Compact Binaries

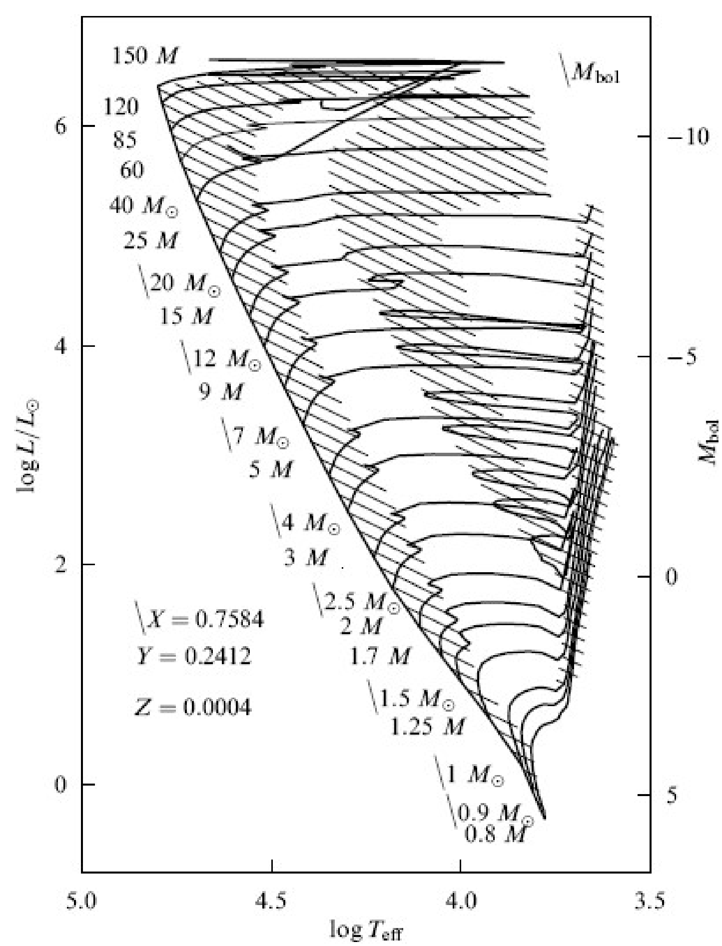
- *Evolution*
- *Roche Lobes & Mass Transfer*
- *Accretion Disks*
- *Winds from accretion disks*
- *Steam-disc interactions*
- *SW Sex, VY Scl stars*

David Buckley
(dibnob@saao.ac.za)

South African Astronomical Observatory
Department of Astronomy UCT
Department of Physic UFS

22 March 2023

Recap: evolution of normal stars



Evolutionary tracks of single stars with masses from 0.8 to 150M. The slowest evolution is in the hatched regions
(Lejeune T, Schaerer D Astron. Astrophys. 366 538 (2001))

Timescale for star on Main Sequence (burning hydrogen in the core):

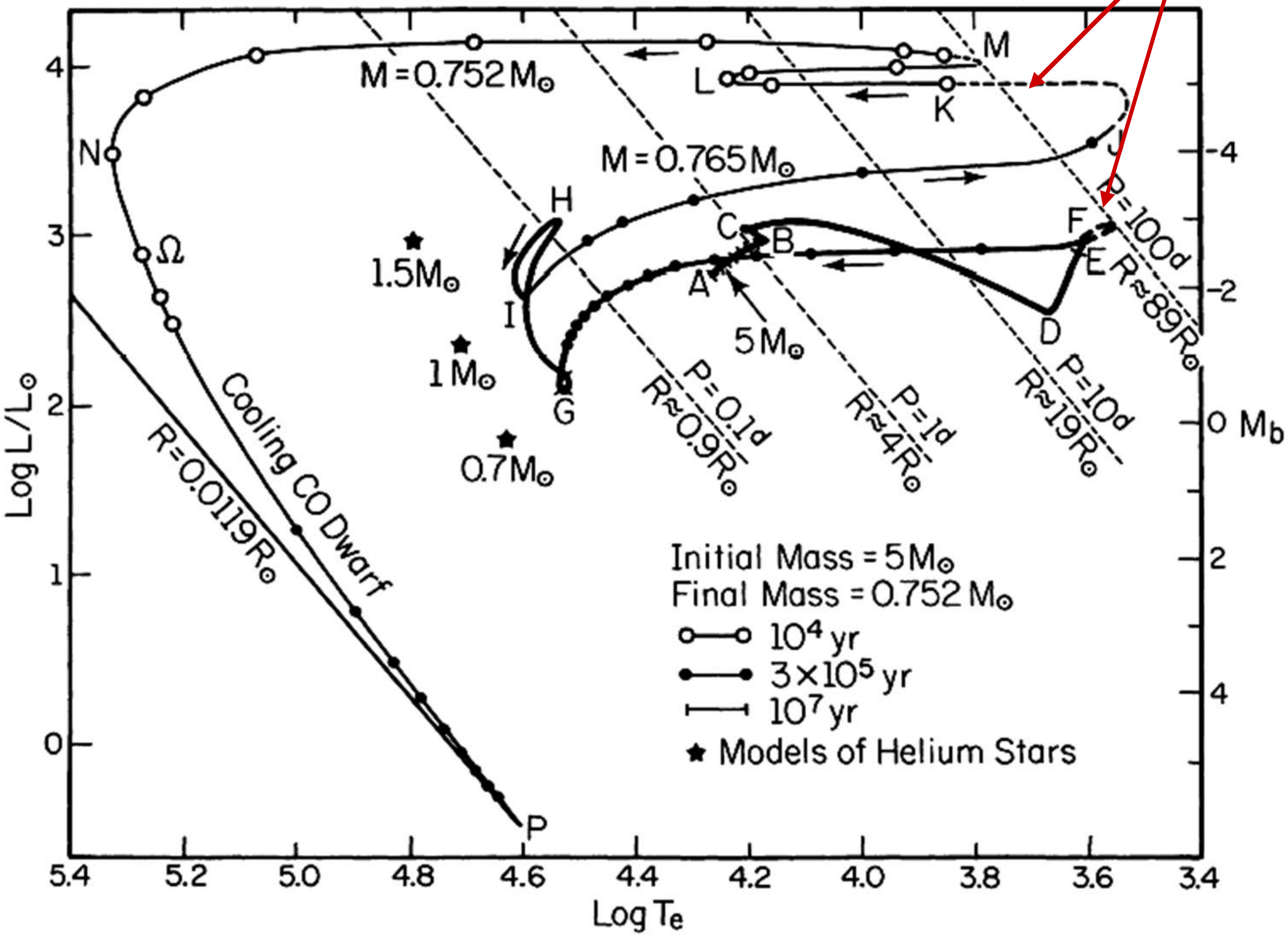
$$T_{MS} = (M_{MS}/M_{\odot})^{-2.5}\ 10^{10}\ \mathrm{y}$$

A 5$M_\odot$ star evolves off the M-S after ~180 Myr
A 10$M_\odot$ star evolves off the M-S after ~30 Myr
A 50$M_\odot$ star evolves off the M-S after ~0.5 Myr

Binary star evolution very much governed by mass too

Evolution of a 5M star in a close binary

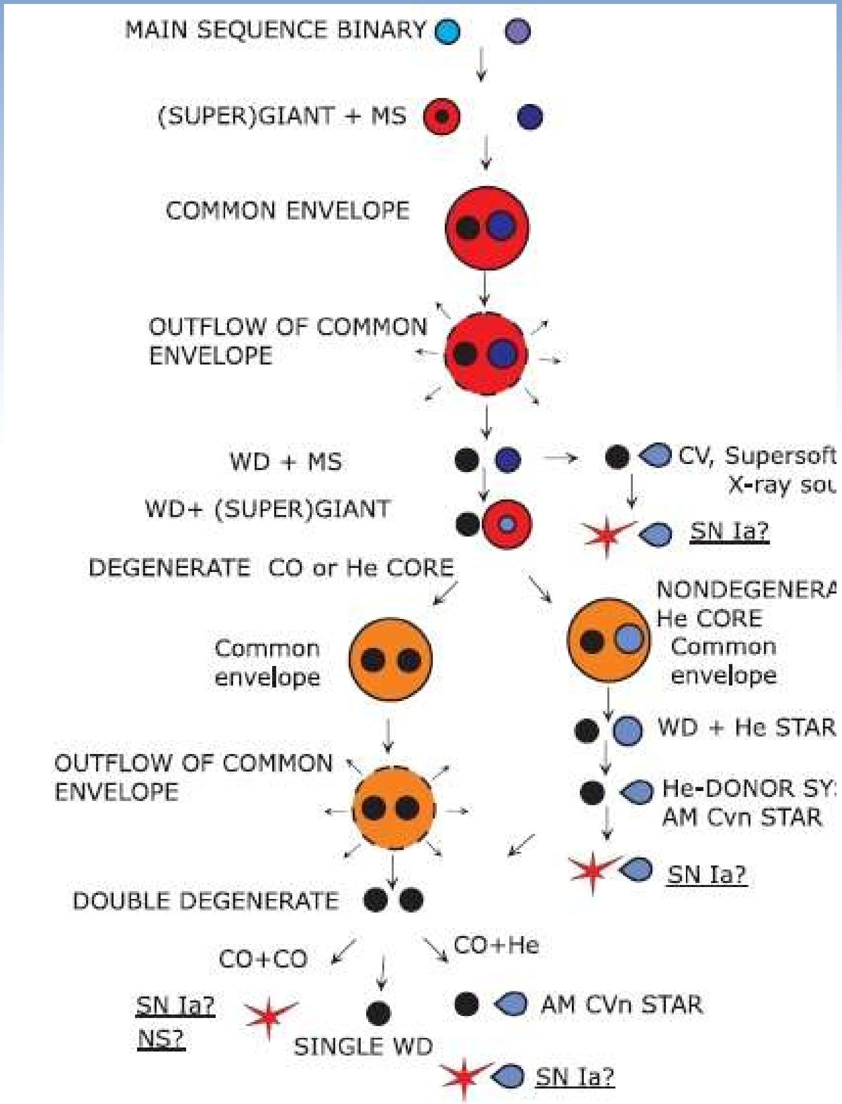
666 IBEN AND TUTUKOV



Mass loss stages

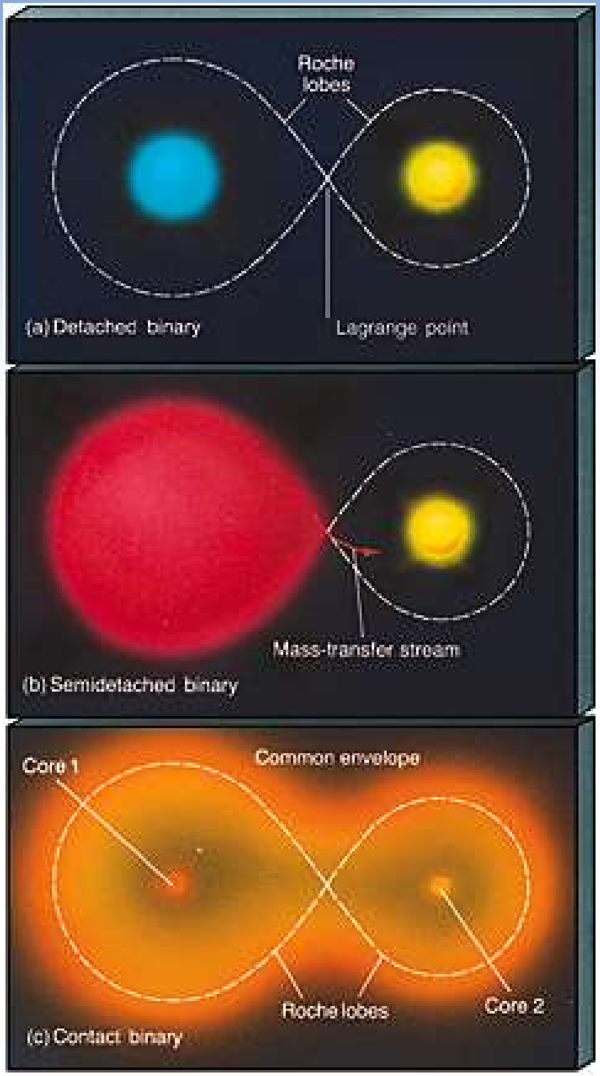
FIG. 1.—Evolution in the H-R diagram of a binary component of initial mass 5 $M_\odot$. Initial composition parameters are $X = 0.7$, $Z = 0.02$. The positions of helium model stars are given by the filled, five-pointed "stars" (Paczyński 1971). Lines of constant orbital period and Roche-lobe radius for a system consisting of two 5 $M_\odot$ unevolved stars are also shown. The temperature of the CO shell reaches a maximum at the point Ω along the track. The main parameters of the stellar model at other labeled points (A,B,...) are presented in Table 1. Mass loss occurs along dashed portions of the track (E to F; J to K). Time evolution is measured by tick marks (10^7 yr), filled circles (3×10^5 yr), and open circles (10^4 yr).

Evolution of close binaries



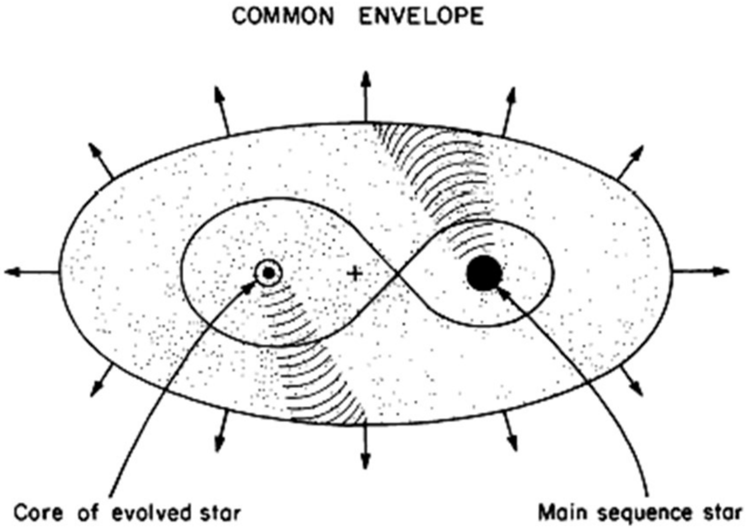
(Postnov, Yungelson 2007)

Common envelope



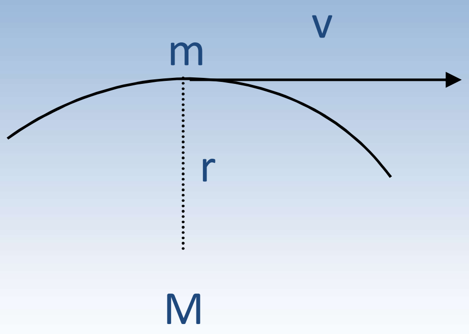
Problem: How to make close binaries with compact stars (CVs, XRBs)?
Most angular momentum from the system should be lost.

Non-conservative evolution:
Common envelope stage
(B.Paczynski, 1976)



Dynamical friction is important

Basic Equations



Keplerian orbit: $$\frac{mv^2}{r} = \frac{GMm}{r^2} \Longrightarrow v = \sqrt{\frac{GM}{r}}$$

Angular frequency: $$\omega = \frac{2\pi}{P} = 2\pi f = \frac{v}{r} = \sqrt{\frac{GM}{r^3}}$$

Angular momentum: $$\underline{L} = m\underline{v} \times \underline{r}$$

$$\begin{aligned} v \perp r \Longrightarrow L &= mvr \\ &= \sqrt{GMrm} \end{aligned}$$

Kinetic energy: $$E_k = \frac{1}{2}mv^2 = \frac{1}{2}m\omega^2 r^2 = \frac{1}{2}\frac{GMm}{r}$$

Keplers law: $$P_{orb}^2 = \frac{4\pi^2 r^3}{G(M+m)}$$

Orbit of a test particle in a gravitational field of a binary

Roche approach

Test particle in the gravitational potential of 2 orbiting bodies (M_1 and M_2)

Assumptions:

1) Massive stars → their orbits not perturbed (Restricted 3-body problem)
2) Circular orbits
3) Stars centrally condensed → point masses

Gas flow between two stars governed by Euler equation (momentum conservation):

In the binary reference frame consider:

Pressure force + Grav. + centrifugal + Coriolis

$$f/ \rho = - \nabla\Phi - 2\omega \times v$$

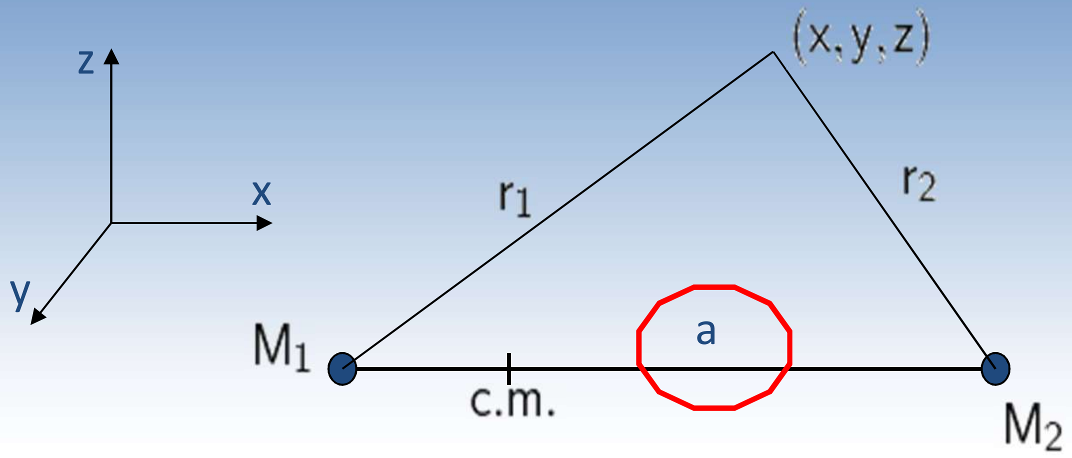
Gravitational + centrifugal term

Coriolis term

Equipotential lines in binary stars

$$r_1^2 = x^2 + y^2 + z^2$$

$$r_2^2 = (x-a)^2 + y^2 + z^2$$



mass ratio $\boxed{q = \frac{M_2}{M_1}}$

$$x_{c.m.} = \frac{M_2}{M_1 + M_2} = \boxed{\frac{q}{1+q}}$$

Gravitational terms

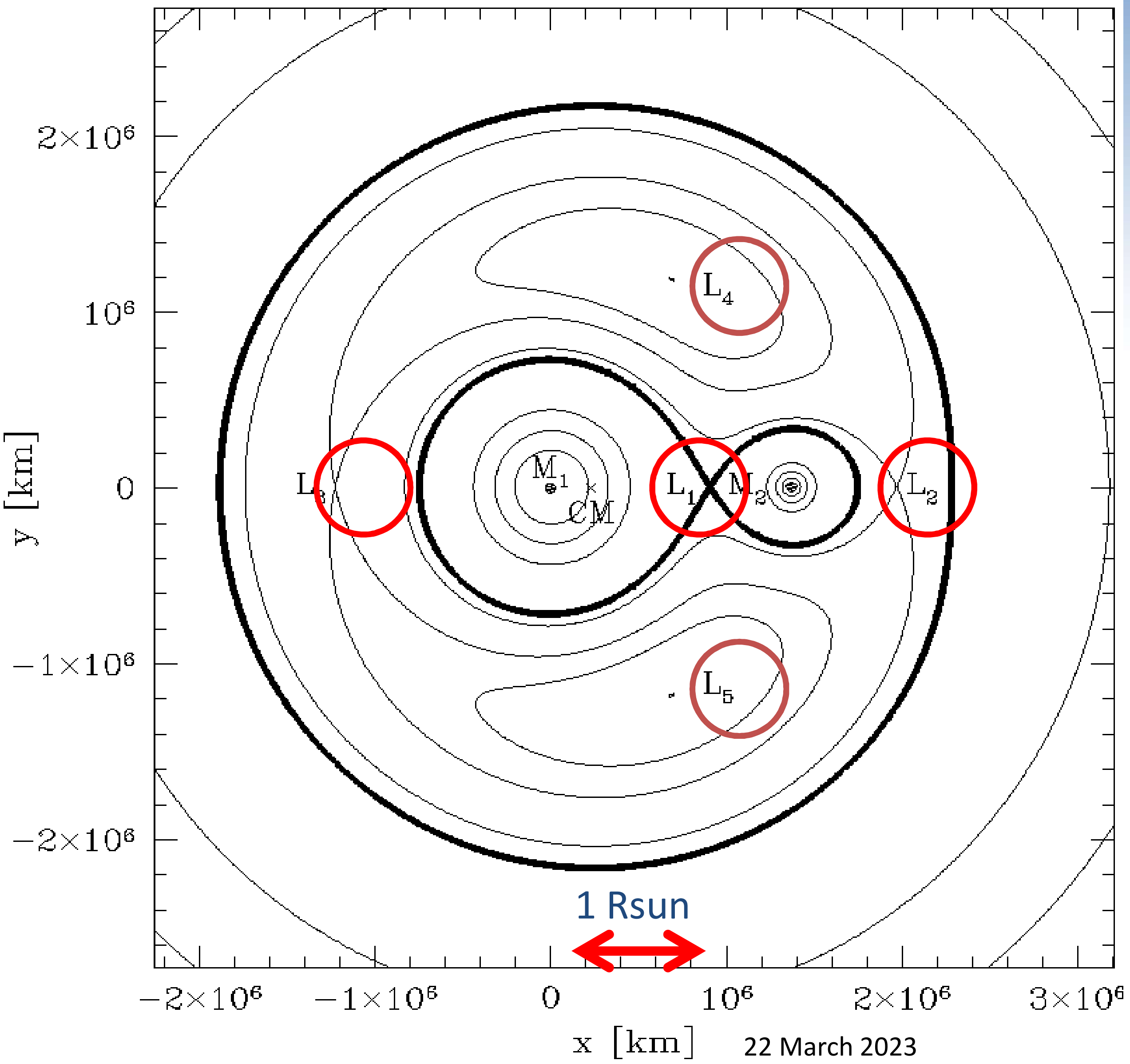
Centrifugal term

Roche potential: $$\phi_R = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{1}{2}\omega\left[(x - x_{c.m.})^2 + y^2\right] \qquad \omega = \frac{2\pi}{P} = 2\pi f$$

