School of Astrophysics "Francesco Lucchin"

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Formation and Evolution of Cataclysmic Variables

Lectures by

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Generic properties of cataclysmic variables

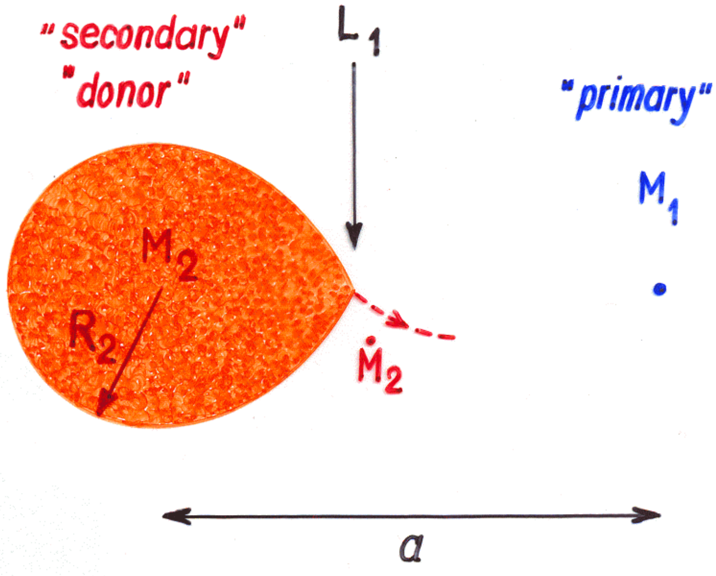
(from the perspective of stellar evolution)

▶ **semi-detached binary**

(donor fills its critical Roche volume)

$\curvearrowright$ $R_2 = a\, f_2\left(\frac{M_1}{M_2}\right)$

$$f_2(q) = \left(\frac{8}{81}\right)^{1/3} (1+q)^{-1/3}$$



▶ **primary: white dwarf**

$\curvearrowright$ typically $0.5\,M_\odot \lesssim M_1 \lesssim 1\,M_\odot$, $\langle M_1 \rangle_{intr} \approx 0.6\,M_\odot$

▶ **donor: low-mass star** $(M_2 \lesssim 1\,M_\odot,\ M_2 \lesssim M_1)$

either
- a MS star (i.e. with central hydrogen burning), or
- a giant (rel. rare), or
- a white dwarf of very low mass, i.e. $M_2 \lesssim 0.05\,M_\odot$ (also very rare)

▶ **derived parameters:**

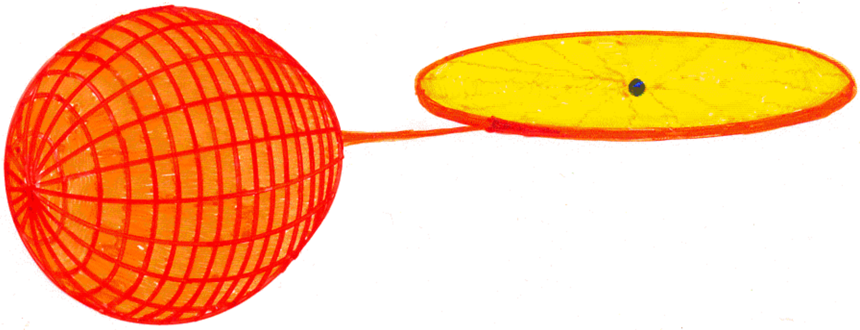
- total mass $\mathfrak{M} = M_1 + M_2 \approx M_\odot$
- orbital separation $a \approx R_\odot$
- orbital period $\sim 80\text{ min} \lesssim P_{orb} \lesssim 10^h$ ($\cdots$ few days)
- orbital angular momentum $J_{orb} = \sqrt{G}\, M_1 M_2 (M_1+M_2)^{-1/2} a^{1/2}$

$$\curvearrowright J_{orb} = J_o \left(\frac{M_1}{M_\odot}\right)\left(\frac{M_2}{M_\odot}\right)\left(\frac{\mathfrak{M}}{M_\odot}\right)^{-1/2}\left(\frac{a}{R_\odot}\right)^{1/2} \approx 1.47\, J_o \left(\frac{M_1}{M_\odot}\right)\left(\frac{M_2}{M_\odot}\right)^{5/6}\left(\frac{\mathfrak{M}}{M_\odot}\right)^{-1/3}\left(\frac{R_2}{R_\odot}\right)^{1/2}$$

$$\curvearrowright \underline{\underline{J_{orb} \approx J_o = G^{1/2} M_\odot^{3/2} R_\odot^{1/2} \approx 10^{51}\text{ cgs}}} \quad \text{for a MS donor}$$

Systems containing a magnetized compact star

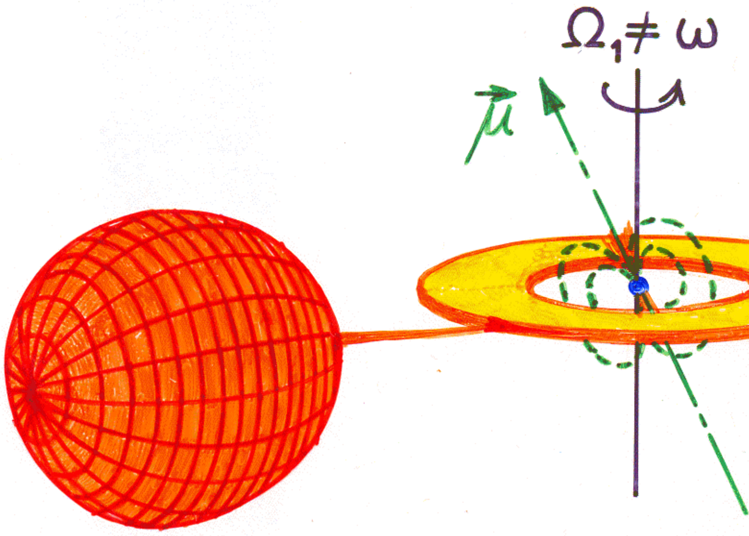
a) $r_M \lesssim R_1 \ll A$



- → non-magnetic systems
- → standard model with an accretion disk

▶ Examples: ~ 80 % of the cataclysmic binaries
X-ray bursters ∈ LMXBs

b) $R_1 < r_M \lesssim \frac{1}{2}A$

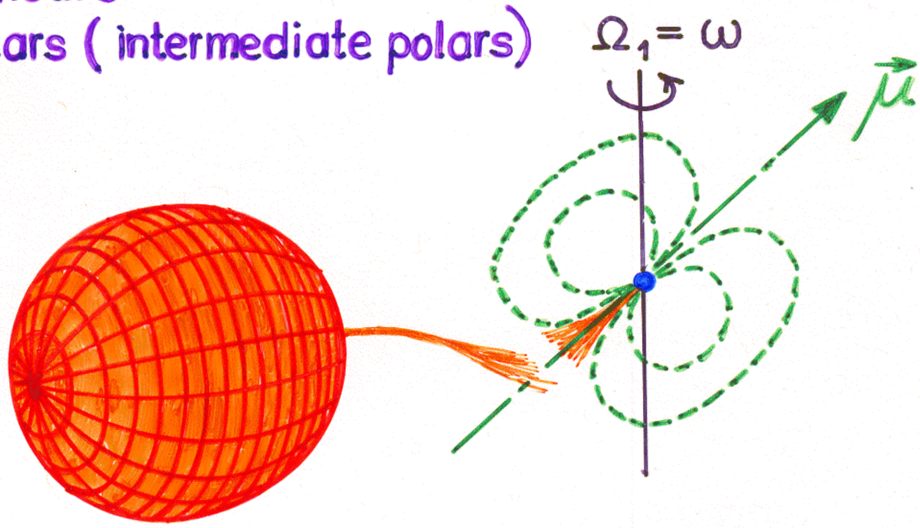


▶ compact star rotates asynchronously, magnetosphere inhibits disk formation inside r_M

▶ accretion on the magnetic poles → lighthouse effect → opt. & X-ray pulses

▶ Examples: X-ray pulsars
DQ Her stars (intermediate polars)

c) $r_M \gtrsim A$



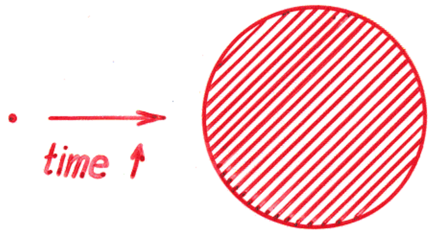
▶ no accretion disk, compact star rotates synchronously

▶ accretion on the magnetic poles

▶ Examples: AM Her stars (polars), $B \approx 20-60$ MG,
$\hat{=}\ \mu \approx 10^{33} - 10^{34}\ \mathrm{G\,cm^3}$

Basic facts about the evolution of single and binary stars

1.) Stars grow considerably (by up to a factor $\gtrsim 10^2$) as they age! (growth is not strictly monotonic)



↝ $\exists$ distinct phases of growth:

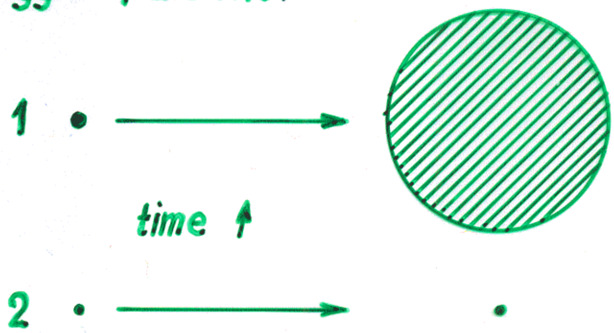
- main sequence
- Hertzsprung gap & evol. towards He ignition ($M \gtrsim 2M_\odot$)
- giant branch up to the He-flash ($M \lesssim 2M_\odot$)
- asymptotic giant branch ($M \lesssim 10M_\odot$)

2.) The more massive a star, the faster it ages,

on the MS: $L \sim M^{3.5} \rightsquigarrow \tau_{nucl} = \frac{M}{L} \sim M^{-2.5}$

↝ Of two stars with the same age (as in a binary) but different mass, the more massive star grows faster, i.e. is the bigger of the two.

