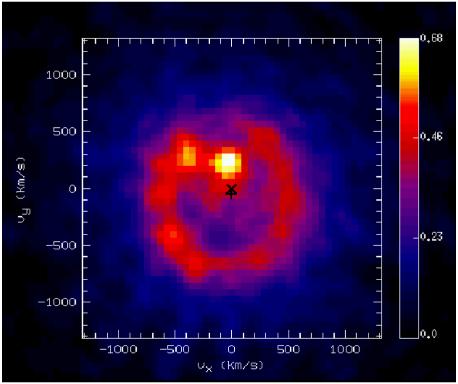

Marsh & Horne (1988)

line profiles = 1-D projections of the 2-D velocity image

⇒ maximum-entropy algorithm

# Doppler Tomography: VW Hyi

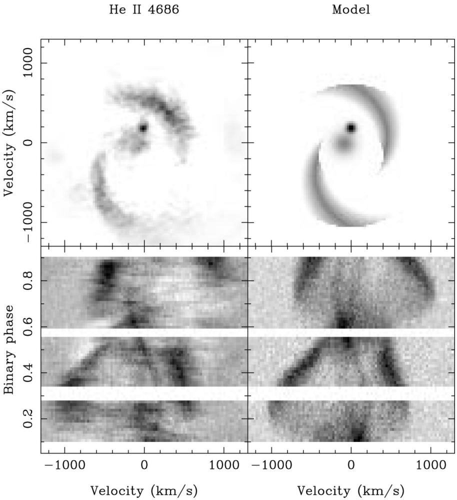



$\Rightarrow$ emission from secondary + bright spot

Note: transformation into positional coordinates not possible without knowledge of the velocity law!

# IP Peg in outburst




*Harlaftis et al. (1999)*

spiral waves as an additional driver of angular momentum

depends on the temperature (works principally in high $\dot{M}$ discs)