Edouard Roche (1820-1883)

Joseph Lagrange (1736-1813)

The Roche potential: equipotential lines



$q = 0.2, \quad P_{orb} = 7h$

5 "Lagrangian" points:

$$\nabla \phi_R = 0$$

Lagrange points

$$\nabla\phi_R = 0$$

- L_1 - Inner Lagrange Point
  - in between two stars
  - matter can flow freely from one star to other
  - mass exchange
- L_2 - on opposite side of secondary
  - matter can most easily leave system
- L_3 - on opposite side of primary
- L_4, L_5 - in lobes perpendicular to line joining binary
  - form equilateral triangles with centres of two stars
- **Roche-lobes**: surfaces which just touch at L_1
  - maximum size of non-contact systems

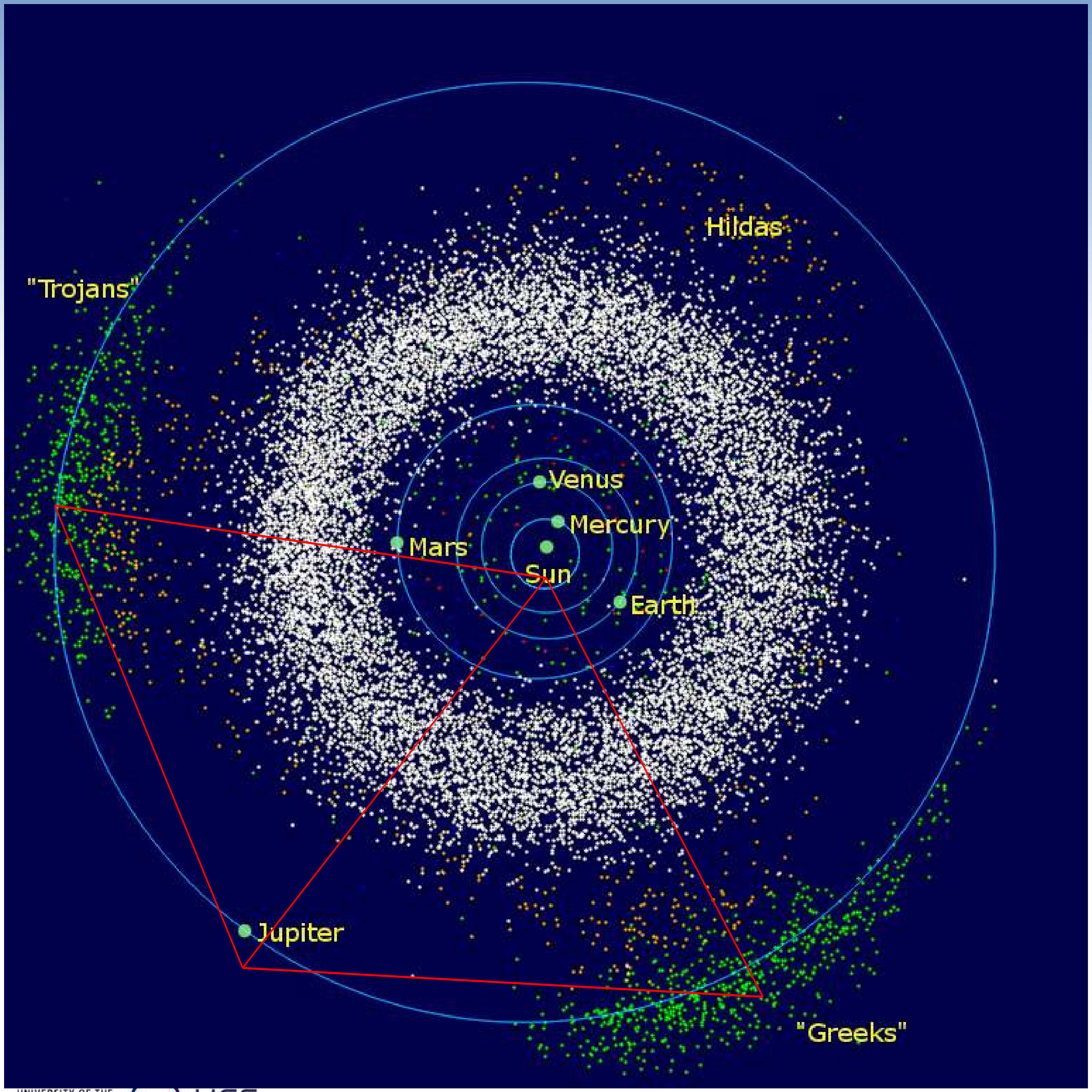
Earth-Sun

L_1: SOHO

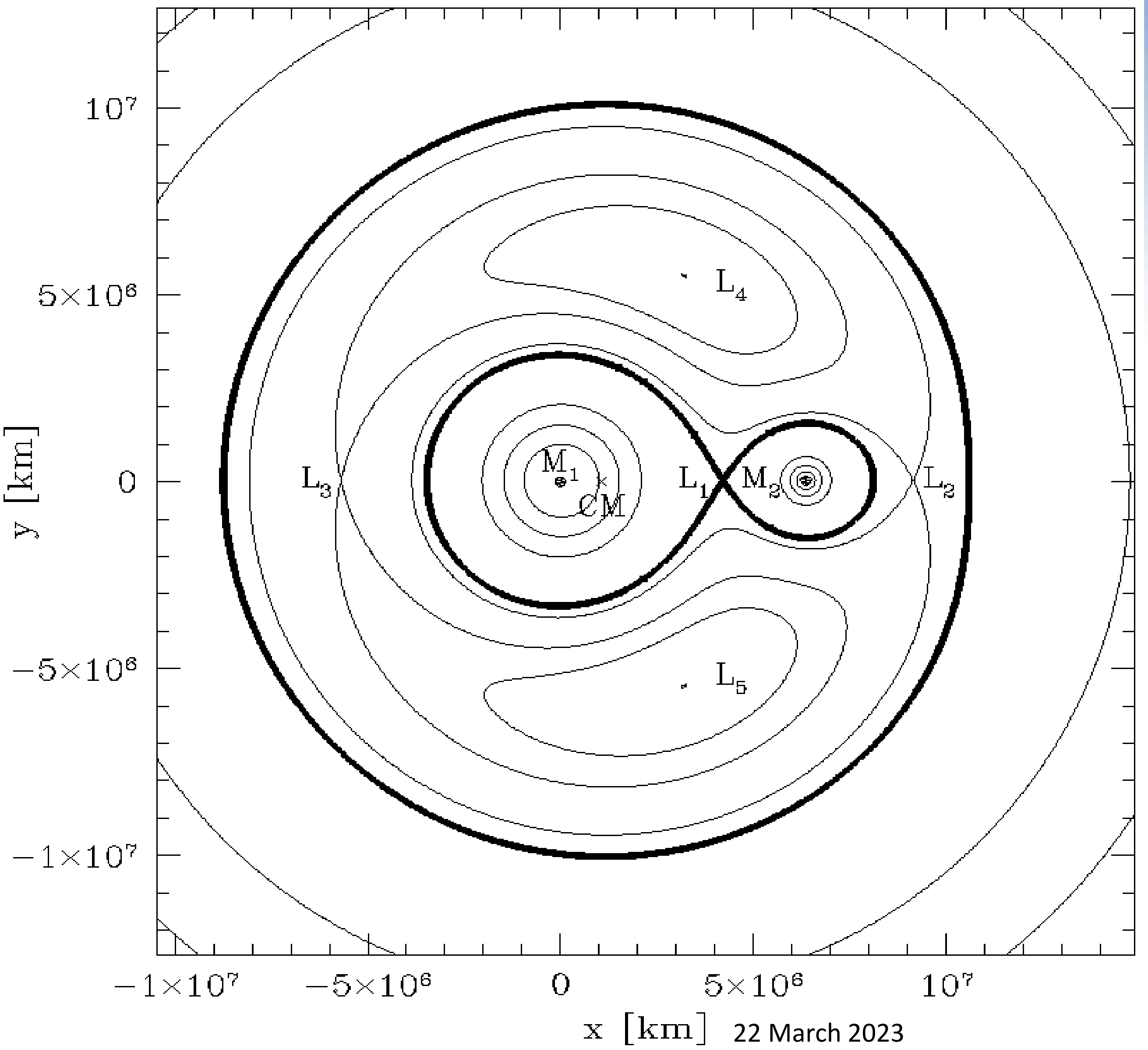
L_2: Gaia, Herschel, JWT
same orientation Sun-Earth

L_1 – L_3 are *unstable*, i.e. a small perturbation will lead the material to leave the L-point; $L_{4\&5}$ are *stable*, i.e. material will return to its initial position following a small perturbation

Jupiter-Sun: Trojan asteroids in $L_{4\&5}$



The Roche potential: scale and shape

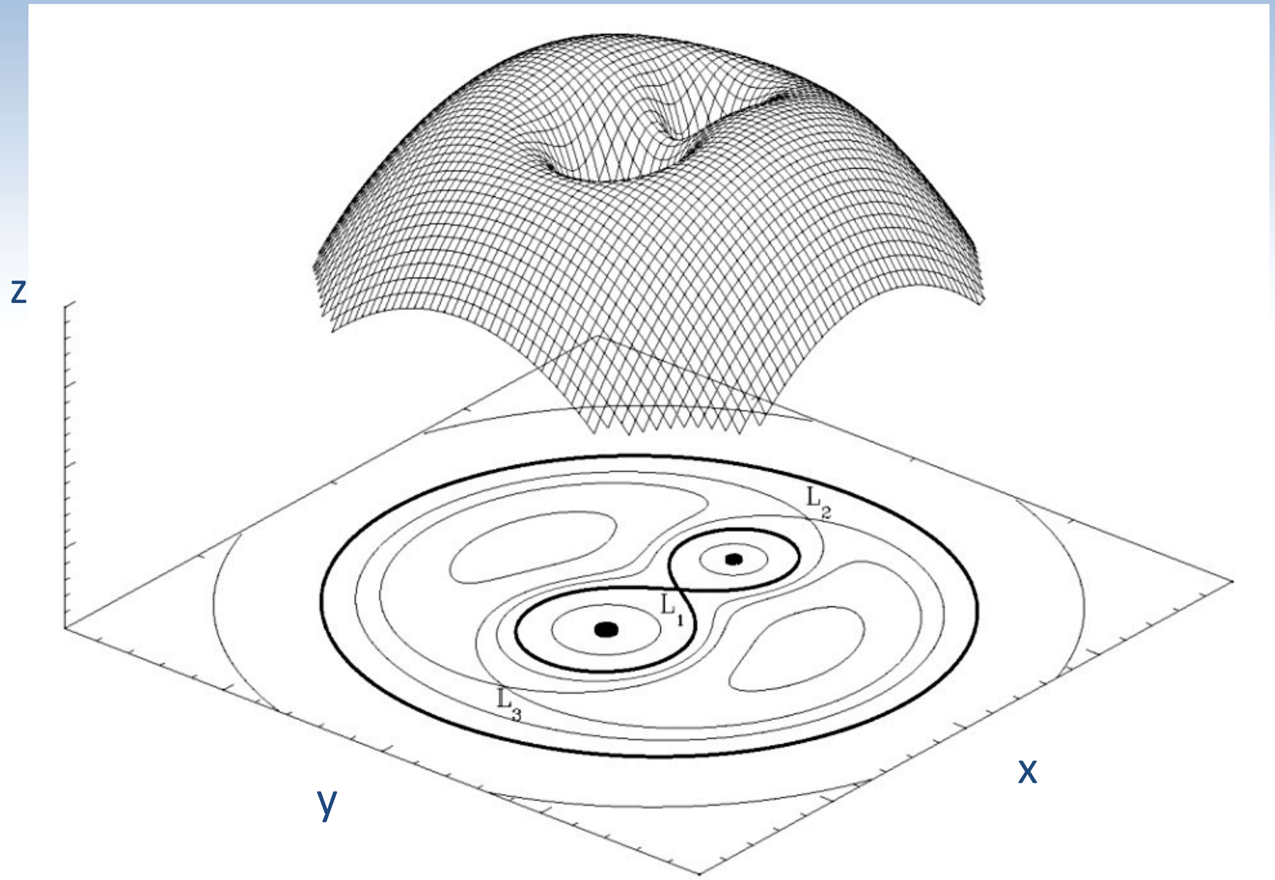


$q = 0.2, \ P_{orb} = 70h$

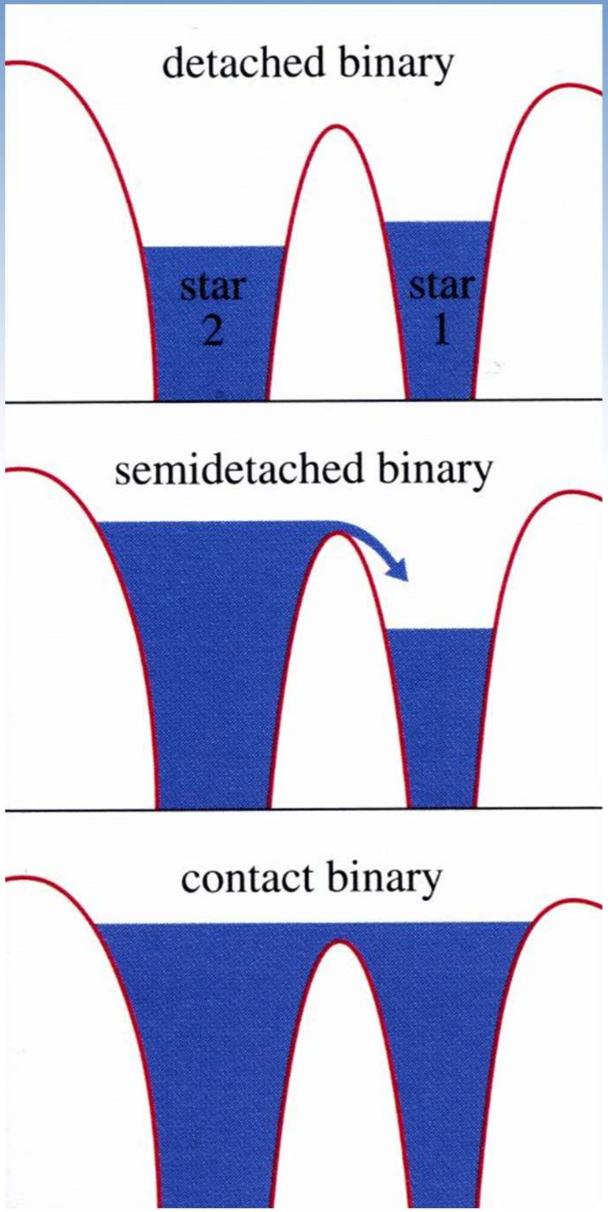
the *shape* of the equipotential lines depends only on q

the *dimension* of the system depends the binary separation a

The Roche potential



Binary configurations and mass transfer

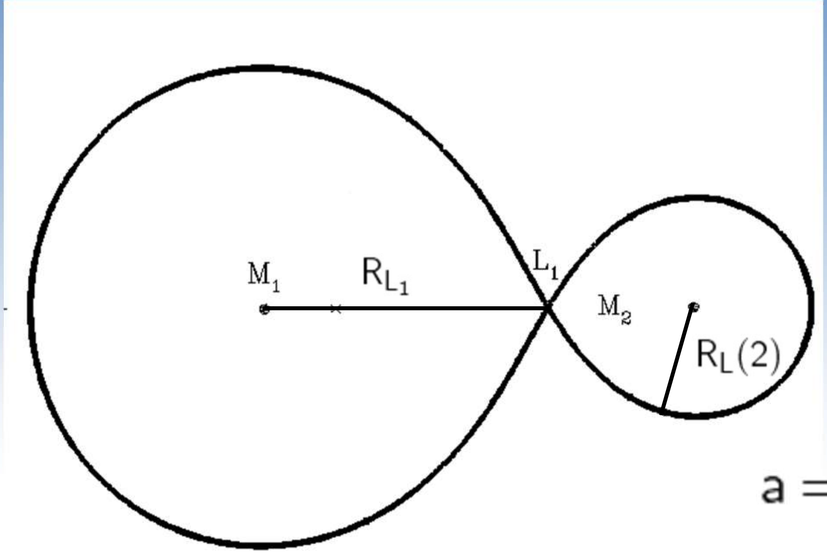


Detached: mass transfer via wind
(High mass X-ray binaries HMXBs, Symbiotics)

Semidetached: mass transfer via Roche lobe overflow (RLOF)
(most of the compact binaries, LMXBs, CVs)

Contact
(W UMa systems, 2 normal stars,
not relevant for X-ray astronomy)

Roche lobes: useful equations



$$a = \left(\frac{P_{orb}^2 G(M_1 + M_2)}{4\pi^2} \right)^{1/3}$$

$$a = 3.53 \times 10^8 (M_1/M_\odot)^{1/3} (1+q)^{1/3} P_{orb}^{2/3}(h) \ m$$

$$\frac{R_{L_1}}{a} = (1.0015 + q^{0.4056})^{-1} \quad (0.04 \leq q \leq 1)$$

$$\frac{R_{L_1}}{a} = 0.5 - 0.227 \log q \quad (0.1 \leq q \leq 10)$$

$$\frac{R_L(2)}{a} = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}$$

volume-equivalent radius of the secondary star Roche lobe

$$\frac{R_L(2)}{a} = 0.462 \left[\frac{q}{1+q} \right]^{1/3}$$

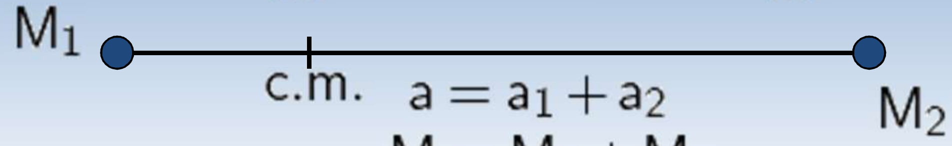
$0.1 \leq q \leq 10$ 2% accuracy   (Paczynski 1971)