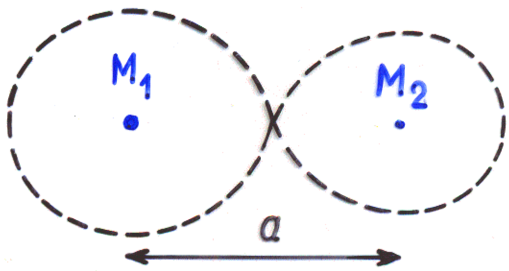
$M_1 > M_2$:



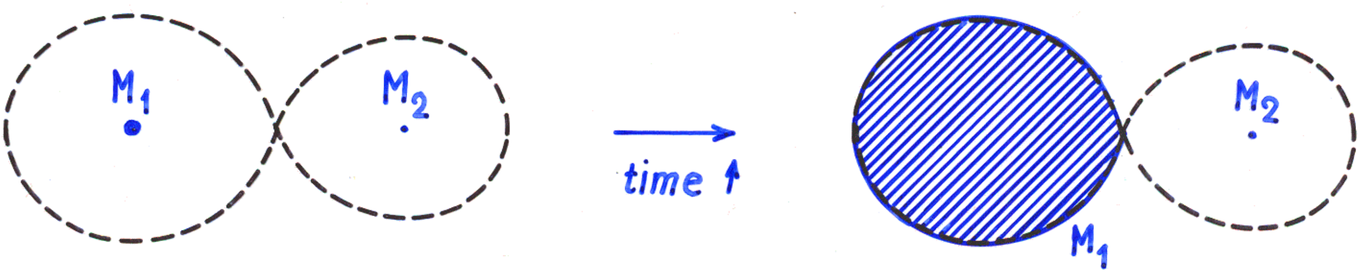
3.) In a binary the presence of a companion limits the size up to which a star can grow (Roche limit) without losing mass to its companion.

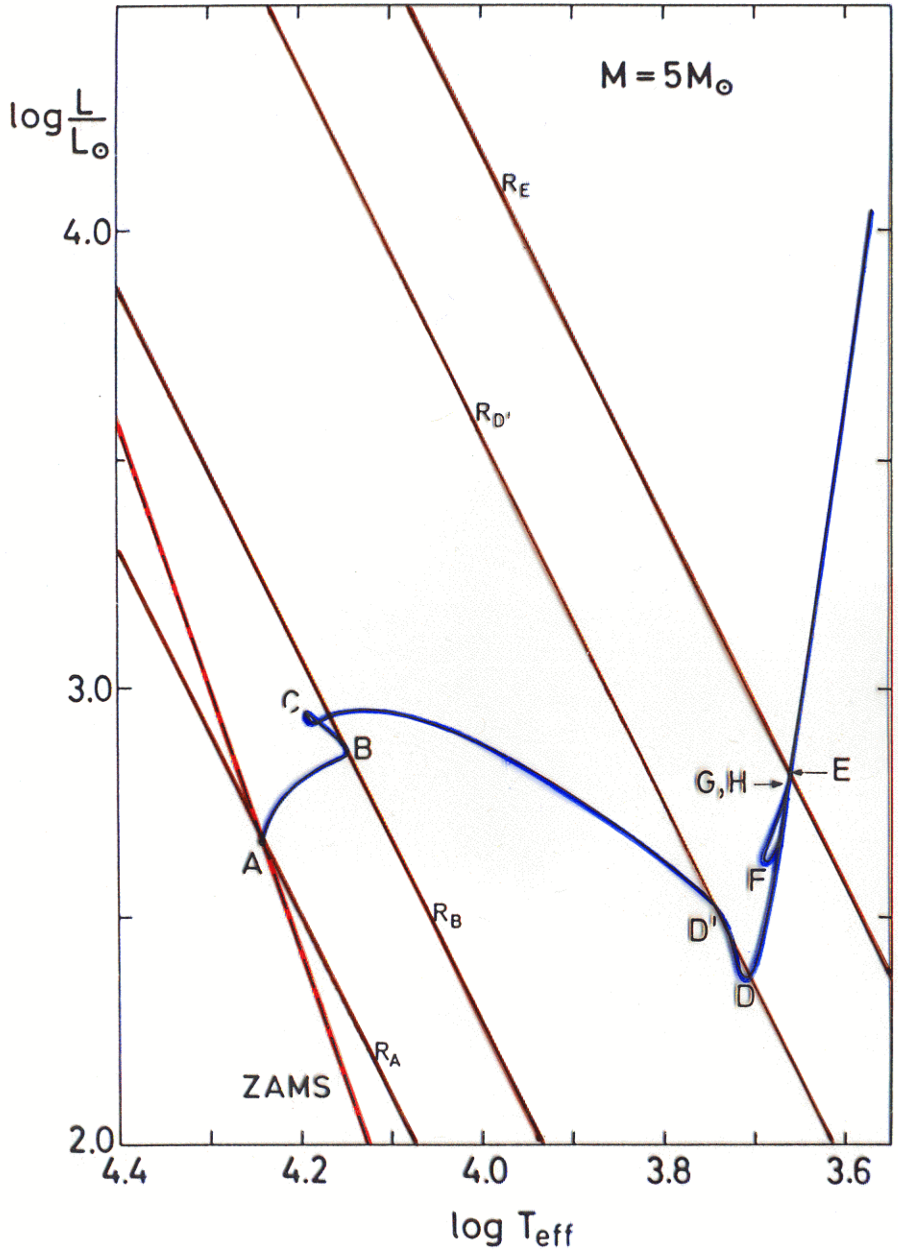
Maximum size for each component:

$$\left.\begin{aligned} R_{1,R} &= a\, f_1\!\left(\frac{M_1}{M_2}\right) \\ R_{2,R} &= a\, f_2\!\left(\frac{M_1}{M_2}\right) \end{aligned}\right\} \quad \begin{aligned} & f_2(q) \approx \left(\frac{8}{81}\right)^{1/3} (1+q)^{-1/3}, \; q \gtrsim 1 \\ & f_1(q) = f_2(q^{-1}) \approx q^{0.45} f_2(q) \end{aligned}$$

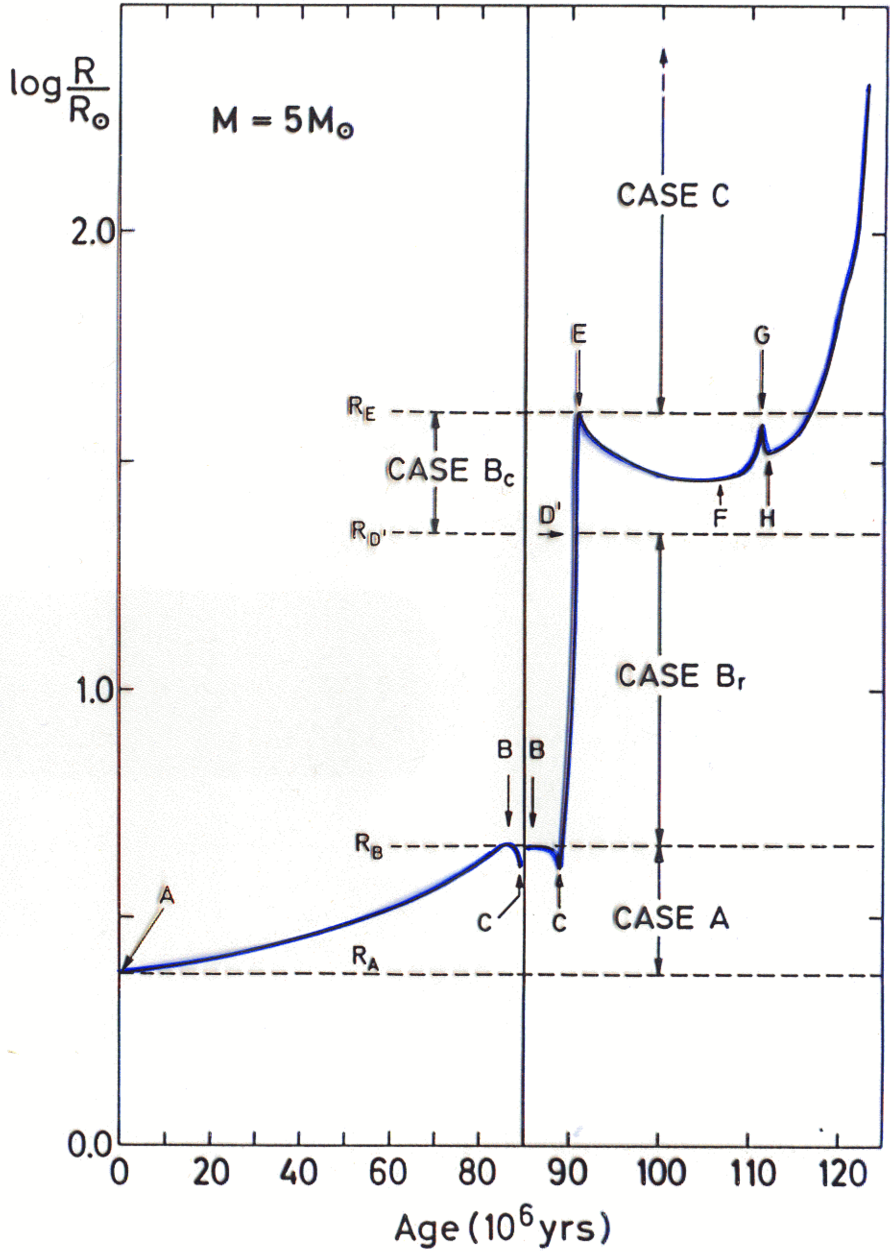


▶ consequence: evolution into a semi-detached system, i.e. towards mass transfer





M = 5M⊙
log L/L⊙
4.0
3.0
2.0
4.4
4.2
4.0
3.8
3.6
log Teff
R_E
R_D'
R_B
R_A
ZAMS
A
B
C
D
D'
E
F
G,H



M = 5M⊙
log R/R⊙
2.0
1.0
0.0
0
20
40
60
80
90
100
110
120
Age (10^6 yrs)
CASE C
CASE Bc
CASE Br
CASE A
R_E
R_D'
R_B
R_A
A
B
B
C
C
D'
E
F
G
H

Prerequisites for white dwarf formation

Main production modes (for single and in binary stars):

- He - WDs: $0.15\,M_\odot \lesssim M_{He\text{-}WD} \lesssim M_{He\text{-}Fl.} \approx 0.45\text{-}0.50\,M_\odot$: loss of stellar envelope on 1st giant branch ($M_i \lesssim 2.2\,M_\odot$)
- CO - WDs: $M_{He\text{-}Fl.} < M_{CO\text{-}WD} \lesssim M_{C\text{-}Fl.} \approx 1.1\,M_\odot$: envelope loss on the AGB ($M_i \lesssim 6\text{-}8\,M_\odot$ for single stars, possibly higher in binaries)
- ONeMg - WDs: $M_{C\text{-}Fl.} < M_{ONeMg\text{-}WD} < 1.38\,M_\odot \approx M_{CH}$: envelope loss on the tip of the AGB of stars with $M_i \approx 8\text{-}12\,M_\odot$ (in binaries)
- Fundamental property of giants/AGB-stars: $\exists$ core mass-radius relation $R(M_c)$

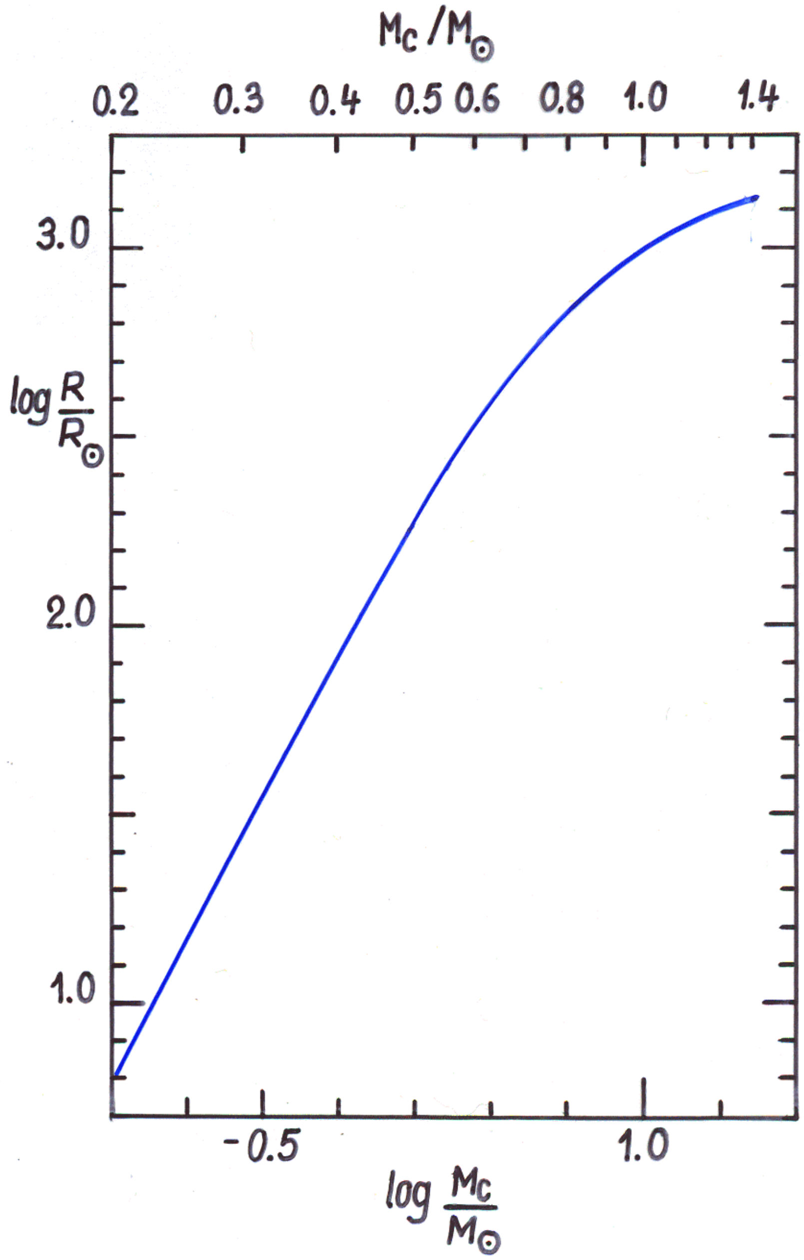
↗ Formation of WDs requires a lot of space, the more massive the WD to be formed the more space!

→ no problem for single stars

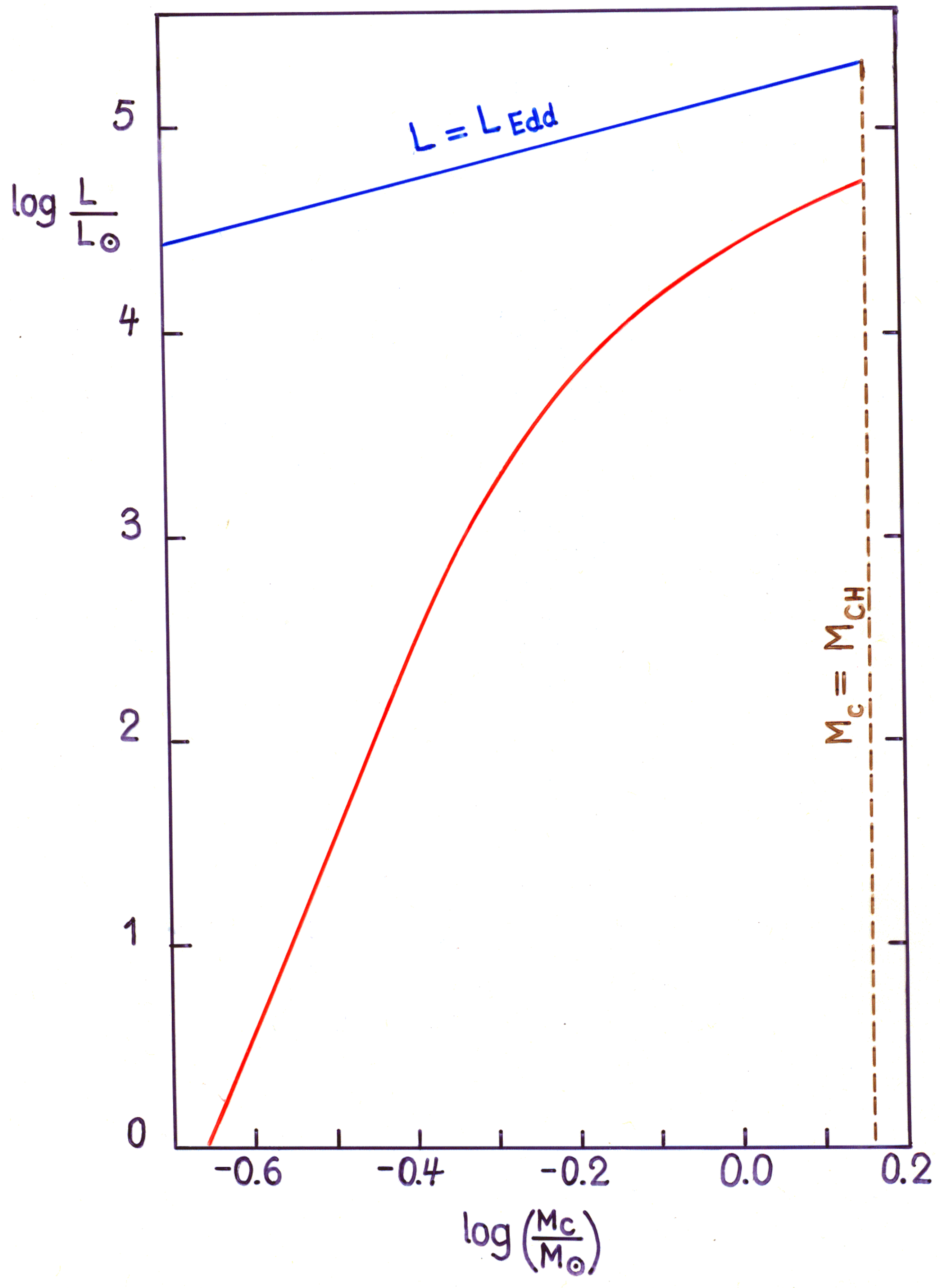
→ in binaries: orbital separation a sets an upper limit to M_{WD}:

$$M_{WD} \lesssim R^{-1}\left(a f_1(M_1/M_2)\right)$$

(reason: Roche limit)



Core mass luminosity relation (Kippenhahn, 1980)



Single star evolution ⟷ binary star evolution

Single star evolution:

▶ **Task:** Solve a well-known set of differential equations with appropriate boundary conditions and initial values.