Angular momentum in a mass-transferring binary

$$\omega = \frac{2\pi}{P} = \frac{v}{r}, \quad L = mvr = m\omega r^2$$

$$P_{\mathrm{orb}}^2 = \frac{4\pi^2 a^3}{GM}, \quad \omega^2 = \frac{GM}{a^3}$$

$$a_1 = a\frac{M_2}{M} \qquad a_2 = a\frac{M_1}{M}$$



$$a = a_1 + a_2$$

$$M = M_1 + M_2$$

$$L_{12} = (M_1 a_1^2 + M_2 a_2^2)\omega \quad = \left(\frac{M_1 M_2^2}{M} + \frac{M_2 M_1^2}{M}\right)\frac{a^2}{M}\left(\frac{GM}{a^3}\right)^{1/2}$$

$$= M_1 M_2 \frac{(M_1 + M_2)}{M}\frac{a^2}{M}\left(\frac{GM}{a^3}\right)^{1/2}$$

$$\boxed{L_{12} = M_1 M_2 \left(\frac{Ga}{M}\right)^{1/2}}$$

Mass transfer and angular momentum conservation

conservative mass transfer: $\dot{M}_2 < 0, \quad \dot{M}_1 = -\dot{M}_2, \quad \dot{M}_1 + \dot{M}_2 = 0, \quad \dot{M} = 0$

$$L = M_1 M_2 \left(\frac{Ga}{M}\right)^{1/2} \Longrightarrow a = \left(\frac{L}{M_1 M_2}\right)^2 \frac{M}{G}$$

$$\frac{\dot{a}}{a} = \frac{2\dot{L}}{L} - \frac{2\dot{M}_2}{M_2} - \frac{2\dot{M}_1}{M_1} = \frac{2\dot{L}}{L} - \frac{2\dot{M}_2}{M_2}\left(1 - \frac{M_2}{M_1}\right)$$

angular momentum is conserved: $\frac{dL}{dt} = 0$

$$q = \frac{M_2}{M_1} \qquad \frac{\dot{a}}{a} = \frac{-2\dot{M}_2}{M_2}(1-q)$$

$$>0$$

$M_2 < M_1 : \ \frac{\dot{a}}{a} > 0$ orbit expands

$M_2 > M_1 : \ \frac{\dot{a}}{a} < 0$ orbit shrinks

Stable and unstable mass transfer

$0.1 \leq q \leq 10$ $$\frac{R_L(2)}{a} = 0.462 \left(\frac{q}{1+q}\right)^{1/3}$$

$$\boxed{L_{12} = M_1 M_2 \left(\frac{Ga}{M}\right)^{1/2}}$$

$$\boxed{\frac{\dot{R}_2}{R_2} = \frac{2\dot{L}}{L} - \frac{2\dot{M}_2}{M_2}\left(\frac{5}{6} - \frac{M_2}{M_1}\right)}$$

$$= 0 \qquad > 0$$

$q > 5/6$: the Roche-lobe of the mass donor *shrinks* as a consequence of its mass loss, the rate at which it loses mass is on τ_{KH}
= unstable mass transfer - short evolutionary epochs

$q < 5/6$: the Roche-lobe of the mass donor *grows* as a consequence of its mass loss, the mass is transferred on $\mathbf{T_{nuc}}$
= stable mass transfer

Accretion rate and luminosity

Accretion rate: $\dot{m}[\mathrm{kg\,s^{-1}}]$ or $[\mathrm{M_\odot\,yr^{-1}}]$ or $[\mathrm{g\ s^{-1}}]$

Accretion luminosity: $\boxed{L_{acc} = \frac{GM\dot{m}}{R}[\mathrm{J\,s^{-1}}]}$ or $[\mathrm{erg\ s^{-1}}]$

Example 1: accretion onto a neutron star with $(M = 1.4M_\odot, R = 10\mathrm{km})$

$L = 10^{30}\,\mathrm{J\,s^{-1}}$ = 10^{37} erg s^{-1}

$$\dot{m} = \frac{LR}{GM} = 7.4 \times 10^{13}\ \mathrm{kg\ s^{-1}} = 1.2 \times 10^{-9}\ M_\odot\ \mathrm{yr^{-1}}$$

Accretion in a binary can be sustained over long timescales

Example 2: accretion onto a supermassive black hole with

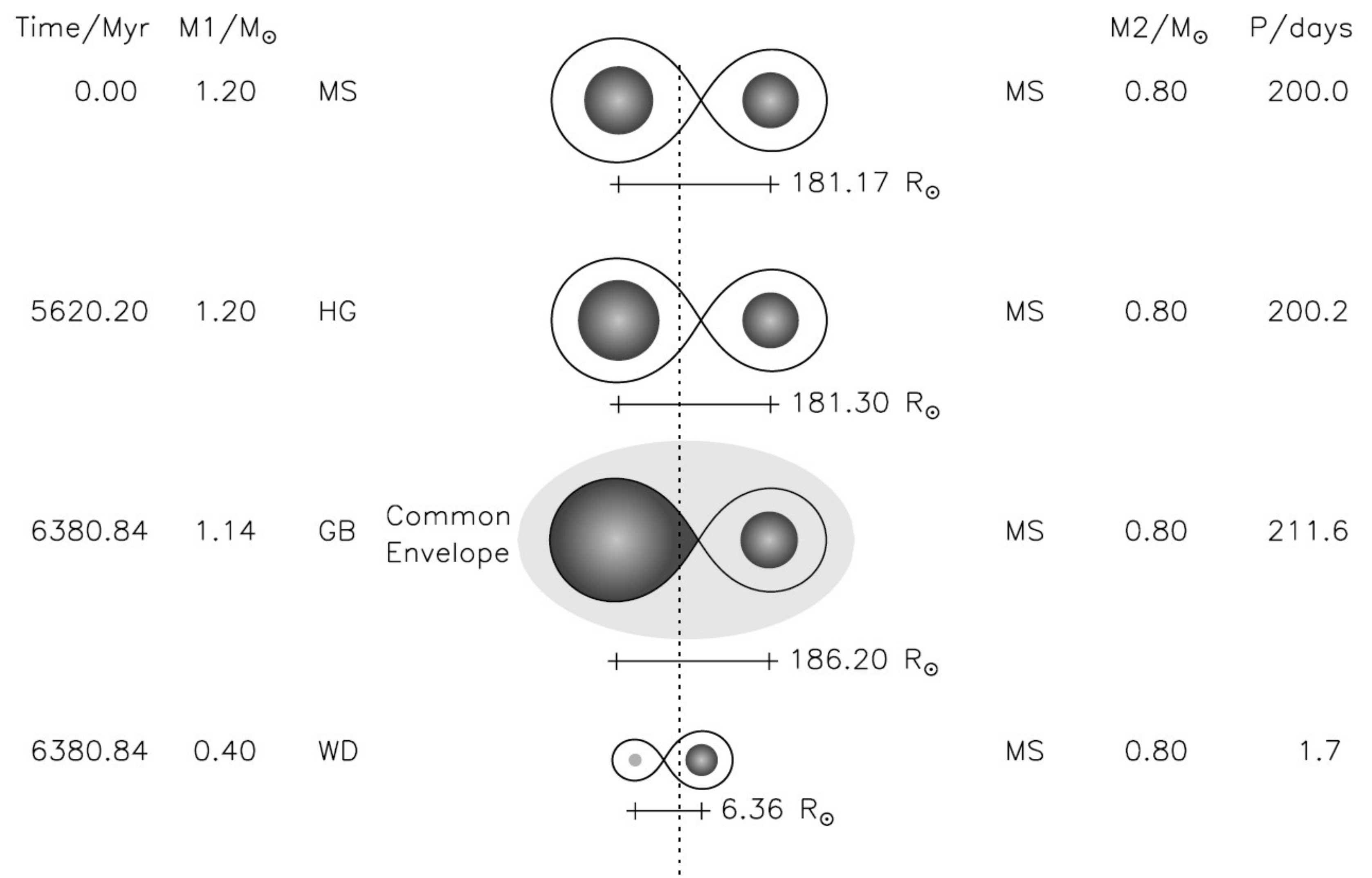
$(M=10^{8}\ M_\odot\ , R=3\mathrm{x}10^{11}\ \mathrm{m})$

$L = 5 \times 10^{39}\,\mathrm{J\,s^{-1}}$

= 5×10^{46} erg s^{-1}

$$\dot{m} = \frac{LR}{GM} = 1.1 \times 10^{23}\mathrm{kg\,s^{-1}} = 1.7M_\odot\,\mathrm{yr^{-1}}$$

Formation of a white dwarf/main sequence binary



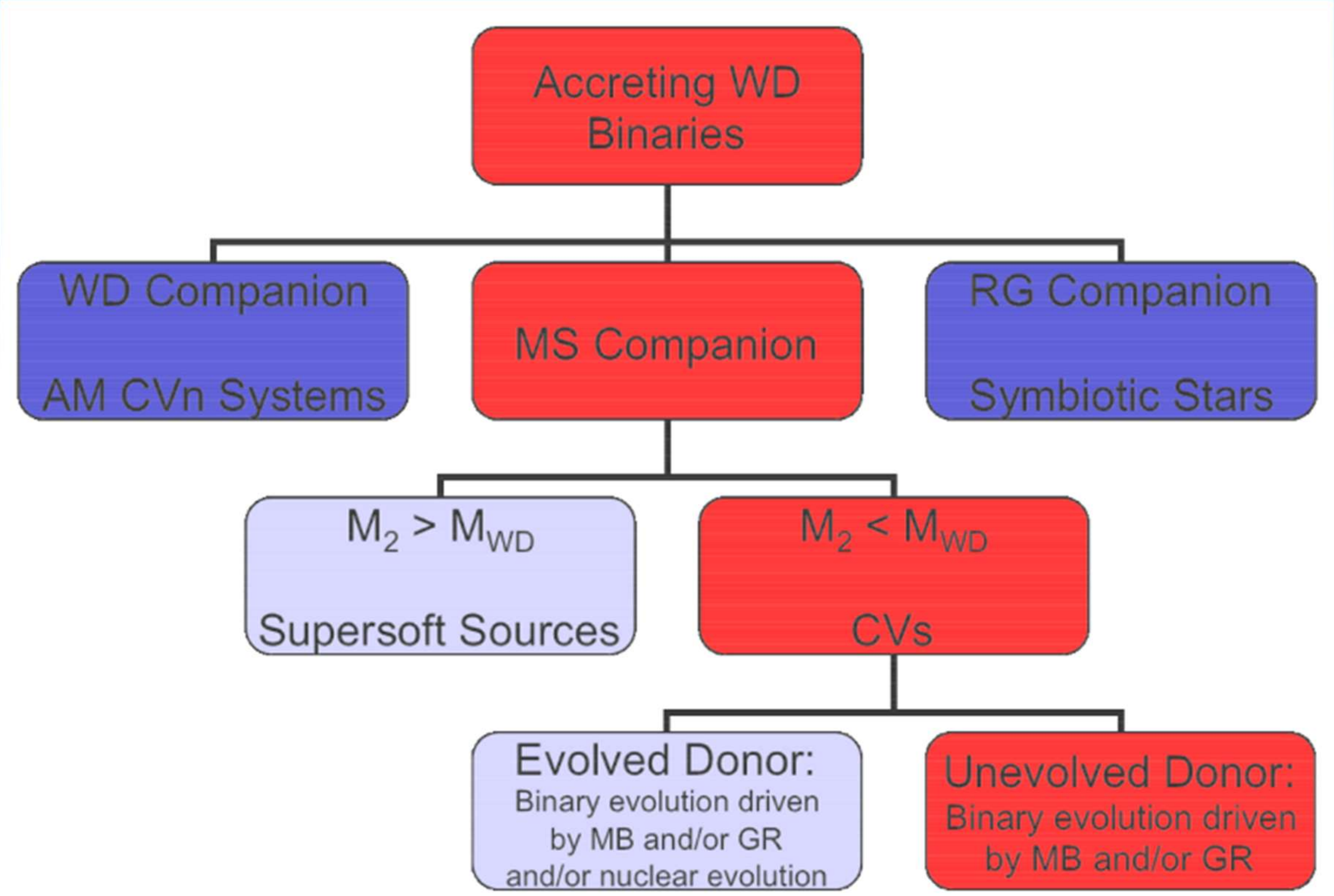
Time/Myr	$M1/M_\odot$			$M2/M_\odot$	P/days
0.00	1.20	MS	MS	0.80	200.0
5620.20	1.20	HG	MS	0.80	200.2
6380.84	1.14	GB	MS	0.80	211.6
6380.84	0.40	WD	MS	0.80	1.7

Binaries with compact components
Semi-detached systems, with mass transfer

M2 companion	**WD**	**NS**	**BH**
WD	AM CVns ~30	LMXBs <10^1	
NS		[GW sources (kilonovae)]	[GW sources]
BH			[GW sources]
MS, M2 < M_0	CVs ~3000	LMXBs ~200	LMXBs few tens
MS, M2 > M_0	SSS	HMXBs 150	HMXBs few
Giant	Few CVs, Symbiotics	Few LMXBs	Few LMXBs
Supergiant	about 200		

SSS: Supersoft X-ray sources; L/HMXB: Low/High-mass X-ray binary

Compact WD Binary taxonomy



Accreting WD Binaries

WD Companion

AM CVn Systems

MS Companion

RG Companion

Symbiotic Stars

$M_2 > M_{WD}$

Supersoft Sources

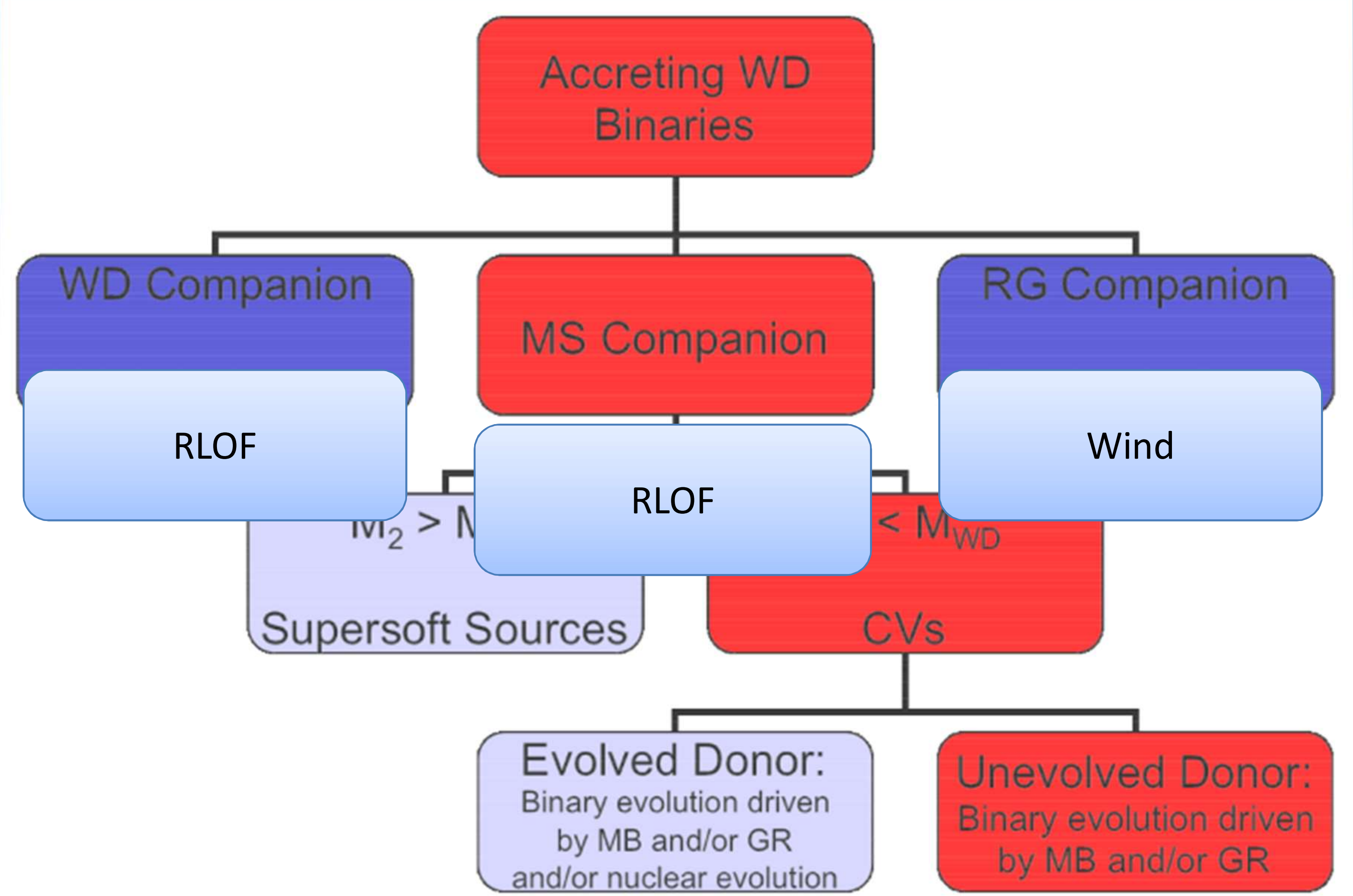
$M_2 < M_{WD}$

CVs

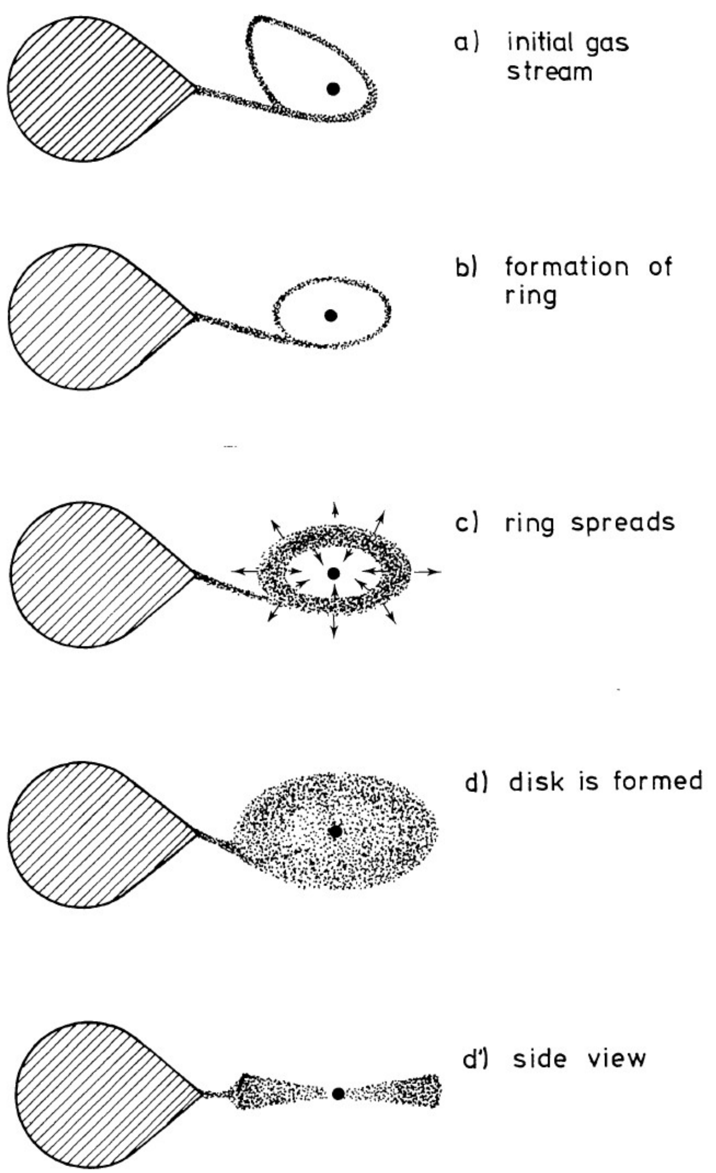
Evolved Donor:
Binary evolution driven by MB and/or GR and/or nuclear evolution