Binary evolution:

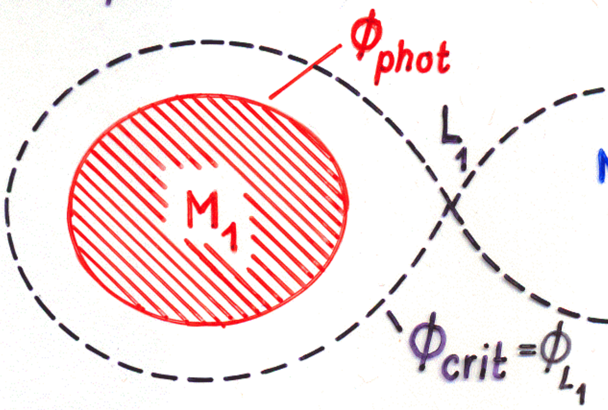
▶ **Task:** In principle the same as for single stars, with an additional boundary condition which derives from the presence of a companion star.

Simplest case: 1 "real" star + 1 point mass

$$\phi_{phot} \leq \phi_{crit}$$

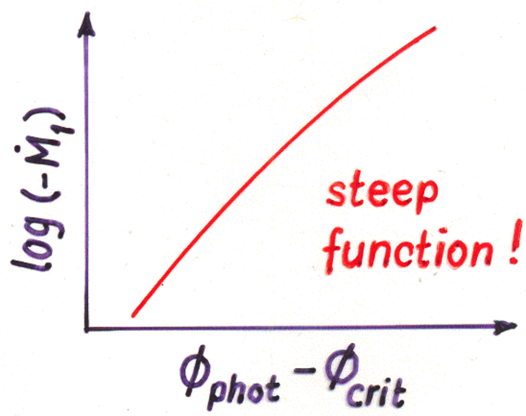
or

$$-\dot{M}_1 = f(\phi_{phot} - \phi_{crit}, \ldots)$$



→ consequence:

significant mass loss of M_1, as soon as $\phi_{phot} \rightarrow \phi_{crit}$

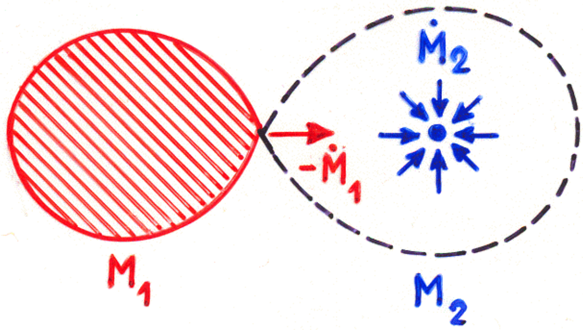


▶ **Problem:** Where does the lost mass go, and how much angular momentum does it carry with it?

$$\dot{M}_2 =: -\dot{M}_1 \cdot \eta$$

$$\rightarrow \dot{\mathfrak{M}} = \dot{M}_1 + \dot{M}_2 = \dot{M}_1 (1-\eta)$$

$$\dot{J} =: J \frac{\dot{\mathfrak{M}}}{\mathfrak{M}} \cdot \nu$$



$\mathfrak{M} = M_1 + M_2$

J = orbital angular momentum

▶ What is known about ν and η?

▶ in general: $0 \leq \eta \leq 1$ and $\nu \geq 0$,

otherwise (almost) free functions of the binary parameters!

→ $\boxed{\text{Binary evolution: Theory with (at least) two (almost) free functions}}$

Low-mass case B evolution of a close binary

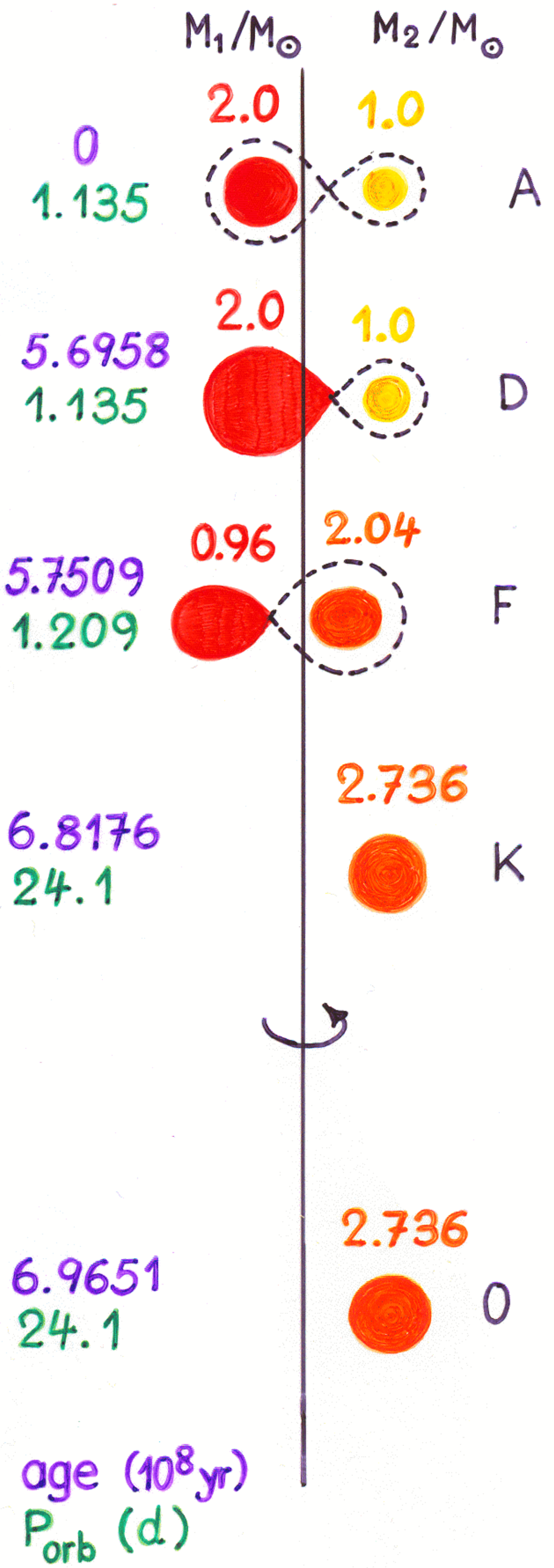
(Kippenhahn, R., Kohl, K., Weigert, A.: 1967, Z. Astrophys. 66, 58)

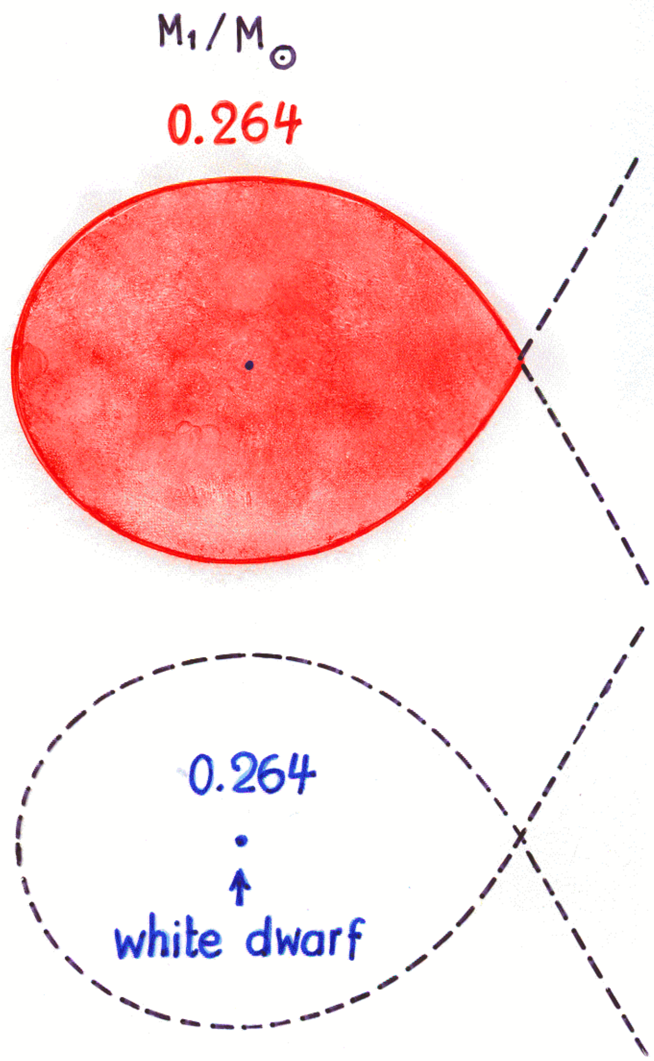
- conservative evolution

→ $M_1 + M_2 = \text{const.}$

$$J = G^{1/2} M_1 M_2 (M_1+M_2)^{-1/2} A^{1/2} = \text{const.}$$

$M_{1,i} = 2.0\ M_\odot$
$M_{2,i} = 1.0\ M_\odot$
$A_i = 6.6\ R_\odot$





Cataclysmic binary with $M_{WD} = 0.26\ M_\odot$ →

Generic properties of CV progenitors

1.) $M_{2,i} = M_2$ (assumption, justification later)

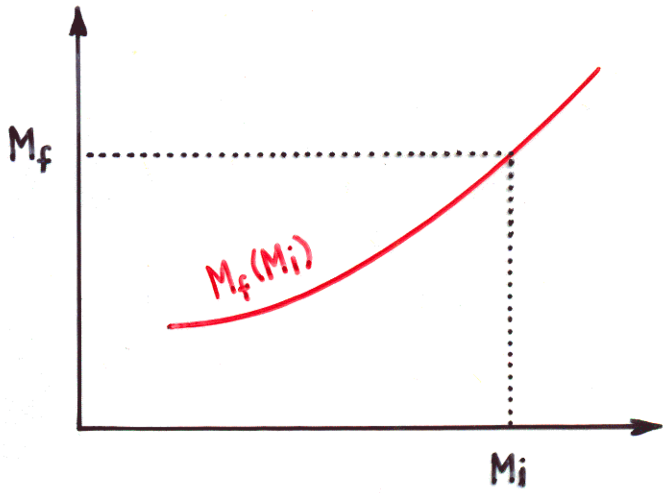
2.) $M_{1,i}$ such that it yields a WD of desired mass

- single star evolution:

  $\exists$ M_i-M_f-relation, i.e.

  $M_{WD} = M_f(M_i)$

  $\curvearrowright$ $M_i(M_{WD}) = M_f^{-1}(M_{WD})$



- binary evolution: premature end of core evolution (onset of mass transfer).

$\curvearrowright$ $M_{WD} < M_f(M_i)$ $\curvearrowright$ $M_i(M_{WD}) > M_f^{-1}(M_{WD})$

3.) Because of core mass radius relation:

$$a_i = \frac{R(M_{WD})}{f_1(M_{1,i}/M_{2,i})}$$ (assuming that $M_{WD} = \text{const.}$ after the onset of mass transfer)

- For typical parameters $M_{WD} \approx 1 M_\odot$, $M_2 \lesssim 1 M_\odot$, $M_{1,i} \gtrsim 5 M_\odot$, $\mathfrak{M} \gtrsim 6 M_\odot$

  $\curvearrowright$ $R(M_{WD}) \approx 10^3 R_\odot$, $f_1(M_{1,i}/M_{2,i}) \approx 0.5$

$\curvearrowright$ orbital angular momentum: $J = J_0 \underbrace{\left(\frac{M_1}{M_\odot}\right)\left(\frac{M_2}{M_\odot}\right)\left(\frac{\mathfrak{M}}{M_\odot}\right)^{-1/2}}_{\sim \text{few}} \underbrace{\left(\frac{a}{R_\odot}\right)^{1/2}}_{\sim 30} \approx 10^2 J_0$

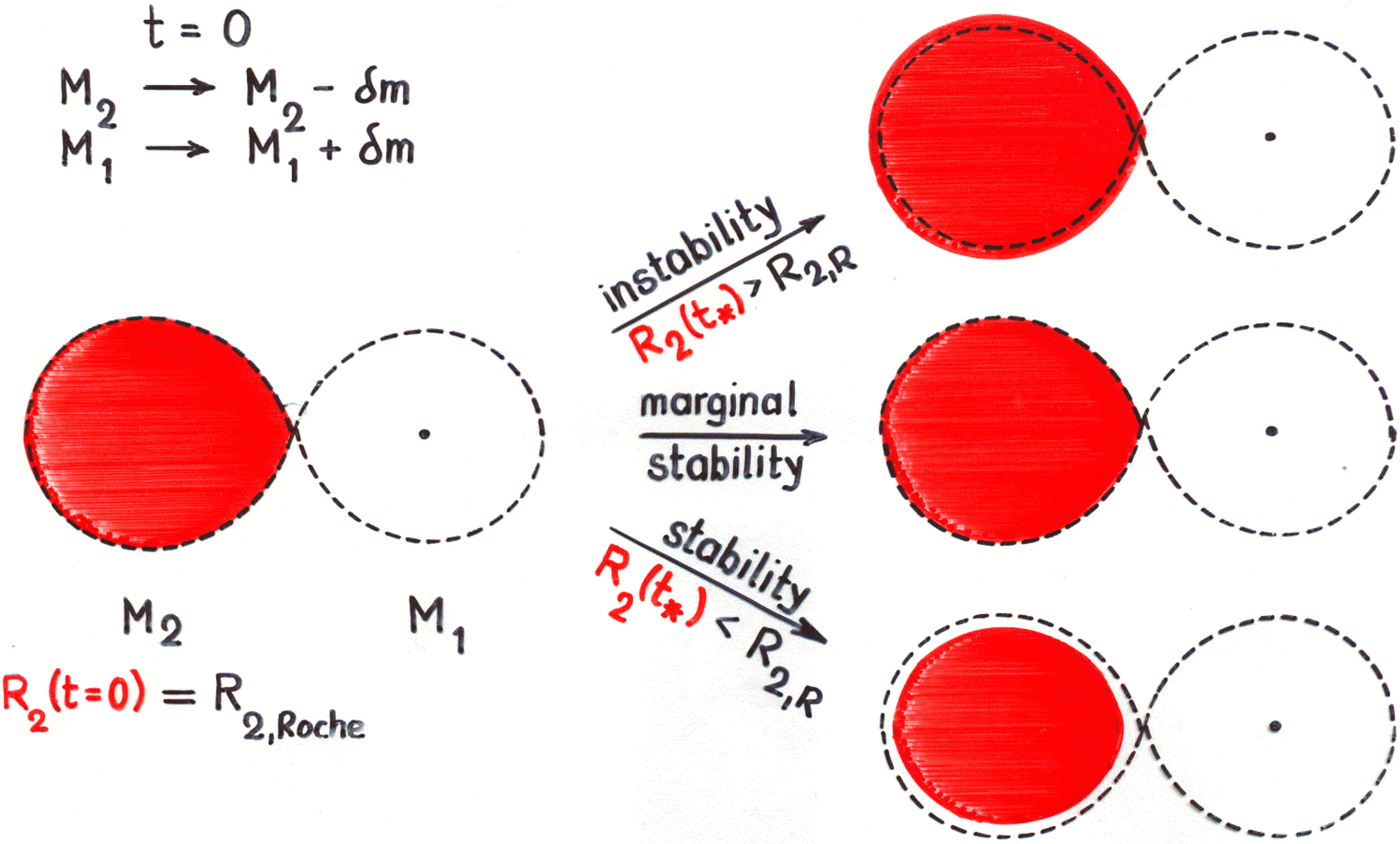
- $$\frac{J_{CV\text{-}prog.}}{J_{CV}} \approx 10^2 \quad , \quad \frac{\mathfrak{M}_{CV\text{-}prog.}}{\mathfrak{M}_{CV}} \approx 5-10$$

STABILITY AGAINST MASS TRANSFER

(conservative mass transfer, $M_1 + M_2 = \text{const.}$) $t = t_* > 0$

$t = 0$

$$M_2 \longrightarrow M_2 - \delta m$$
$$M_1 \longrightarrow M_1 + \delta m$$



1) Dynamical Stability: $\tau_h \approx \left(\frac{R_2^3}{G M_2}\right)^{1/2} \approx P_{orb} \lesssim t_* \ll \tau_{th}, \tau_{nuc}$

$$\text{if} \quad \left(\frac{\partial \ln R_2}{\partial \ln M_2}\right)_s - \left(\frac{\partial \ln R_{2,R}}{\partial \ln M_2}\right)_{\mathfrak{M},J} = \frac{2(q-1)}{q} + \frac{q+1}{q}\beta_2(q) + \zeta_{2,s} > 0 ,$$

$$q = \frac{M_1}{M_2} , \quad \beta_2(q) = \frac{d\ln(R_{2,R}/A)}{d\ln q} , \quad \zeta_{2,x} = \left(\frac{\partial \ln R_2}{\partial \ln M_2}\right)_x$$

▶ $\zeta_s = -\frac{1}{3}$ for fully convective stars, $\zeta_s > 0$ for radiative stars

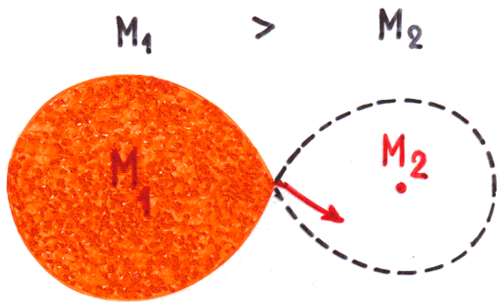
2) Thermal Stability: $\tau_h \ll \tau_{th} \approx \tau_{KH} = \frac{G M_2^2}{R_2 L_2} \lesssim t_* \ll \tau_{nuc}$

$$\text{if} \quad \left(\frac{\partial \ln R_2}{\partial \ln M_2}\right)_{\frac{\partial s}{\partial t}=0} - \left(\frac{\partial \ln R_{2,R}}{\partial \ln M_2}\right)_{\mathfrak{M},J} = \frac{2(q-1)}{q} + \frac{q+1}{q}\beta_2(q) + \zeta_{\frac{\partial s}{\partial t}=0} > 0$$

▶ $\zeta_{\frac{\partial s}{\partial t}=0} \approx 0.5 - 1.5$ on the main sequence

3) Nuclear Stability: $t_* \approx t_{nuc}$, if $(\partial \ln R_2/\partial t)_{nuc} < 0$

Stability of mass transfer



- Upon onset of mass transfer: What happens?

a) to the size of the donor's critical Roche radius?