Unevolved Donor:
Binary evolution driven by MB and/or GR

Accretion mode



Accretion disks: formation



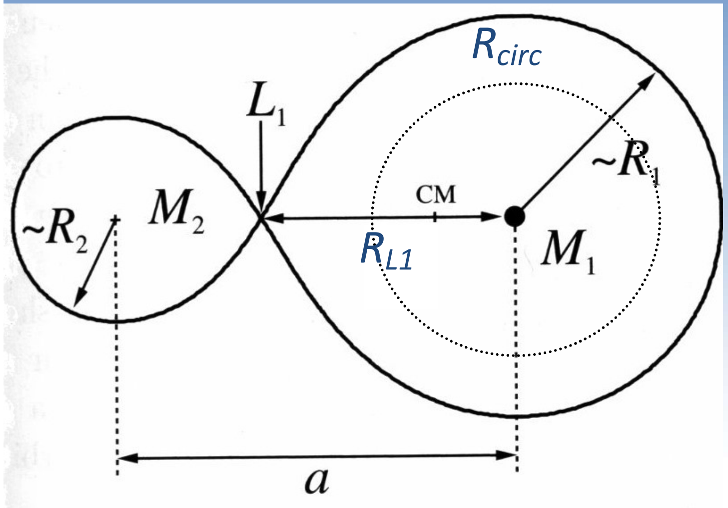
transport of
- $\dot{M}$ inwards/outwards
- L outwards

$$E_{tot} = -\frac{GMm}{r} + \frac{1}{2}mv^2$$
$$= -\frac{GMm}{r} + \frac{1}{2}\frac{GMm}{r}$$
$$= -\frac{1}{2}\frac{GMm}{r}$$

$$L_{disc} = \frac{1}{2}\frac{GM\dot{m}}{R} = \frac{1}{2}L_{acc}$$

(the other half: boundary layer between disc and star)

The circularisation radius



angular momentum conservation:

$$L_{L_1} = L_c$$

$$L_{L_1} = mR_{L_1}v_{L_1} = m\frac{2\pi R_{L_1}^2}{P_{orb}}$$

$$v_{L_1} = \frac{2\pi R_{L_1}}{P_{orb}}$$

$$L_c = mr_cv_c = m\sqrt{r_cGM_1}$$

$$\boxed{r_c} = \frac{4\pi^2R_{L_1}^4}{GM_1P_{orb}^2} = \frac{(M_1+M_2)R_{L_1}^4}{M_1a^3} = (1+q)\frac{R_{L_1}^4}{a^3} = \boxed{a(0.5-0.227\log q)^4(1+q)}$$

$$P_{orb}^2 = \frac{4\pi^2a^3}{G(M_1+M_2)}$$

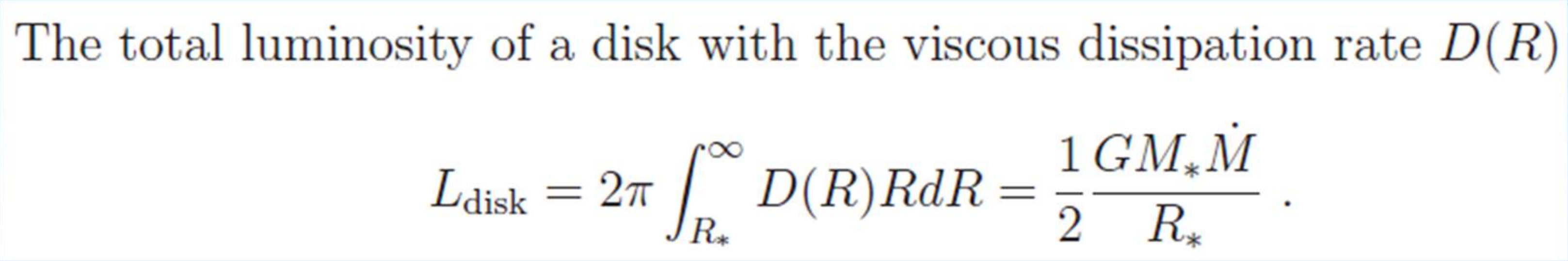
mass ratio: $q = \frac{M_2}{M_1}$

Roche-lobe radius of primary: $R_{L_1} = a(0.5 - 0.277\log q)$

Example: $q = 0.5 \Longrightarrow r_c = 0.16a$ $R_{L1} = 0.58a$

If $R_1 \leq r_c \leq R_{L1}$ ⟶ Ring spreads into disc (spiral in and outward)

Accretion Disk Temperatures



The total luminosity of a disk with the viscous dissipation rate $D(R)$

$$L_{\rm disk} = 2\pi \int_{R_*}^{\infty} D(R) R dR = \frac{1}{2} \frac{G M_* \dot{M}}{R_*} \, .$$

For an optically thick disk, the luminosity is determined by the summed blackbody emission as a function of disk radius

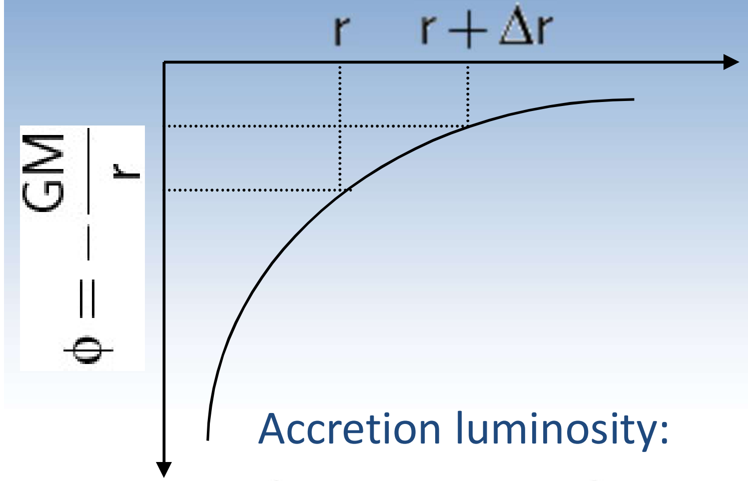
$$\sigma_{SB} T_{bb}^4 = \frac{1}{2} D(R)$$

$$T_{bb}(R) = T_* \left(\frac{R}{R_*} \right)^{-3/4} [1 - (R_*/R)^{1/2}]^{1/4}$$

The $R^{-3/4}$ temp law

$$T_* = \left(\frac{3 G M_* \dot{M}}{8 \pi R_*^3 \sigma_{SB}} \right)^{1/4} \, .$$

Radial temperature profile: simple approach



Taylor expansion:

$$f(r+\Delta r) \approx f(r) + \Delta r \frac{df}{dr}$$

$$\Longrightarrow \Delta r \frac{df}{dr} = f(r) - f(r+\Delta r)$$

Accretion luminosity:

$$L(r) = -\left(\frac{GM}{r} - \frac{GM}{r+\Delta r}\right)\dot{m} = -\Delta r \frac{d}{dr}\frac{GM\dot{m}}{r} = \Delta r \frac{GM\dot{m}}{r^2}$$

Optically thick disc:

$$L(r) = 2 \times 2\pi r \Delta r \sigma T_{\mathrm{eff}}(r)^4 \quad \Longrightarrow T_{\mathrm{eff}}^4 = \frac{GM\dot{m}}{4\pi\sigma r^3}$$

and

$$\boxed{T(r) \propto r^{-3/4}}$$

properly done (Spruit 2010):

$$\boxed{T^4(r) = \frac{3GM\dot{m}}{8\pi\sigma r^3}\left[1 - \left(\frac{R}{r}\right)^{1/2}\right]}$$

More generally:
$T(r) \infty r^{-ß}$
Real accretion discs have $0 \leq ß \leq 1$

(see Spruit 2010, arXiV:1005.5279)

Maximum temperature of the disc

$$T^4(r) = \frac{3GM\dot{m}}{8\pi\sigma r^3}\left[1 - \left(\frac{R}{r}\right)^{1/2}\right]$$

“characteristic disc temperature”
:

$$T_d = \left(\frac{3GM\dot{m}}{8\pi\sigma R^3}\right)^{1/4}$$

$$\left(\frac{T(r)}{T_d}\right)^4 = \left(\frac{R}{r}\right)^3\left[1 - \left(\frac{R}{r}\right)^{1/2}\right]$$

substitute

$r/R = x$ and $(T/T_d)^4 = y$

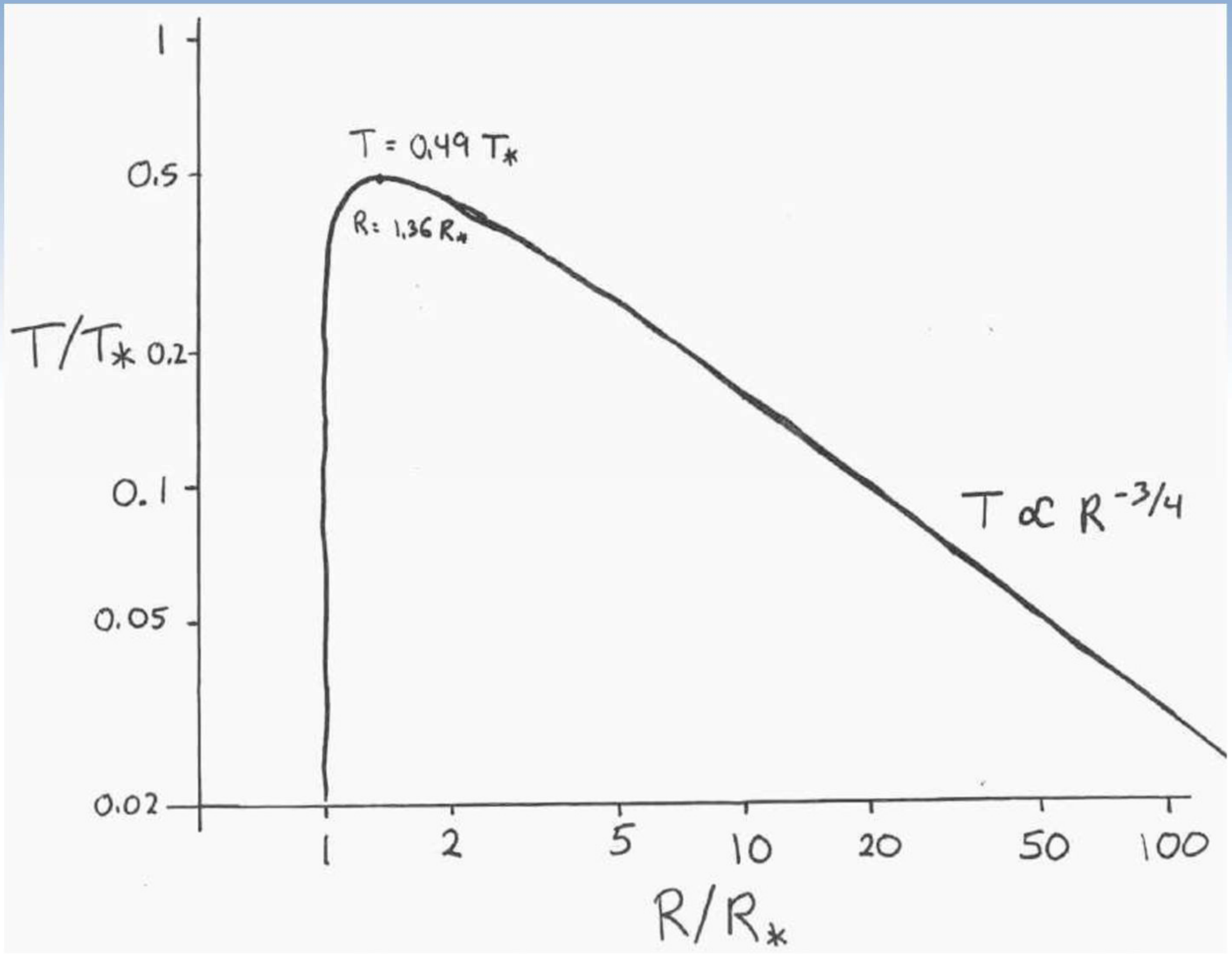
$$y = x^{-3}(1 - x^{-1/2}) = x^{-3} - x^{-7/2}$$

$$\frac{dy}{dx} = -3x^{-4} + \frac{7}{2}x^{-9/2} \doteq 0$$ to find the maximum of y

$$\boxed{r_{max} = 49/36R}$$

$$\boxed{T(r_{max}) = 0.488\left(\frac{3GM\dot{m}}{8\pi\sigma R^3}\right)^{1/4} = 0.488T_d}$$

Accretion Disk Temperature



Spectra of accretion discs: summing blackbodies

$$I_\nu = B_\nu[T(r)] = \frac{2h\nu^3}{c^2(e^{h\nu/kT(r)} - 1)}$$

blackbody intensity

$$F_\nu = \frac{2\pi \cos i}{d^2}\int_{R_{in}}^{R_{out}} r I_\nu dr = \frac{4\pi h \cos i \nu^3}{c^2 d^2}\int_{R_{in}}^{R_{out}} \frac{r}{e^{h\nu/kT(r)} - 1} dr$$

(1) $\nu \ll kT(R_{out})/h \Longrightarrow B_\nu \approx \frac{2kT\nu^2}{c^2} \qquad \Longrightarrow F \propto \nu^2$ Rayleigh-Jeans tail

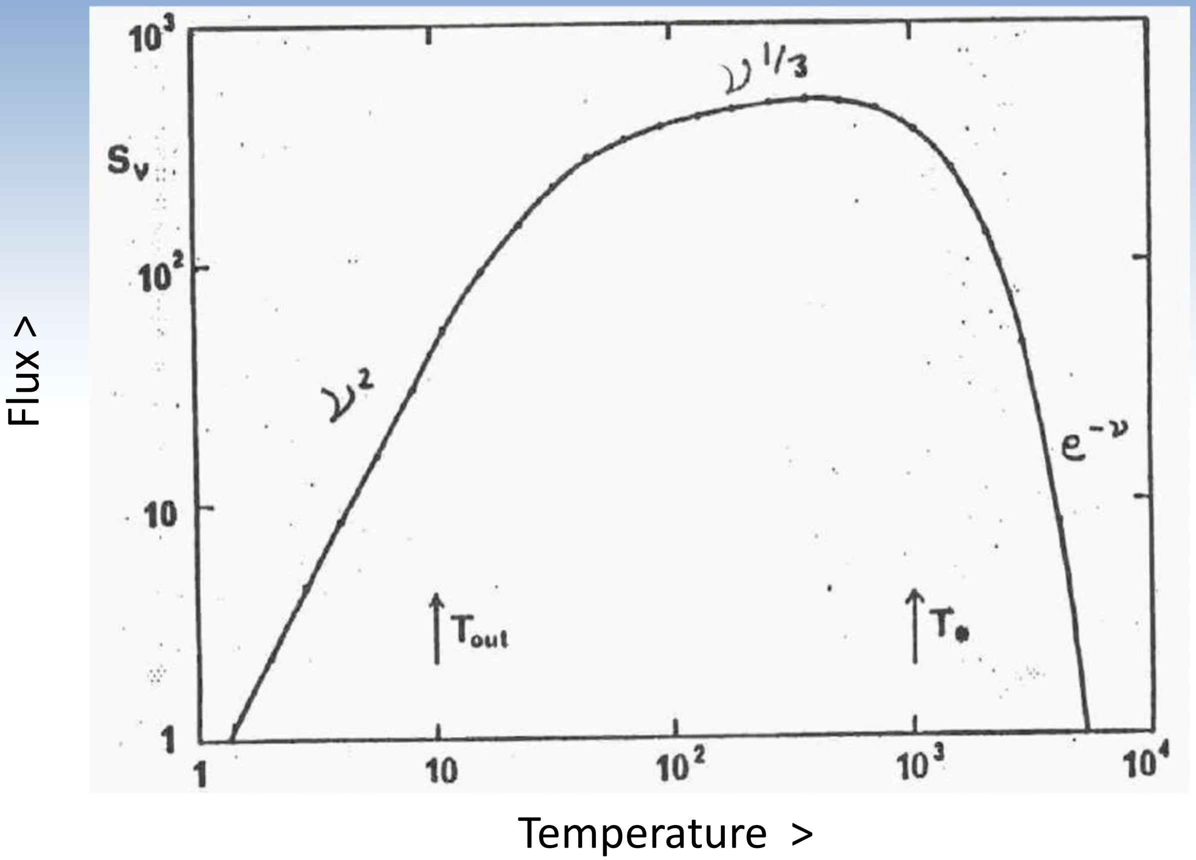
(2) $\nu \gg kT(R_{in})/h \Longrightarrow B_\nu = \frac{2h\nu^3}{c^2} e^{-h\nu/kT}$ Wien tail

(3) intermediate case

$$x = h\nu/kT(r) \approx h\nu/kT_*(r/R_*)^{3/4}$$

$$F_\nu \propto \nu^{1/3}\int_0^\infty \frac{x^{5/3}}{e^x - 1} dx \propto \nu^{1/3}$$

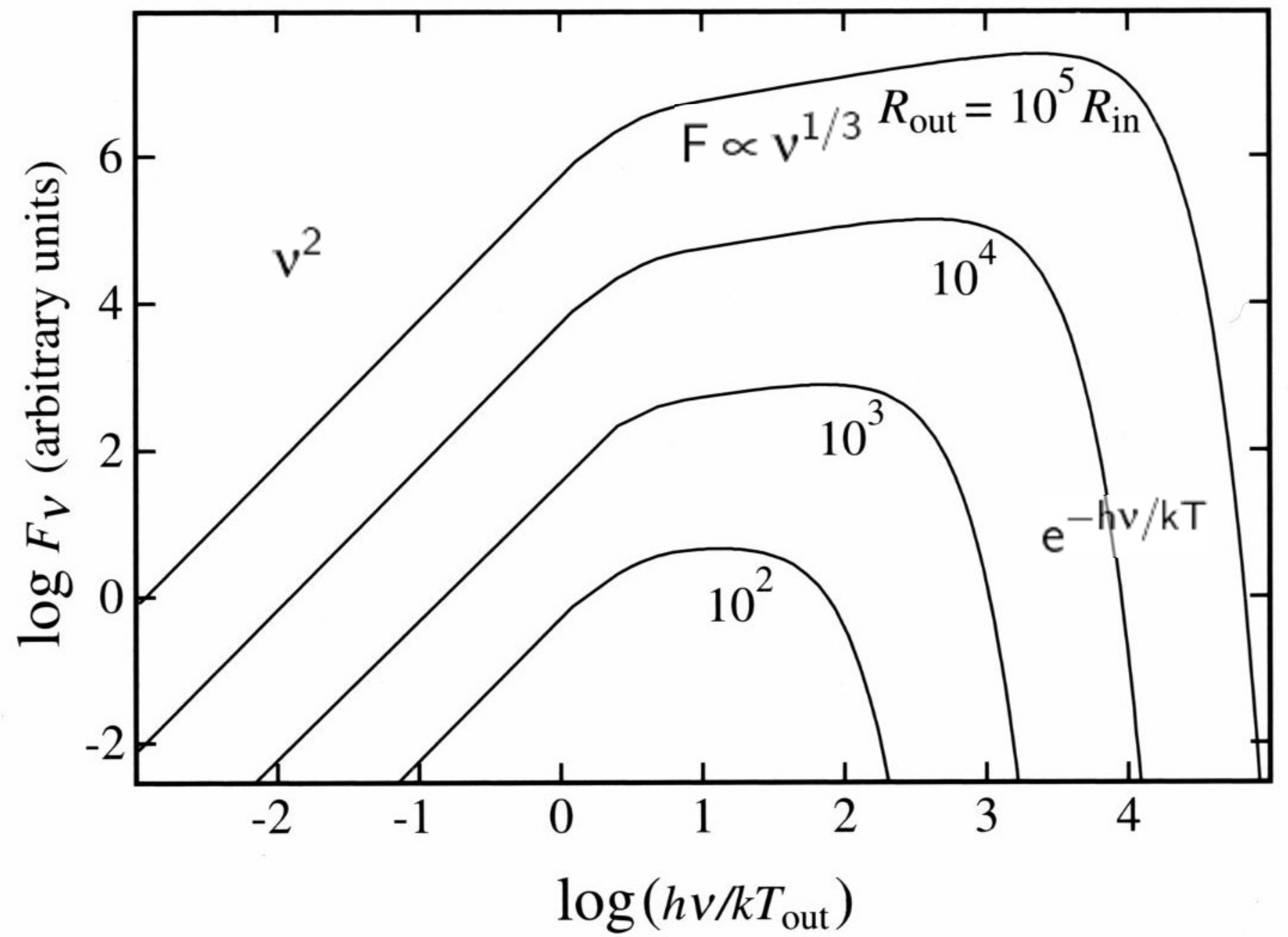
Spectra of accretion discs: summing blackbodies



Spectrum of an optically thick accretion disk (arbitrary units).