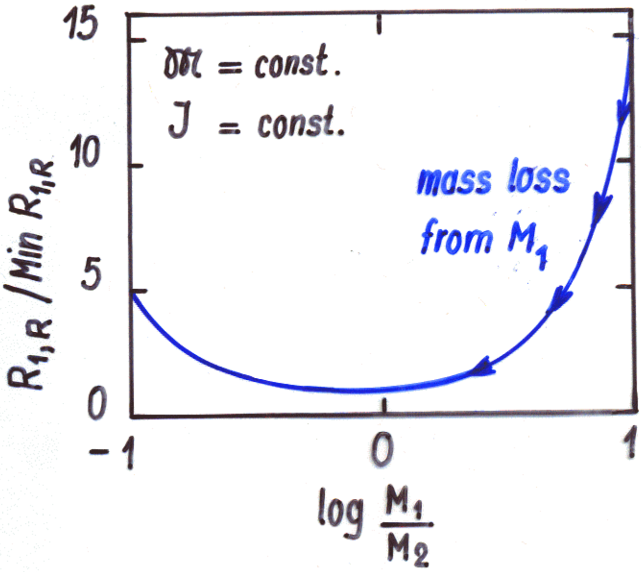
consider the simplest case: conservative mass transfer, i.e.

$$\mathfrak{M} = M_1 + M_2 = \text{const.}$$

$$J = G^{1/2} M_1 M_2 (M_1+M_2)^{-1/2} a^{1/2}$$
$$= G^{1/2} M_1 (\mathfrak{M}-M_1) \mathfrak{M}^{-1/2} a^{1/2}$$

$$\curvearrowright \quad a = \frac{J^2 \mathfrak{M}}{G} \left[M_1 (\mathfrak{M}-M_1) \right]^{-2}$$

$$R_{1,R} = \frac{J^2 \mathfrak{M}}{G} \, \frac{f_1 \left(M_1 / \mathfrak{M}-M_1 \right)}{M_1^{\,2} (\mathfrak{M}-M_1)^2} = R_{1,R}(M_1)$$



$\curvearrowright$ as $M_1 \downarrow$ $R_{1,R} \downarrow$ $\longleftrightarrow$ $\dfrac{\partial \ln R_{1,R}}{\partial \ln M_1} \equiv \zeta_{R,1} > 0 \;\; \forall \; \dfrac{M_1}{M_2} > 0.8$

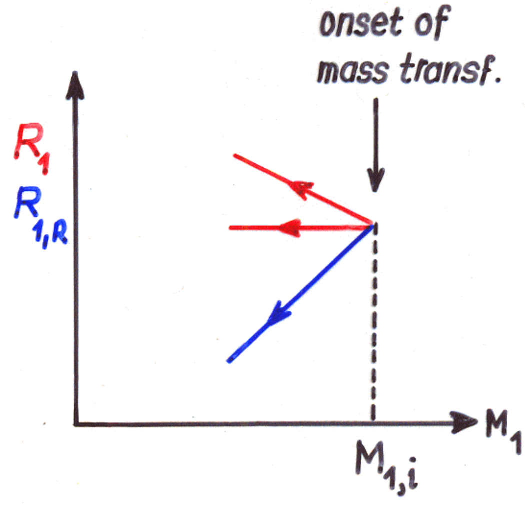
b) to the radius of the donor?

donor star: - star with a deep outer convective envelope (giant, AGB star)
- obeys the core mass-radius relation as long as $\dot{M}_1$ small

$\curvearrowright$ $\dfrac{dR_1}{dM_1} \approx 0$ as long as the mass loss rate is small

$R_1 \sim M_1^{\alpha}$ with $\alpha \approx -1/3$ for rapid (adiabatic) mass loss from convective envelope ($\tau_{th} > \tau_{\dot{M}_1} > \tau_{conv}$), and

$\alpha \rightarrow > 0$ if $\tau_{\dot{M}_1} \rightarrow \tau_{conv}$
$\hat{=} -\dot{M}_1 \rightarrow M_1 / \tau_{conv} \sim M_\odot / yr$



- Onset of mass transfer: $\dfrac{d}{dt}(R_1 - R_{1,R}) > 0$

$\curvearrowright$ <u>mass loss accelerates!</u>

Stability of mass transfer

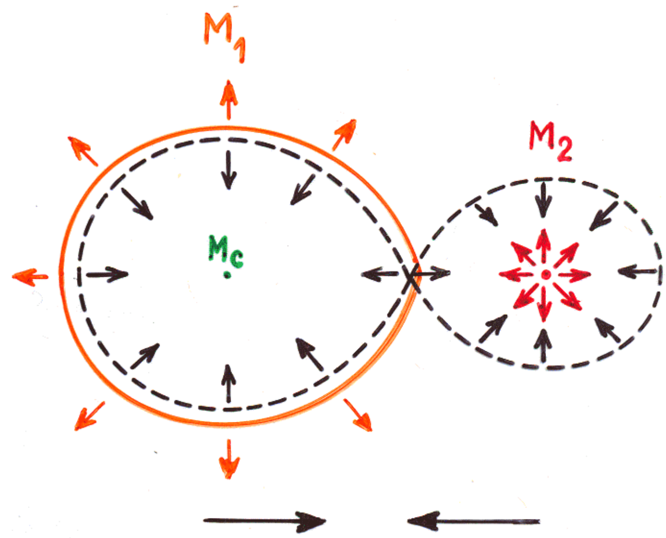
▶ Upon onset of mass transfer: What happens?

c) to the radius of the secondary?

- slow accretion ($\dot{M} < M/\tau_{KH}$) on MS star:

$$\frac{dR_2}{dM_2} \approx \left(\frac{dR_2}{dM_2}\right)_{MS}$$

→ $R_2 \sim M_2^{0.5}$ → rel. small increase



- rapid accretion ($\dot{M} > \cdots \gg M/\tau_{KH}$) on MS star:

R_2 grows the more the faster the mass transfer (accretion) by up to $\Delta \log R \gtrsim 2$!

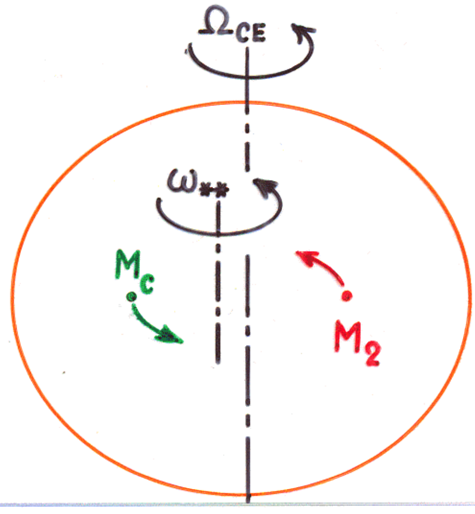
Summary and consequences

▶ Upon onset of mass transfer

- Roche radii shrink
- primary's and secondary's radius increase
- mass transfer rate grows catastrophically up to values of order $-\dot{M}_1 \approx M/\tau_{conv} \sim M_\odot/yr$!

➡ $\boxed{\text{Evolution into deep contact}}$

→ ∃ binary system consisting of the primary's core (mass M_c) and of the secondary (mass M_2) immersed in a common envelope (mass $M_{CE} = M_{1,i} - M_c$) which does not rotate synchronously, i.e. $\Omega_{CE} < \omega_{**}$

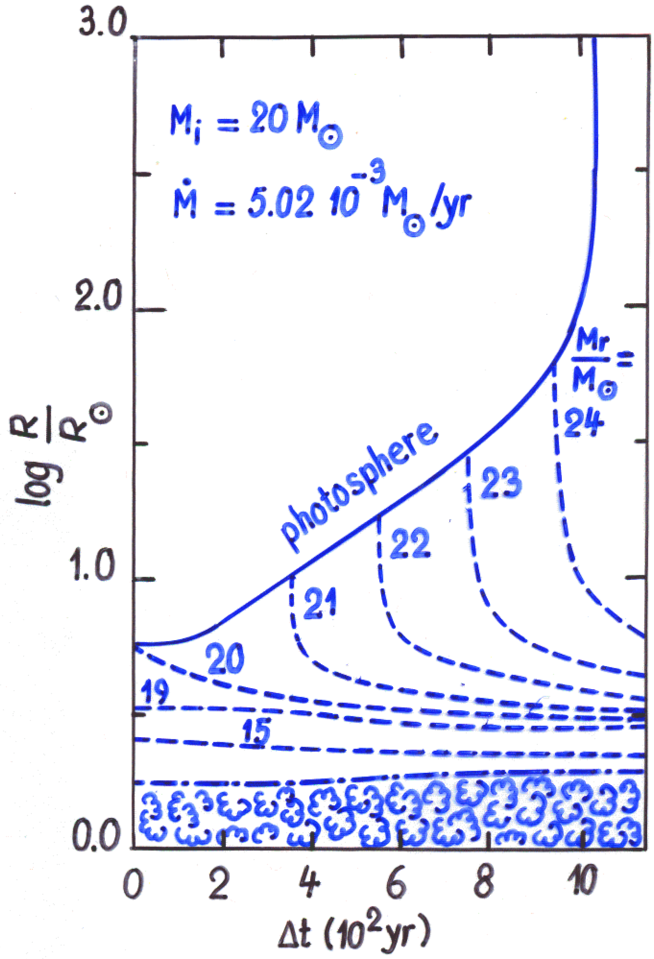


Reaction of MS stars on mass accretion

▶ Upon accretion onto a (MS) star:

- newly added mass compresses (old and new) layers underneath
- compression releases gravitational binding energy

(Neo et al. 1977, PASJ 29, 249; Kippenhahn & Meyer-Hofmeister 1977, A&A 54, 539)



→ for very low accretion rates

$\dot M \lesssim M/\tau_{KH}$

the star remains near thermal equilibrium and follows the MS mass radius relation.

→ for high accretion rates

$\dot M > M/\tau_{KH}$

- $L \uparrow$ $(\sim \dot M)$
- envelope becomes convective, star evolves towards the Hayashi line (HL)
- on the HL: $T_{eff} \approx$ const.

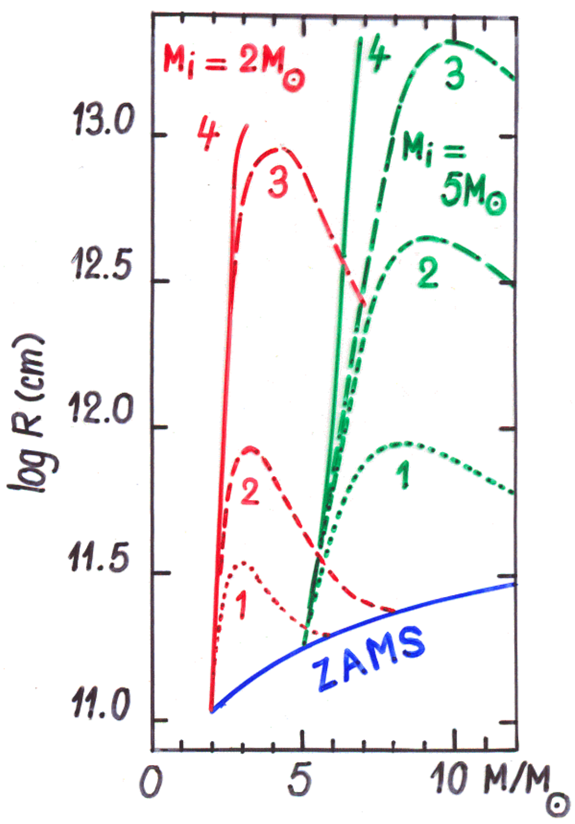
→ $R \sim \dot M^{1/2}$

→ the star grows the faster the higher $\dot M$.

accretion rate

1: $2\,10^{-5}\,M_\odot/yr$
2: $5\,10^{-5}\,M_\odot/yr$
3: $2\,10^{-4}\,M_\odot/yr$
4: $10^{-3}\,M_\odot/yr$

1: $5\,10^{-4}\,M_\odot/yr$
2: $1\,10^{-3}\,M_\odot/yr$
3: $1.5\,10^{-3}\,M_\odot/yr$
4: $5\,10^{-3}\,M_\odot/yr$

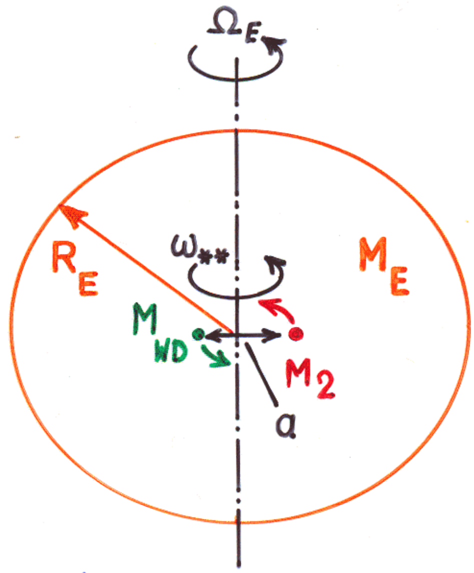


Darwin instability and common envelope evolution

▶ Consider a binary $(M_{WD}, M_2, a, \omega_{**})$ embeded in an envelope $(M_E, R_E$, gyration radius $r_{gE}, \Omega_E)$.

If $\omega_{**} > \Omega_E$ ∃ friction ↝ energy release and transport of angular momentum from the binary to the envelope, i.e. $\dot{J}_{**} = -\dot{J}_E < 0$

↝ $\dot{\omega}_{**} > 0$ and $\dot{\Omega}_E > 0$



▶ Question: $\dot{\omega}_{**} - \dot{\Omega}_E \gtrless 0$?

▶ If $\omega_{**} - \Omega_E > 0$ and $\dot{\omega}_{**} - \dot{\Omega}_E < 0$ ↝ envelope is synchronized, $\Omega_E \to \omega_{**}$

If $\omega_{**} - \Omega_E > 0$ and $\dot{\omega}_{**} - \dot{\Omega}_E > 0$ ↝ Darwin instability (Darwin, G.H. 1879, Proc. Roy. Soc. London 29, 168)

↝ runaway friction, ** spirals in

↝ common envelope evolution

$$J_{**} = G^{2/3} \frac{M_{WD} M_2}{(M_{WD}+M_2)^{1/3}} \omega_{**}^{-1/3} = \theta_{**} \omega_{**}, \quad \theta_{**} = \frac{M_{WD} M_2}{M_{WD}+M_2} a^2 = \text{orb. moment of inertia}$$

$$J_E = r_{gE}^2 R_E^2 M_E \Omega_E = \theta_E \Omega_E$$

$$\frac{\partial}{\partial t}(J_{**} + J_E) = 0 \quad \leftrightarrow \quad \underline{\dot{\omega}_{**} - \dot{\Omega}_E = \dot{\omega}_{**} \left\{1 - \frac{1}{3}\frac{\theta_{**}}{\theta_E}\right\}}$$

↝ stability if $\theta_E < \frac{1}{3}\theta_{**}$

instability, i.e. spiral-in, if $\theta_E > \frac{1}{3}\theta_{**}$

▶ for typical binary parameters $\theta_E > \frac{1}{3}\theta_{**}$ before mass transfer can stabilize

↝ spiral-in, CE evolution is unavoidable in most cases (considered here).

Common envelope evolution

▶ Time scale

Frictional angular momentum and energy transport is self-regulated by radiation pressure caused by the frictional energy release (Meyer & Meyer-Hofmeister 1979).

$$\rightarrow \quad L_{\mathrm{friction}} \lesssim L_{\mathrm{Edd}} = \frac{4\pi G c \mathfrak{M}}{\varkappa_{es}} = \text{Eddington luminosity,}$$

$\varkappa_{es}$ = electron scattering opacity

Evolution of binary (M_{WD}, M_2) from $a = a_i \rightarrow a = a_f \ll a_i$ releases orbital binding energy

$$\Delta E_B \approx \frac{G M_{WD} M_2}{2 a_f}$$

$\rightarrow$ timescale of CE-evolution

$$\tau_{CE} \approx \frac{\Delta E_B}{L_{\mathrm{friction}}} \gtrsim \frac{\Delta E_B}{L_{\mathrm{Edd}}} \approx \frac{\varkappa_{es}}{8\pi c} \frac{M_{WD} M_2}{(M_{WD}+M_2)} \frac{1}{a_f}$$

$$\gtrsim 400\,\mathrm{yr} \left(\frac{M_{WD}}{M_\odot}\right)\left(\frac{M_2}{M_\odot}\right)\left(\frac{M_{WD}+M_2}{M_\odot}\right)^{-1}\left(\frac{a_f}{R_\odot}\right)^{-1}$$

$\rightarrow$ $\boxed{\text{duration of CE-evolution is very short}}$ $\rightarrow$ practically unobservable!

$\rightarrow$ secondary has no time to accrete! $\rightarrow$ Justification for $M_{2,f} = M_{2,i}$

▶ Ejection of the CE: theoretically still not fully understood

▶ Prediction of CE scenario:

Successful ejection of CE $\longrightarrow$ $\boxed{\text{planetary nebula + short-period (detached) binary central star (hot WD + companion)}}$

▶ Short-period, detached binary central stars of planetary nebulae are observed! (Currently 20 objects known).

Strongest support for the concept of CE-evolution!