Typical outer disk temp = 0.01 T_*

Spectra of accretion discs: summing blackbodies

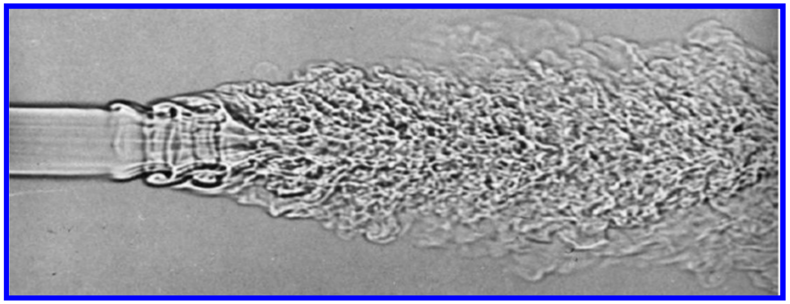


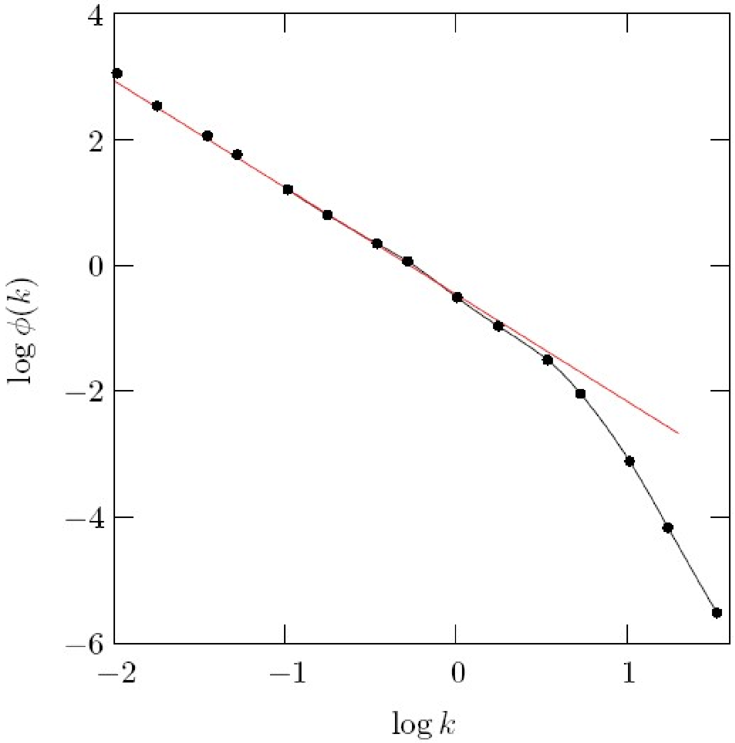
Accretion disc turbulence

- Matter spirals into gravitational potential of accreting object
- Energy is extracted as radiation

Dissipation process converts kinetic energy into heat

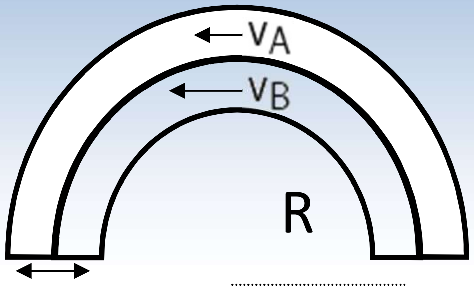
Transport of mass and angular momentum due to chaotic turbulent process (Kolmogorov) known as shear viscosity

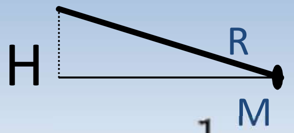




Transport of mass and angular momentum

Mass and angular momentum transported in the disc due to friction between layers due to chaotic process known as viscosity (Shakura & Sunyaev 1973)





$$H \approx c_s \frac{1}{\omega_K(r)}$$

Mass transfer rate $\dot M = -2\pi R V_R \Sigma \quad (\Sigma = 2\rho H)$

Keplerian & drift velocities

$$V_R << V_k, \qquad V_k = (GM/R)^{1/2}$$

$$V_R = -\frac{3\nu}{2R}\left[1-(\frac{R_{in}}{R})^{1/2}\right]^{-1}$$

ν : kinematic viscosity coefficient

α : viscosity parameter $\alpha \leq 1$

(Shakura & Sunyaev 1973) no prescription

Turbulence driven by MRI instability (Balbus&Hawley1991)

Hot discs: α ≈ 0.1-0.4 (King, Pringle, Livio 2007)

Cool discs:α ≈ 0.02-0.04 (Hamuery et al. 1998)

$$\nu\Sigma = \frac{\dot M}{3\pi}[1-\sqrt{R_{in}/R}], \qquad \nu = \alpha c_s H$$

Viscosity also dissipates kinetic energy:

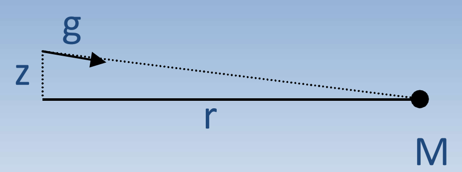
Heating rate per unit surface: $Q^+ = \frac{1}{2}\nu\Sigma(rd\Omega_k dr)2 = \frac{3GM\dot M}{8\pi R^3}[1-\sqrt{R_{in}/R}]$

Stability condition =

Cooling rate per unit surface $Q^- = \sigma T^4$

$$L_d = \frac{GM\dot M}{2R_{in}}$$

Vertical structure of accretion discs



$$U_g = \frac{GM}{(r^2+z^2)^{1/2}}$$ (gravitational potential)

Hydrostatic equilibrium in z-direction:

$$\frac{\partial P}{\partial z} = \rho g = \rho \frac{\partial U_g}{\partial z} = \rho \frac{\partial}{\partial z}\left(\frac{GM}{(r^2+z^2)^{1/2}}\right)$$

$$= -\rho \frac{1}{2} \frac{GM}{(r^2+z^2)^{3/2}} \frac{\partial}{\partial z}(r^2+z^2) \quad \Longrightarrow \frac{1}{\rho}\frac{\partial P}{\partial z} = -\frac{GM}{r^3} z$$

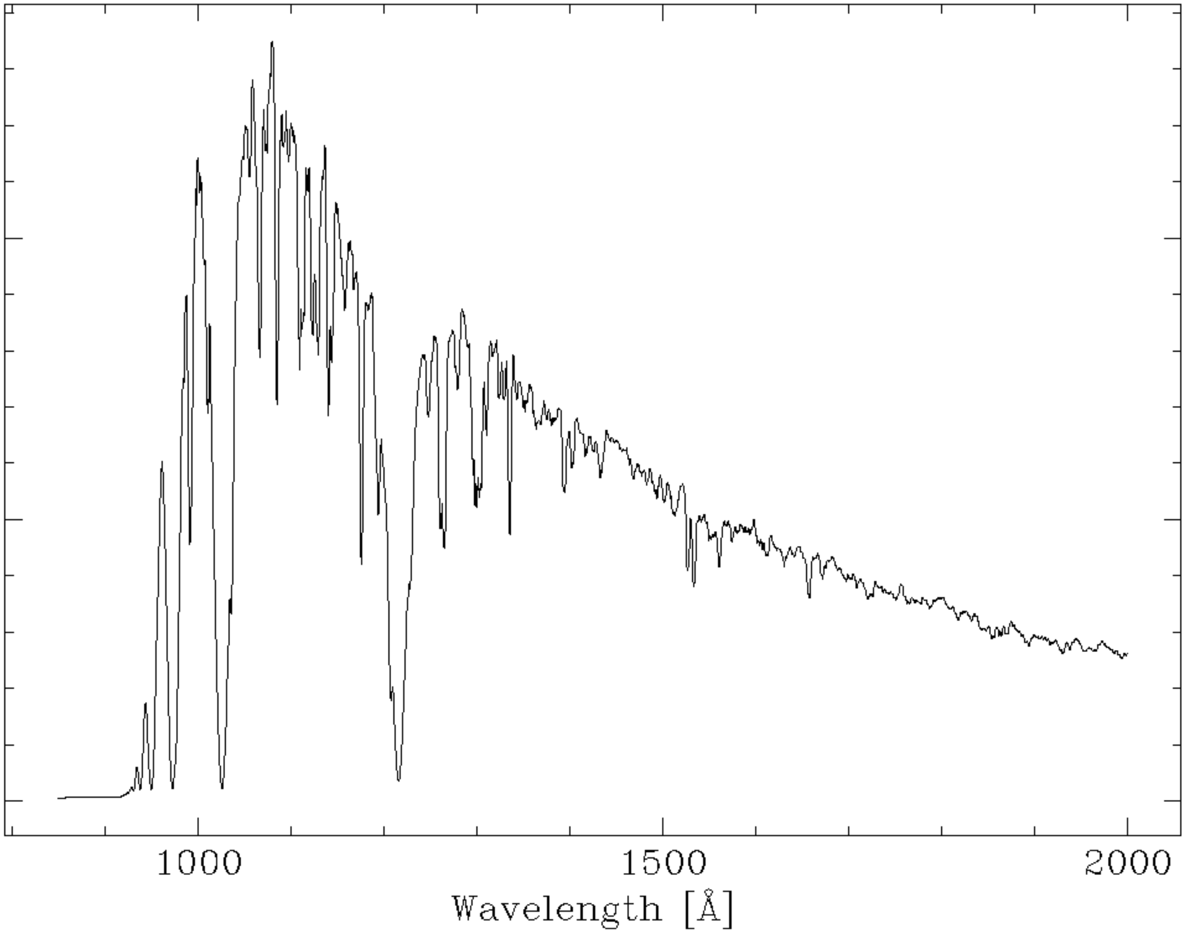
$$P = \frac{\rho}{\mu_{m_H}} kT$$ (ideal gas) $$\Longrightarrow \frac{1}{\rho}\frac{\partial \rho}{\partial z} = -\frac{\mu_{m_H} GM}{T r^3} z$$

$$\int dz, \quad \exp, \quad T \neq T(z) \quad \Longrightarrow \rho(z) = \rho_c \exp\left[-\frac{1}{2}\left(\frac{z}{H}^2\right)\right]$$

with the scale height $$H = \sqrt{\frac{kT}{\mu_{m_H}}} \sqrt{\frac{r^3}{GM}} \quad \approx c_s \frac{1}{\omega_K(r)}$$

Accretion disc model spectra

$$M_{wd} = 0.8M_{\odot}, \quad \dot{m} = 3.2 \times 10^{-10} M_{\odot} yr^{-1}, \quad i = 8^{\circ}$$



TLUSTY – Model atmosphere disc spectra (Hubeny et al. 1998)

Emission from the boundary layer

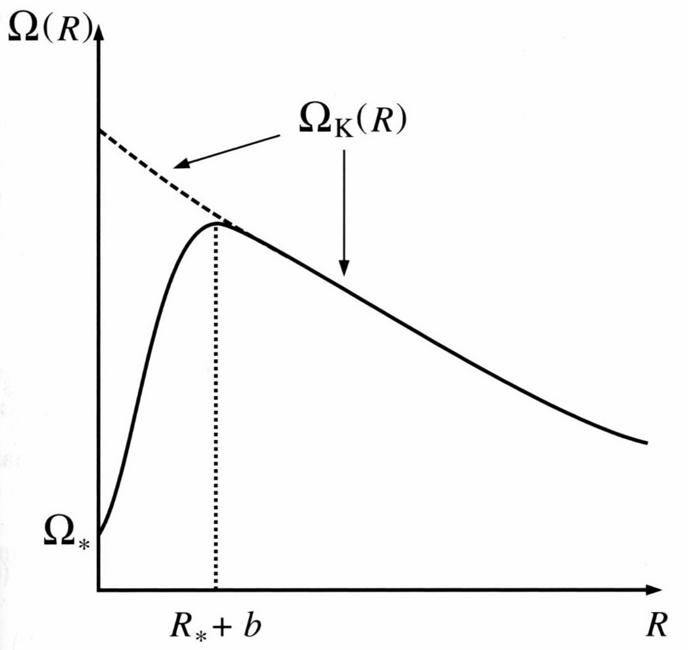
$$L_{disc} = \frac{1}{2}\frac{GM\dot{m}}{R} = \frac{1}{2}L_{acc}$$

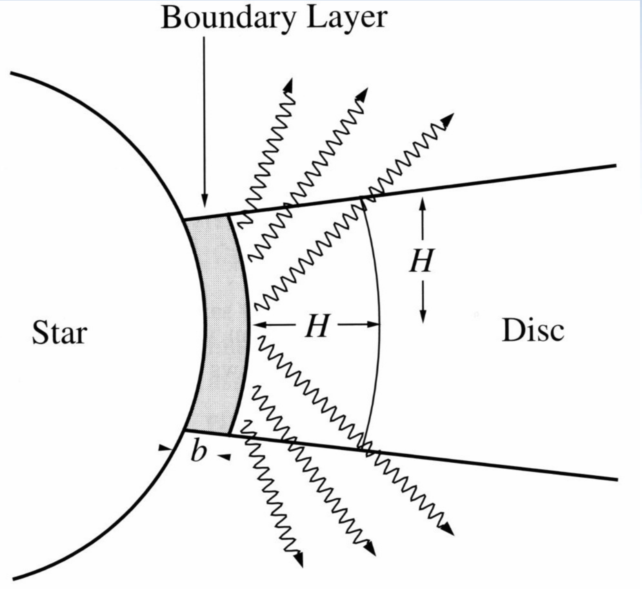
$$\Longrightarrow L_{bl} = \frac{GM\dot{m}}{2R}\left[1 - \left(\frac{\omega_*}{\omega_K}\right)\right]^2$$

$\omega_* << \omega_{\mathbf{breakup}}$

WD ≈ 10 sec

NS 0.3msec





$$L_{bl} = A\sigma T^4_{eff} = 4\pi RH\sigma T^4_{eff}$$

$$T_{eff} = \left(\frac{L_{bl}}{4\pi RH\sigma}\right)^{1/4}$$

b << H << R

$$A = 2 \times 2\pi RH$$

The Boundary Layer

$$H = \sqrt{\frac{kT}{\mu m_H}}\sqrt{\frac{r^3}{GM}} \approx c_s \frac{1}{\omega_K(r)}$$

$T_{\mathbf{eff,bl}} \sim T_d (T_s/T_d)^{1/8}$

$T_s = 3/8\, GM\, \mu\, m_H/kR$

shock Temperature

1) White dwarf: M = 0.85 Mʘ R = 6.6×10^6m $\dot{m} = 1.6\times10^{-10}$ Mʘ/yr

$$L_{bl} = \frac{GM\dot{m}}{2R} = 8.6 \times 10^{25}\,\mathrm{J\,s^{-1}}$$

$T_{eff,bl}$= 130000 K $T_{max} = 26200\mathrm{K}$

λT= 0.0029 mK λ= 22nm (EUV)

2) Neutron Star: M = 1.4 Mʘ R = 10km $\dot{m} = 1.6\times10^{-10}$ Mʘ/yr

$L_{bl} = 9.5 \times 10^{28}$ J s^{-1} $T_{eff,bl}$= 8.5×10^7 K $T_{max} = 3.9 \times 10^6\mathrm{K}$

E ≈ 7keV (hard X-rays)

BUT:

Boundary layer may become optically thin at low-intermediate mass transfer rates

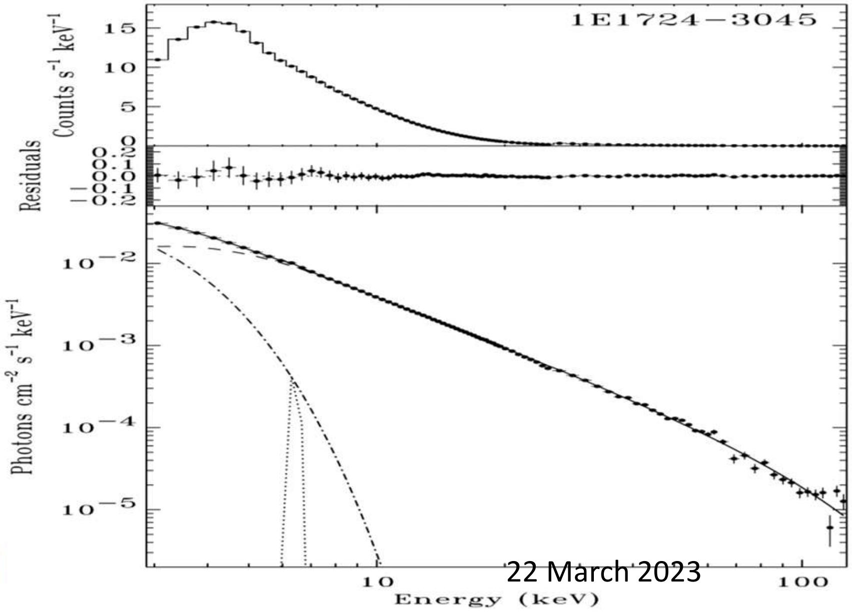
$\dot{m} \leq 10^{-9}$ M⊙/yr

Electrons hotter than photons → cooling via Compton scattering

Hot Boundary layer may expand spherically

X-ray Spectra:

Absorbed multi-color blackbody disc (kT_{in} = 1.2keV) +
Comptonized component (kTe=26keV; τ=3.3 - spherical) +
Gaussian line 6.4keV



1E1724-3045
a LMXB in Terzan 2

RXTE Data

(Barret et al. 2000)

Accretion Disk Winds

- Boundary layer the final transition of accreted material to the accretor
  - At high mass transfer rates it is *optically thick* and hot, with a thermal SED
  - Typical T_{BL} ~200,000 K (UV emitter) which is 6 x T_{disk} *(max)*

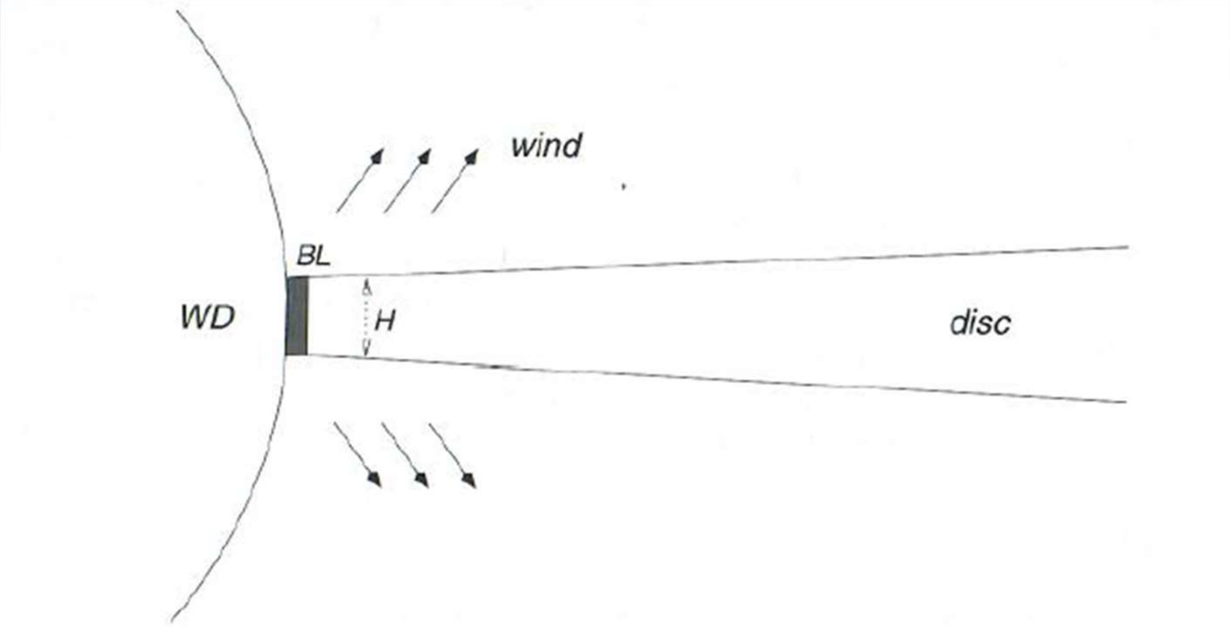


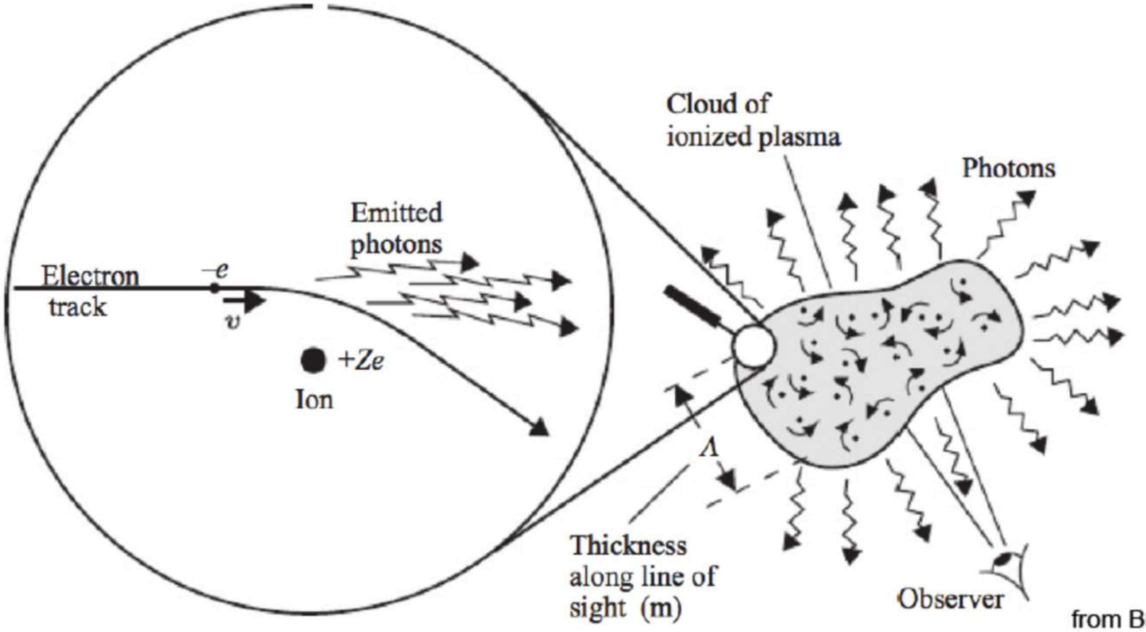
Fig. 7.2: An edge-on view of the boundary layer (BL) at high accretion rates. The height of the disc (H) is only $\sim 0.01\ R_{\rm wd}$, and the radial extent of the boundary layer is smaller still. This small strip around the white dwarf can emit up to half the total luminosity of the system. A wind outflow is driven by radiation from the boundary layer and/or the inner disc.

Accretion Disk Winds

- At low mass transfer rates ($< 5 \text{ x } 10^{10} M_{\odot}$ /yr) it is *optically thin*
- Dominant cooling through bremsstrahlung X-ray emission
- Low density => few collisions => inefficient cooling

consider a hot optically thin plasma transparent to its own radiation in thermal equilibrium

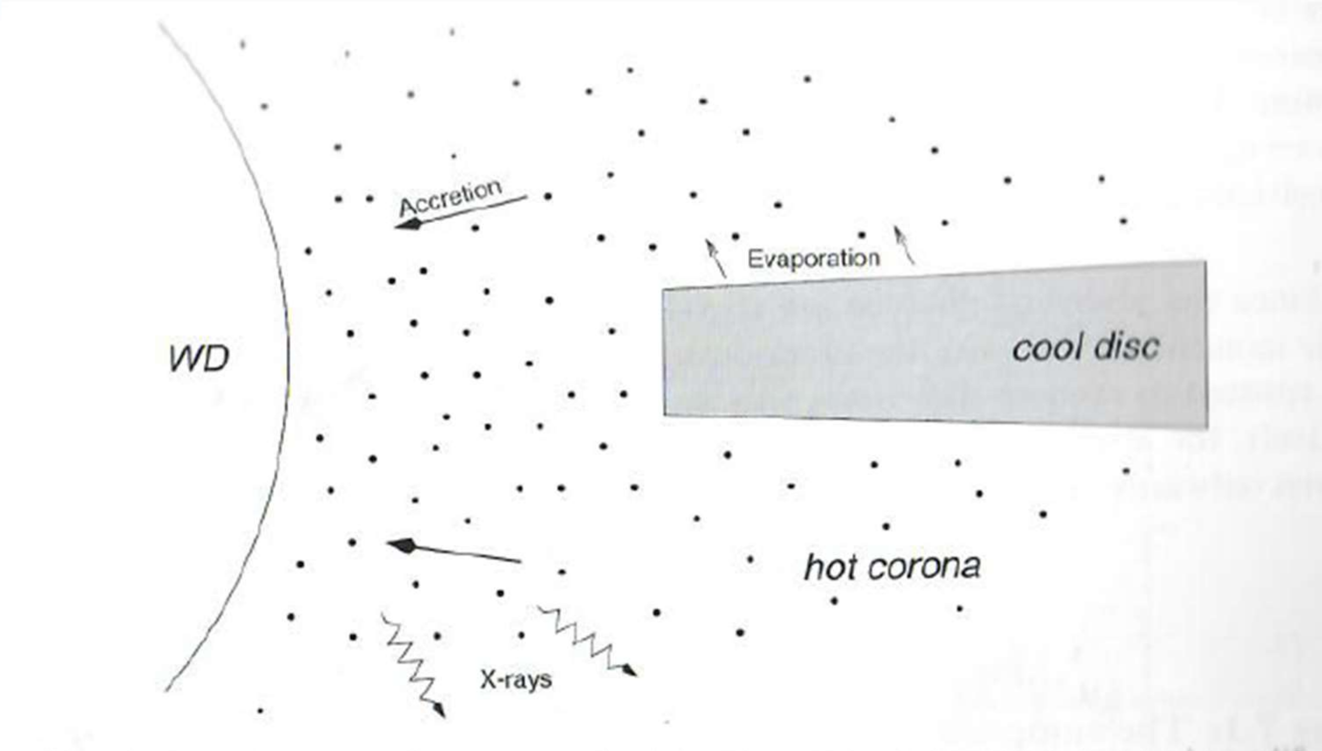
Thermal Bremsstrahlung by electrons (Maxwellian velocity distribution)



from Bradt 2008

Accretion Disk Winds

- Optically thin BL form an expanded diffuse corona with $T \sim 10^8$ K
- "siphon" effect where accreted material looses gravitational energy
  - Keeps pumping E into corona, keeping it hot
  - Corona evaporates the disk, replenishing the accreted material from the corona
  - Energetic photons (X-rays) can drive away some accreting material in a wind



Observing Wind Outflows

- Energetic photons from the BL can be absorbed by ions and atoms
- Energy matches electron transitions from ground state to next highest level
- Excitation
- Excited ion/atom de-excites, emitting photon
- The process is know as "resonance transitions"
- Because of the random direction of emitted photon, it "scatters" photons
- Lead to absorption along the line of sight
- Spectra lines can take on "P Cygni" line profile shapes
- Radiation drive wind

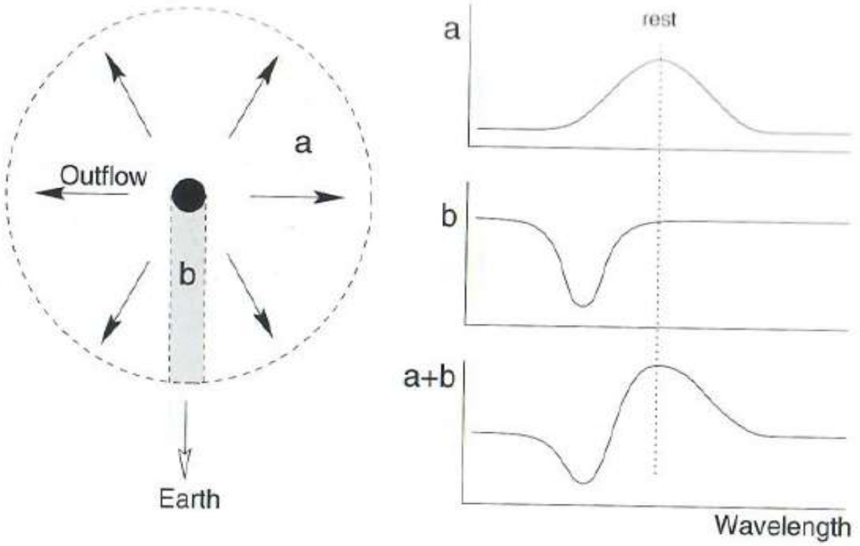
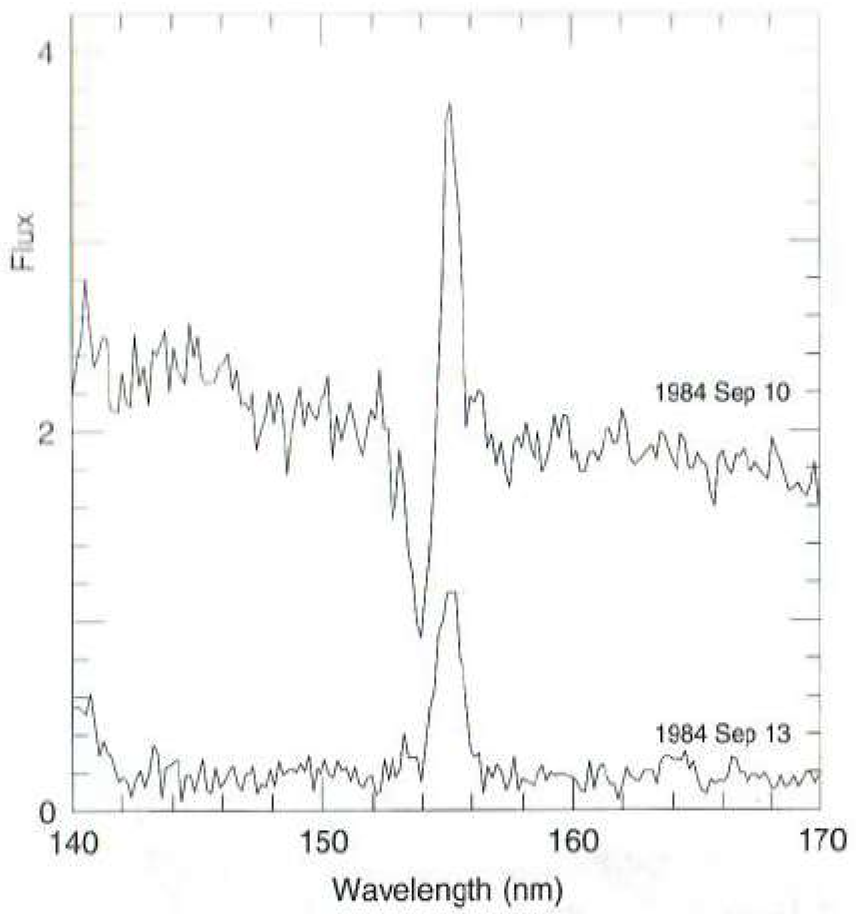


Fig. 7.5: A wind outflow from a white dwarf giving rise to P Cygni line profiles. The bulk of the outflow (a) emits scattered resonance-line photons, with a Doppler-broadened profile owing to the wind's motion. From the white dwarf (b) we see a hot continuum minus the photons scattered by the wind (which are blueward of the line's rest wavelength due to the wind's motion towards us). The overall line profile thus contains the mixture of line emission and blue-shifted absorption characteristic of outflows.

Compact Binaries

Observing Wind Outflows

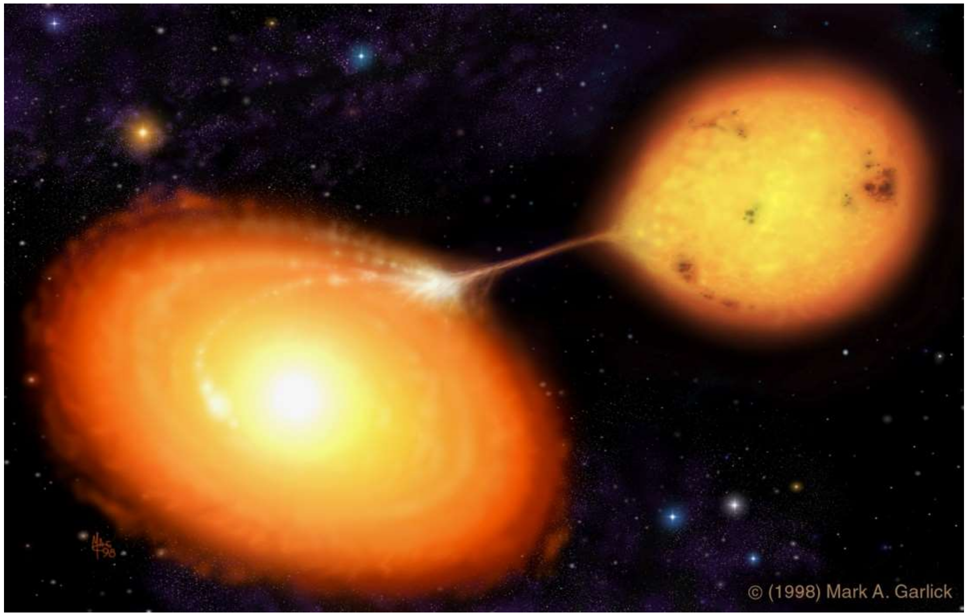
- Resonances lines from hot BL or disk are most easily seen in the UV
  - UV resonance lines
- So P Cyg profiles produced in hot winds are seen in Novalike CVs (e.g. hot bright disks) or Dwarf Novae in outburst (hot boundary layer/disk)
- Remaining questions:
  - Does wind primarily originate in BL or inner disk (where Keplerian velocity is higher)?
  - Role of disk magnetic fields (slingshot) ?
  - How bi-polar is the flow?
  - How symmetrical ?
  - How much mass is driven off ?
- Results from computational models
- Will come back to winds in X-ray binaries



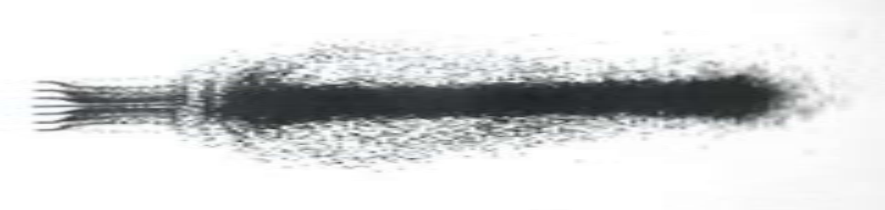
UV obserevations (*IUE*) of Dwarf Nova WX Hyi in quiescence (lower) and outburst (upper)

Disk-Stream Impacts

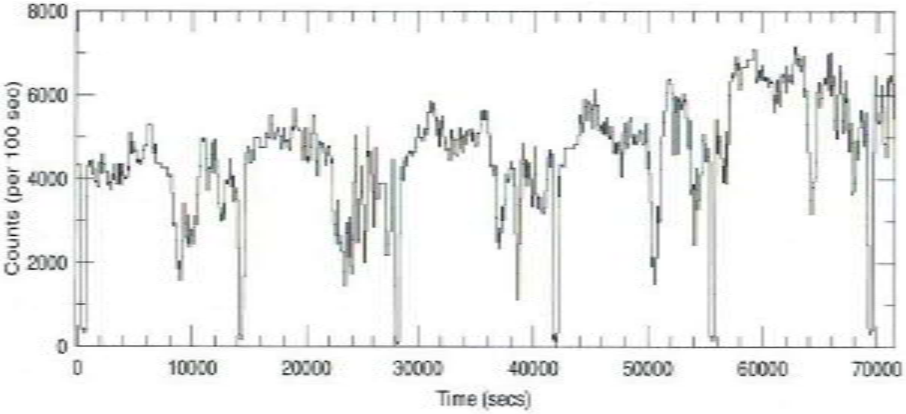
- Canonical accretion disk models include emission from the hot/bright spot on the outer edge where accretion stream impacts
- The hot-spot can emit a significant amount and is much hotter than the surrounding



© (1998) Mark A. Garlick

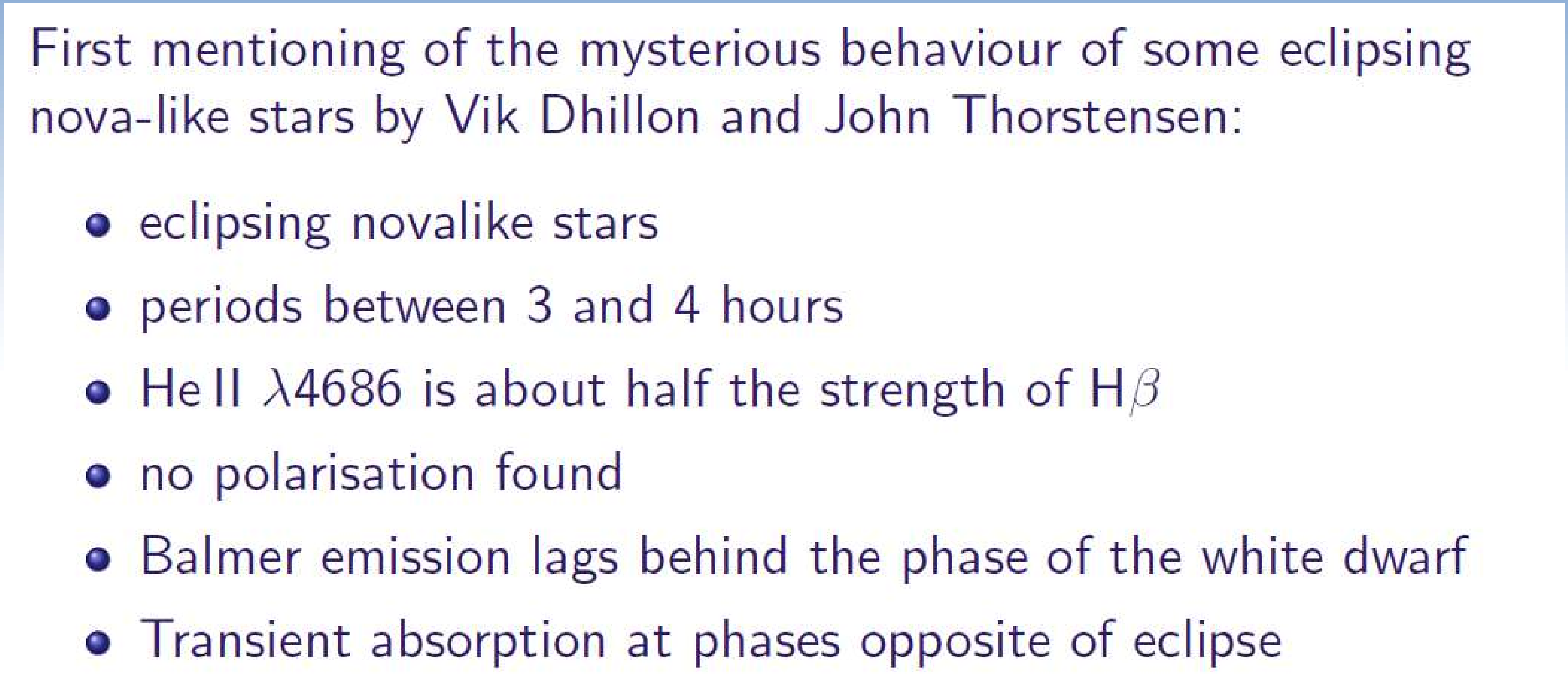


- Depending of dM/dt through the L_1 point, stream can cause material in disk to “puff up”, i.e. extend well above the disk
  - Evidence from “dips” in light curves



- Stream can also overflow the disk and penetrate further, perhaps causing secondary impact regions

SW Sex stars

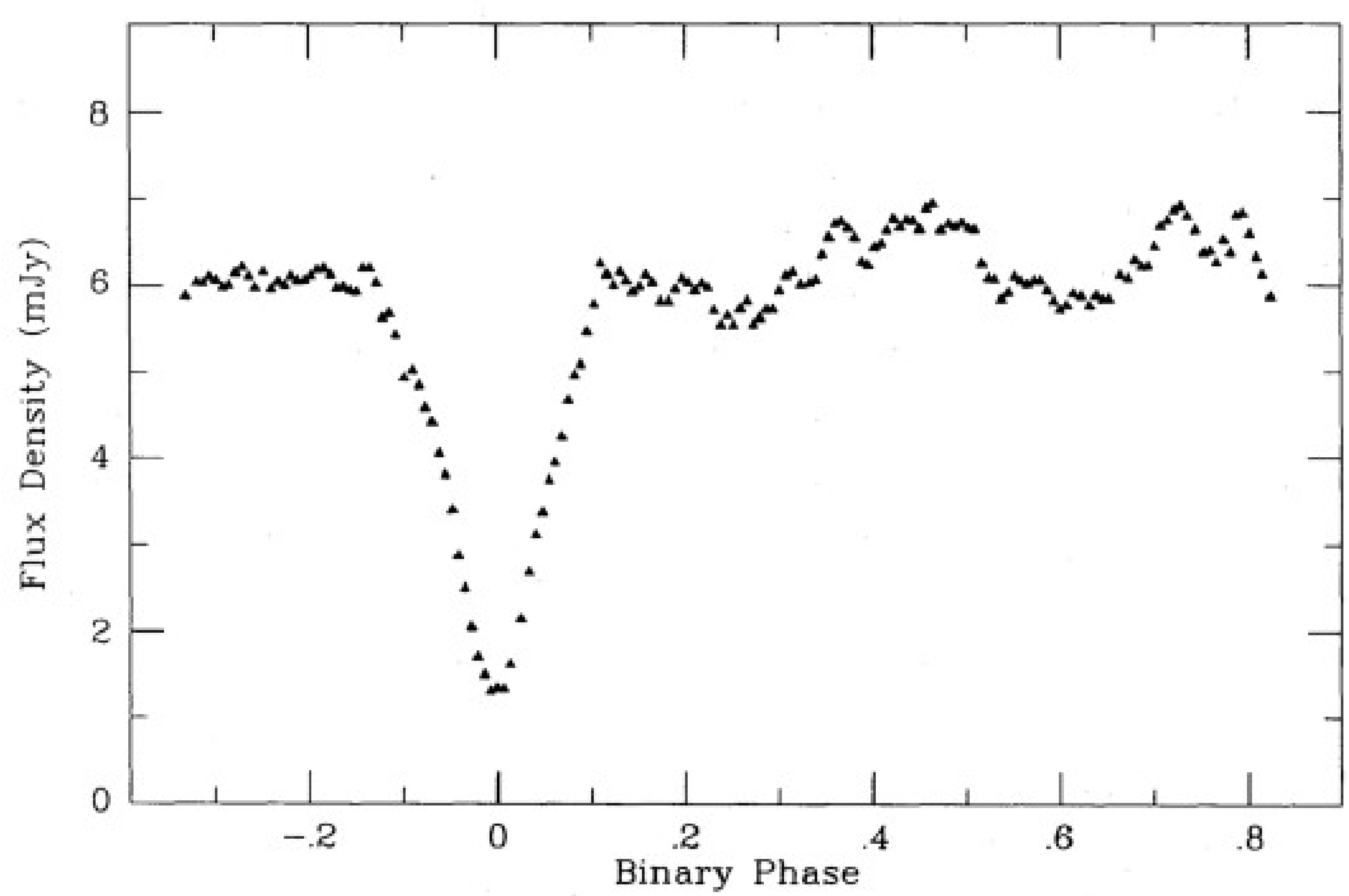


First mentioning of the mysterious behaviour of some eclipsing nova-like stars by Vik Dhillon and John Thorstensen:

- eclipsing novalike stars
- periods between 3 and 4 hours
- He II $\lambda4686$ is about half the strength of Hβ
- no polarisation found
- Balmer emission lags behind the phase of the white dwarf
- Transient absorption at phases opposite of eclipse

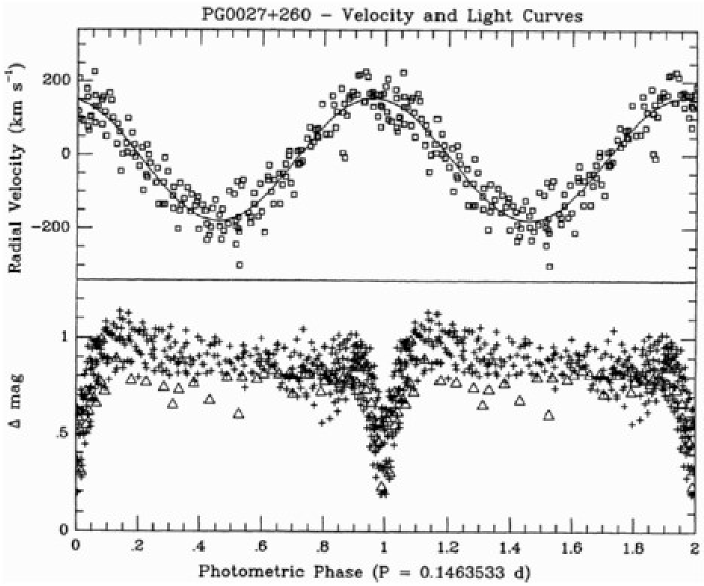
- Evidence of stream-disk overflow

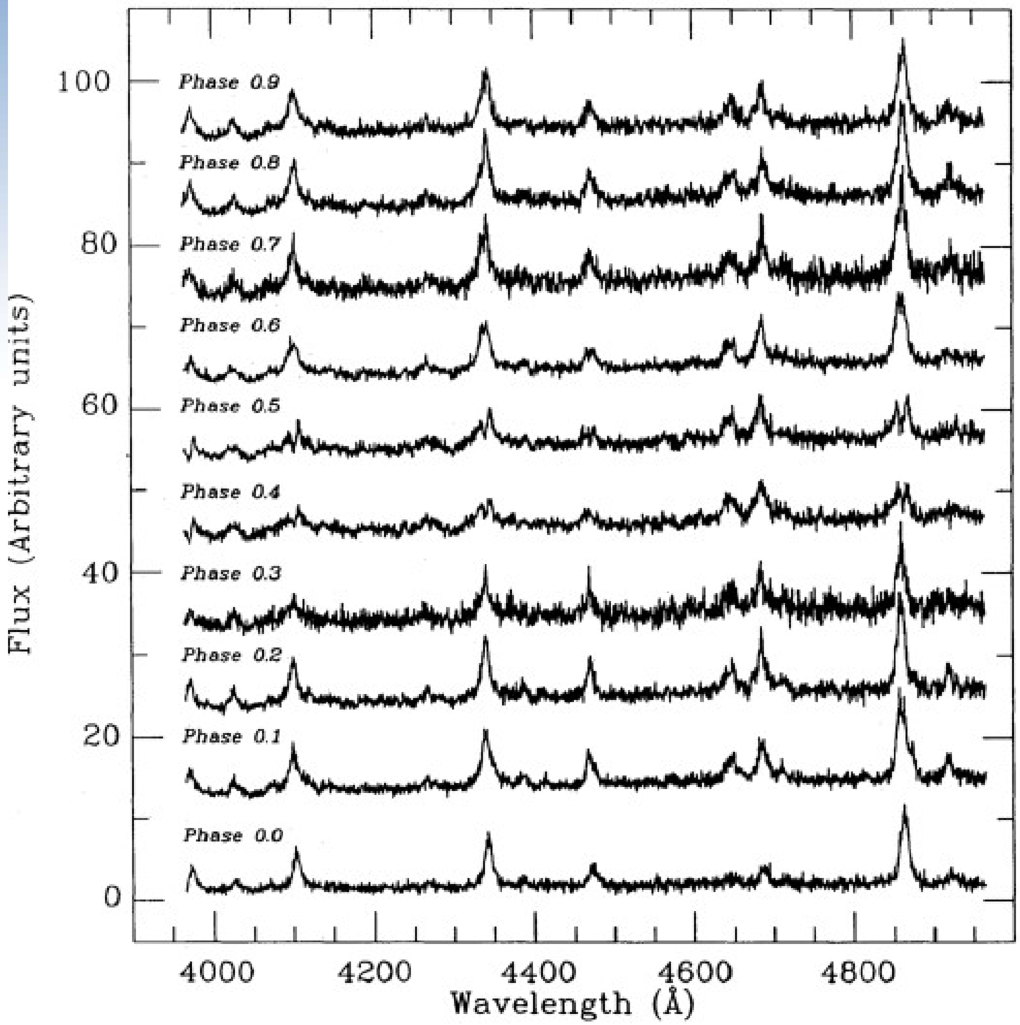
SW Sex stars



SW Sex stars

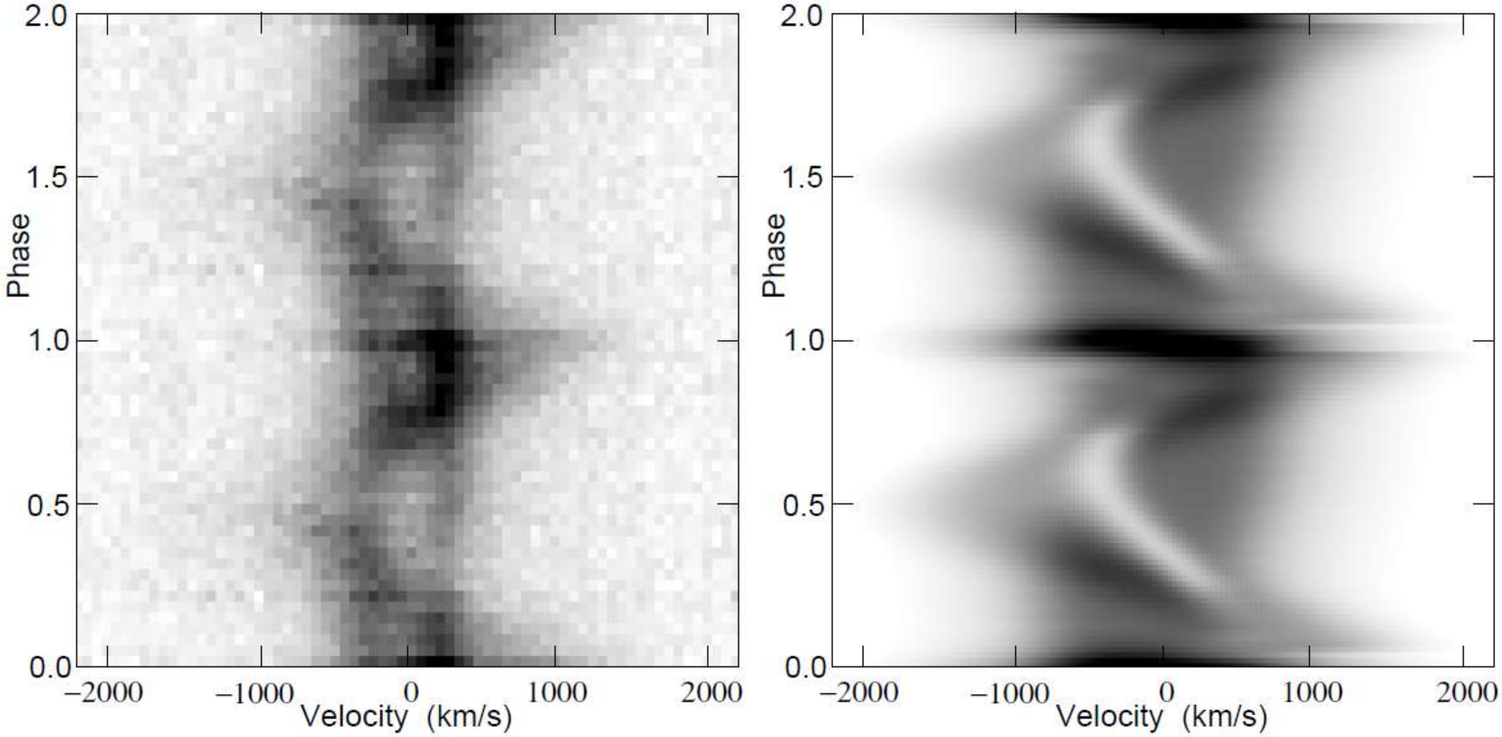
- Radial Velocities out of phase with eclipse
- Phase-dependent absorption components in emission lines
    - i.e. lines become double peaked





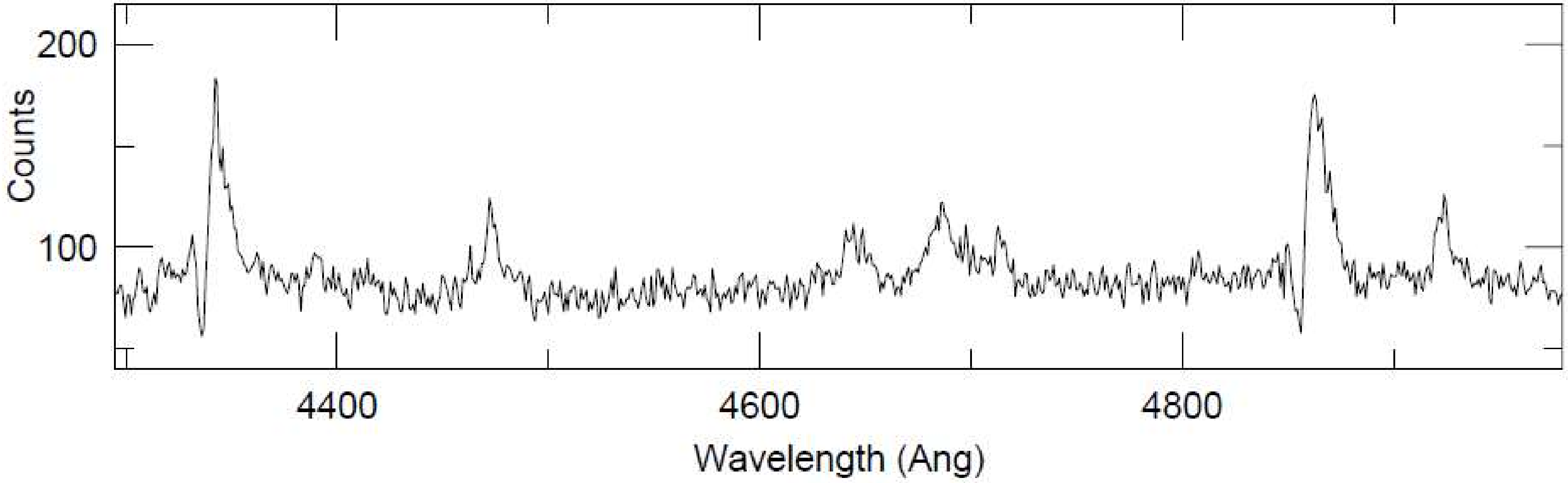
SW Sex stars

- Complex emission lines structures with off-set RV curves compared to eclipse
- High velocity “zig zag” explained as either
  - – modulation could be due obscuring of inner disk (high velocity) regions, by the outer asymmetrically flared disc rim
  - – stream penetration into inner disc where stream absorbs light from disk
  - – new impact stream-disk impact region would appear to show and absorption line *S*-wave



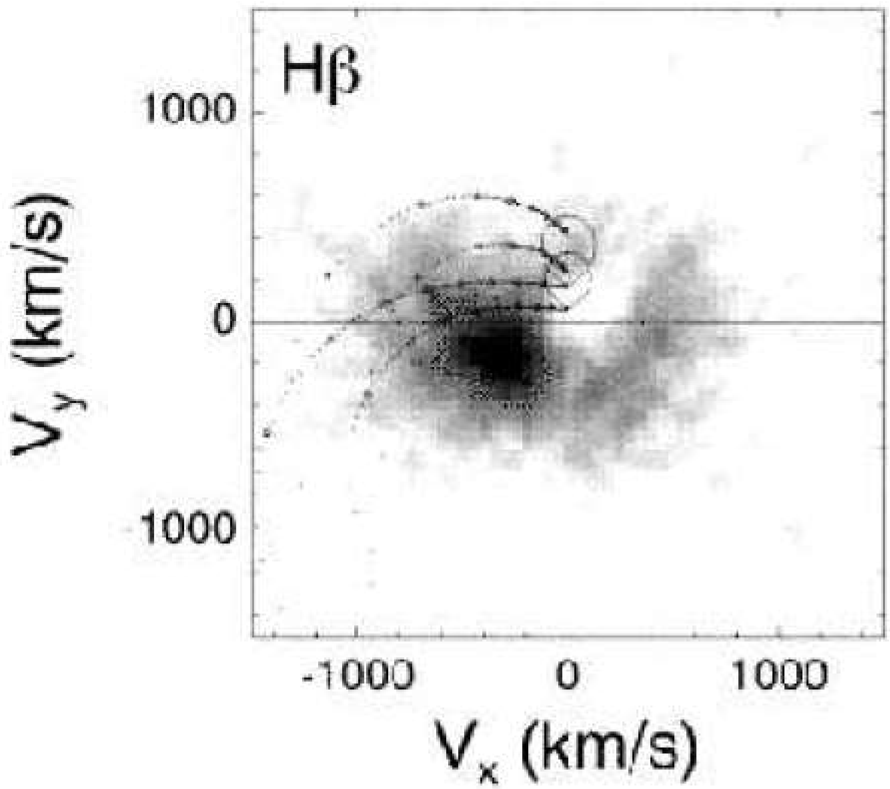
SW Sex stars

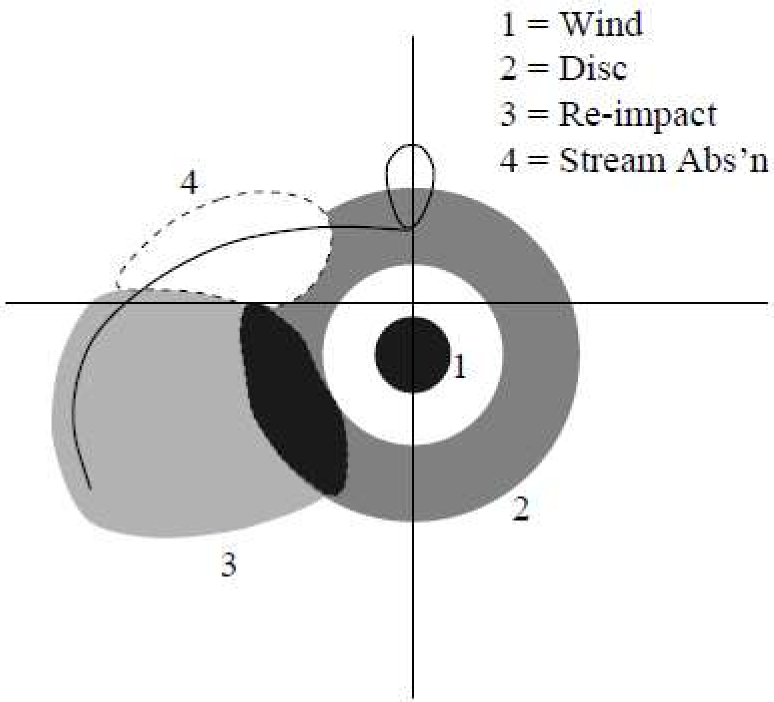
- Emission lines are mostly single-peaked
- Suggestion that they arise in a disc wind, which is evidenced in P Cyg profiles seen in some systems (e.g. V1315 Aql below)



SW Sex stars

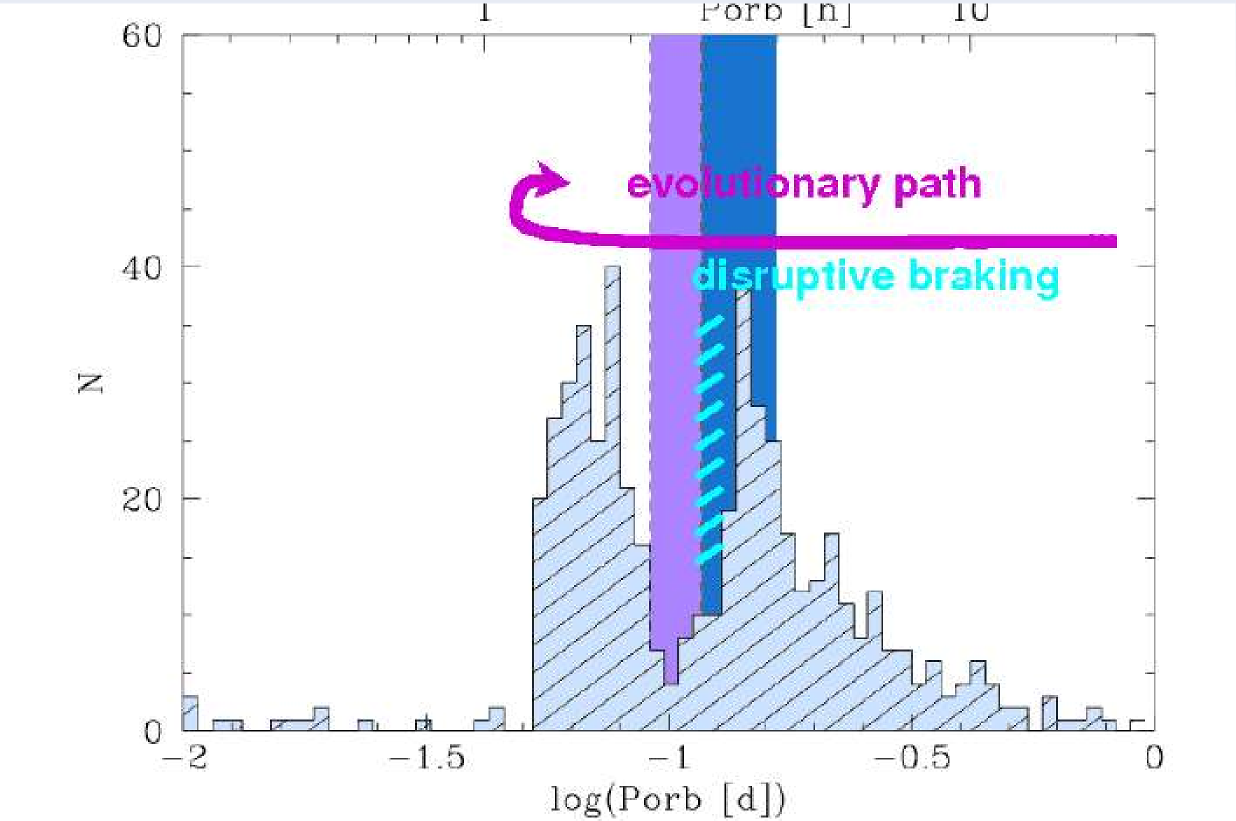
- Doppler tomography shows evidence of disk, wind & stream





SW Sex stars

- Current belief is that *all* novalike CVs evolving from longer -> shorter orbital periods pass through a “SW Sex” phase.
- Not so obvious in low inclination systems, since harder to see obscuration effects

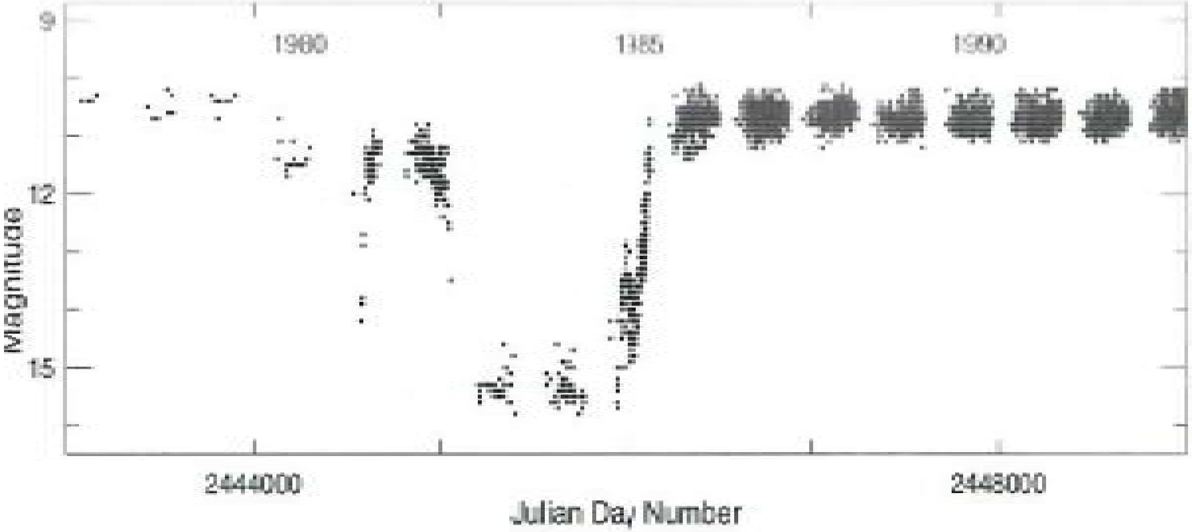


SW Sex stars

- **Recent suggestion of possible connection to magnetic CVs**
  - White dwarfs with magnetic fields of > 5 MG that can influence accretion
  - About 33% of CVs
- **Maybe SW Sex stars have magnetic WDs, but because of high *dM/dt* this buries the usual magnetic signatures?**
- **Part of the whole problem of missing magnetic WDs in post-common envelope (detached) binaries**
- **Where are mCV progenitors ?**

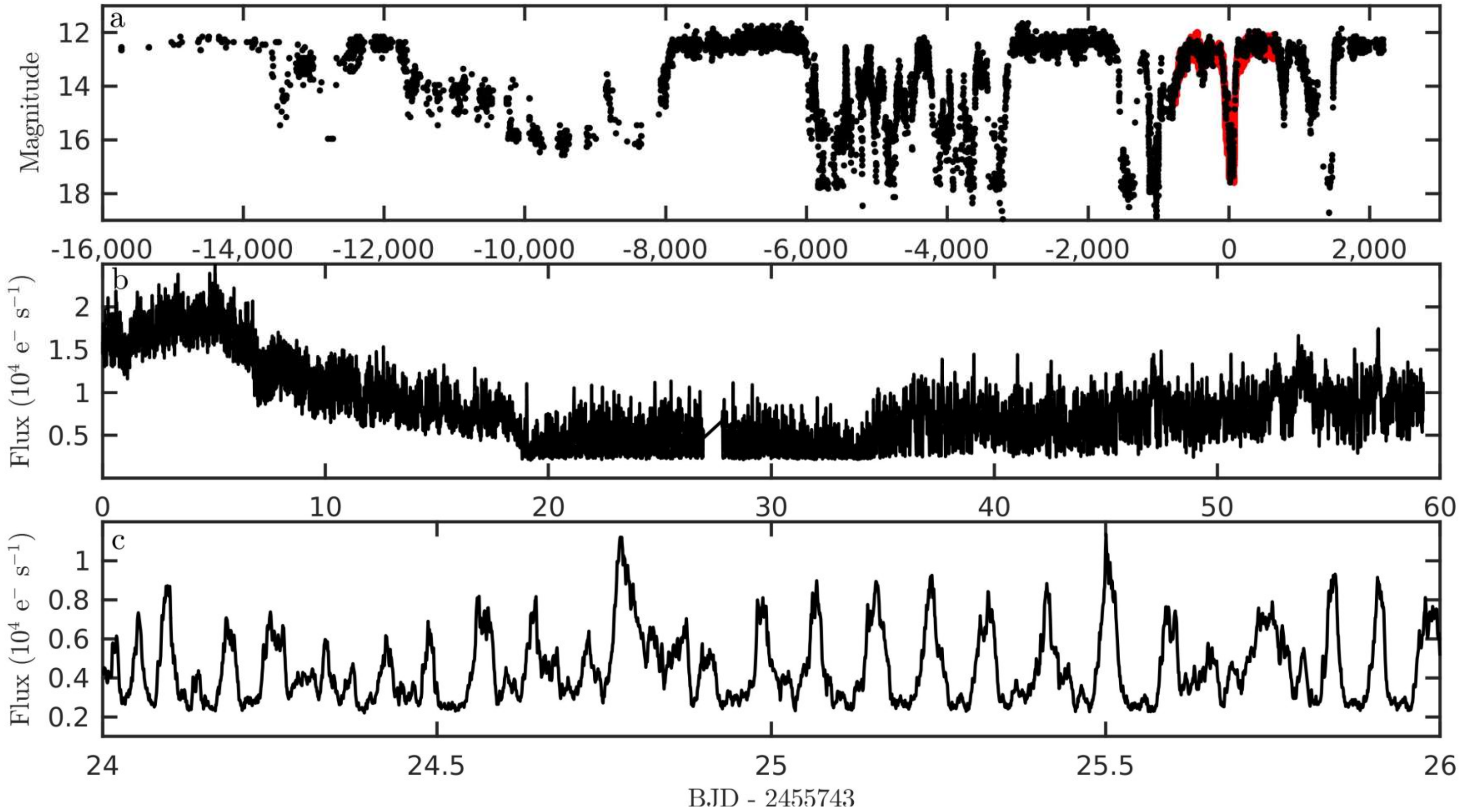
VY Scl stars: dipping Novalike CVs

- A small fraction of Novalike CV (supposedly stable high *dM/dt*, optically thick accretion disks) show unexpected dips in their light curves (e.g. TT ari below)
- Different characteristic to Dwarf Novae (DNe)
  - Deeper dips
  - No quasi-periodic behaviour (as in the Z Cam DNe)
  - Not disk o/b related (similar to some low states of mCVs where there are no disks
- Explanation suggested initially due to hot WD irradiating inner disk and keeping it stable and high *dM/dt* through disk, so empties quickly.
- Change in state brought about by reduced mass loss through L_1
  - Perhaps due to star spots on the secondary star



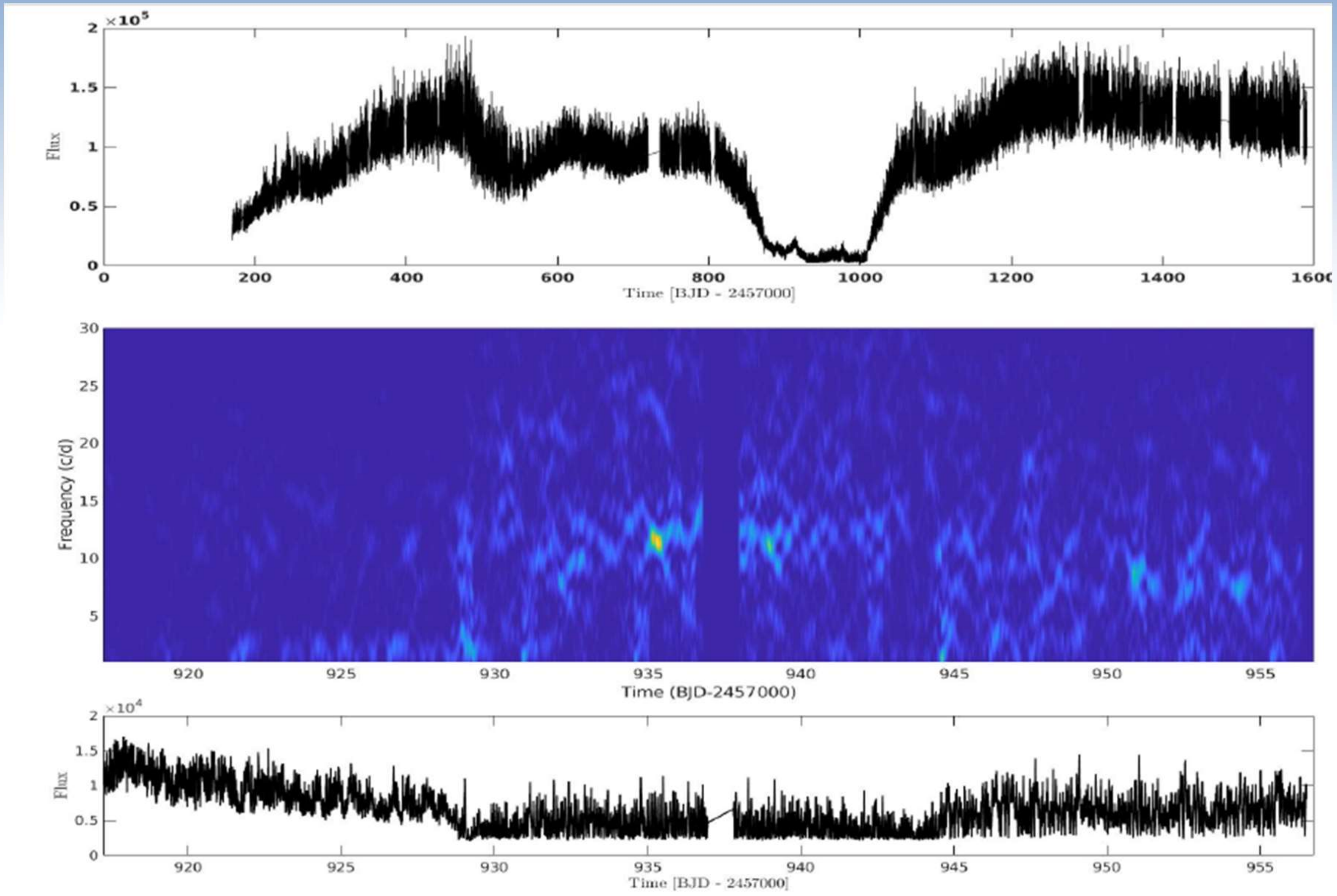
VY Scl stars: dipping novalikes

- New insights from observations with *Kepler* & *TESS*
- Example below MV Lyr covering ~50 yr (AAVSO) including 3.9 yr of Kepler semi-continuous observations (bottom panels; Scaringi *et al.* 2017)



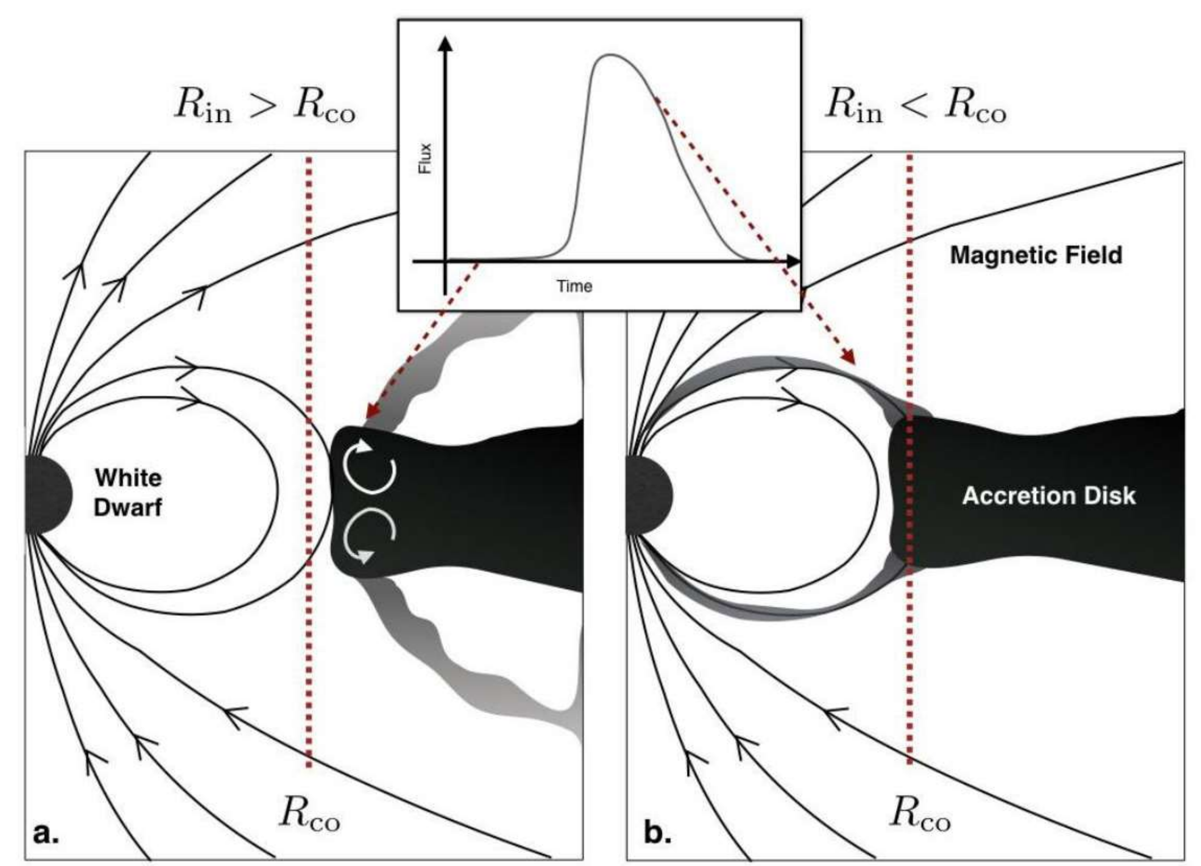
MV Lyr: *Kepler* data

- Periodicity of accretion gating is ~2 h (viscous timescale)



Accretion gating

- Explanation for above behaviour is magnetism and accretion "gating"
- Build up of material just outside magnetosphere which eventually penetrates and is accreted



The End!