Formal treatment of common envelope phase (Webbink 1984)

- pre CE $(M_{1,i}, M_{2,i}, a_i) \xrightarrow{CE} (M_{1,f}, M_{2,f}, a_f)$ post CE

- working assumptions:

$M_{1,f} = M_{c,i}$ = pre-CE core mass

$M_{2,f} = M_{2,i}$

$R_{1,i} = a_i \, f_1\left(\frac{M_{1,i}}{M_{2,i}}\right)$, f_1 from Roche geometry

$M_{env,1} = M_{1,i} - M_{c,i}$ = pre-CE envelope mass

gravitational binding energy of the envelope $BE_{env} \overset{def.}{=} -\frac{G M_{1,i} M_{env,1}}{\lambda R_{1,i}}$

↝ definition for λ. λ is in principle computable, but ∃ problem: mass cut!

orbital binding energy $BE_{orb}(M_1, M_2, a) = -\frac{G M_1 M_2}{2a}$

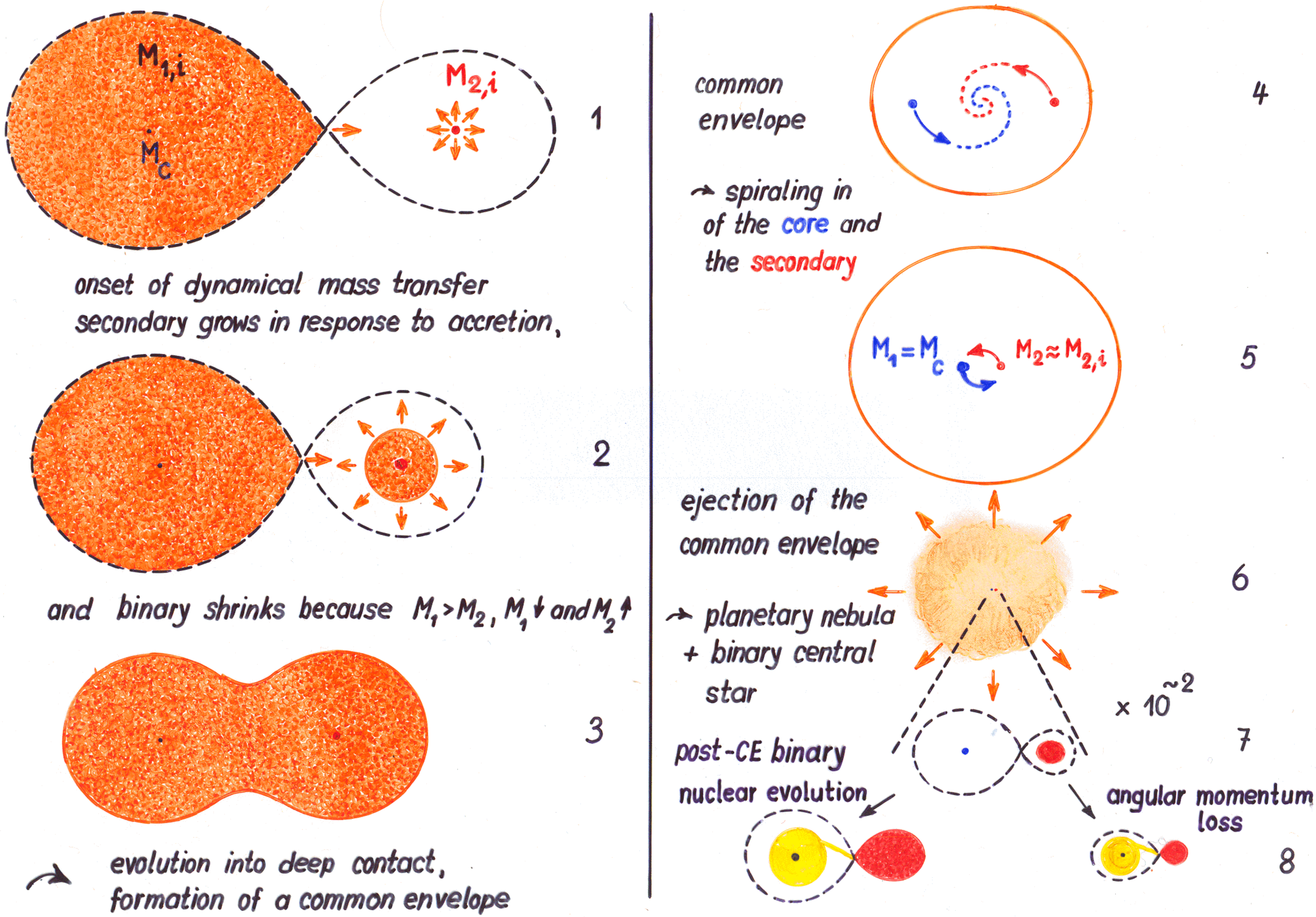
$$\alpha_{CE} \left[BE_{orb}(M_{1,i}, M_{2,i}, a_i) - BE_{orb}(M_{1,f}, M_{2,f}, a_f) \right] = -BE_{env}$$

essentially a free parameter ($\alpha_{CE} \lesssim 1$)

$$\rightarrow \quad \underline{\underline{a_f = a_i \left[\frac{2 M_{1,i} (M_{1,i} - M_{c,i})}{\alpha_{CE} \lambda M_{1,c} M_{2,i} f_1(M_{1,i}/M_{2,i})} - \frac{M_{1,i}}{M_{1,f}} \right]^{-1}}}$$

- so far: $\alpha_{CE} \lambda$ is the real free parameter of the problem!

The formation of semi-detached compact binaries through common envelope evolution

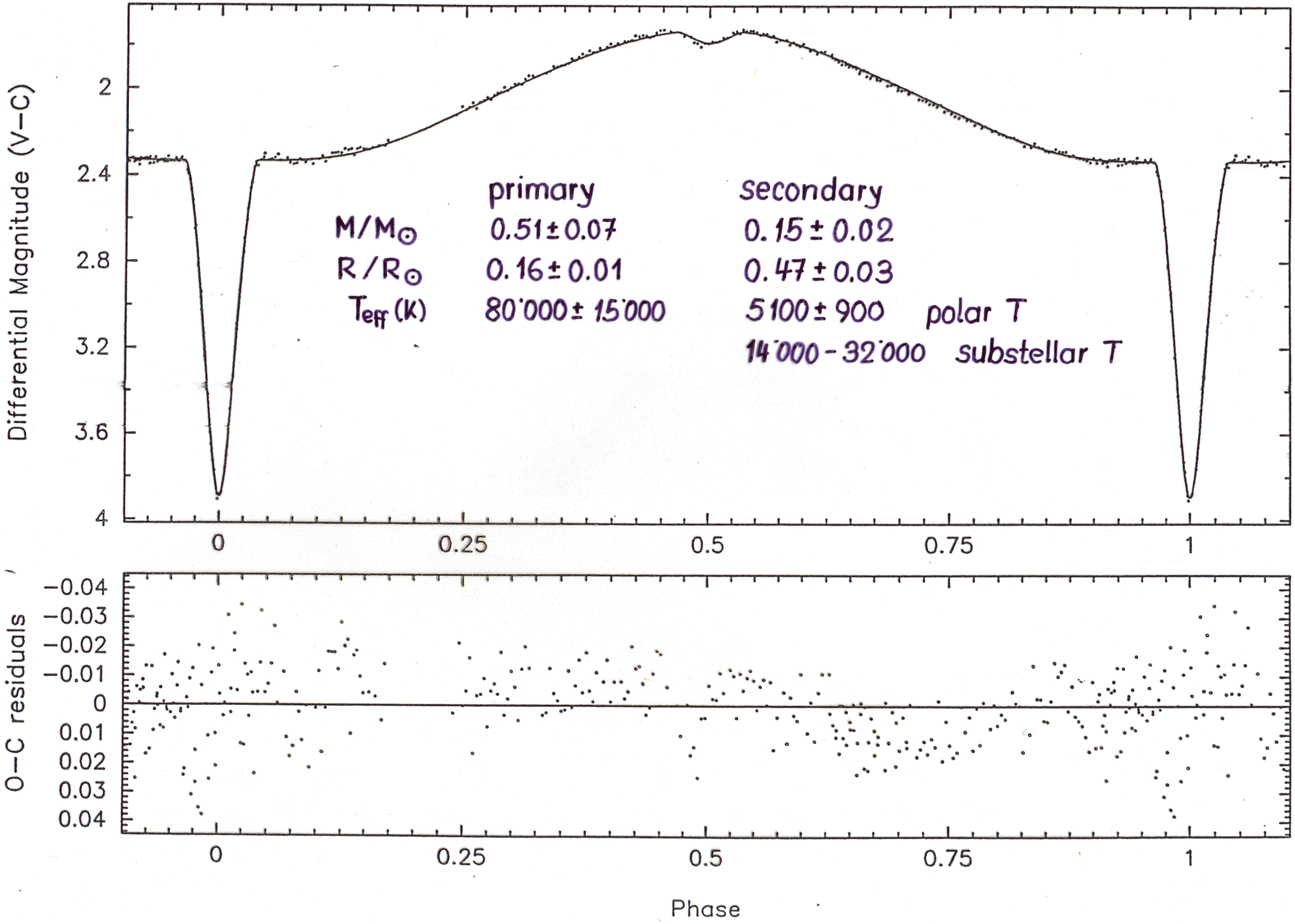


S/C**/1

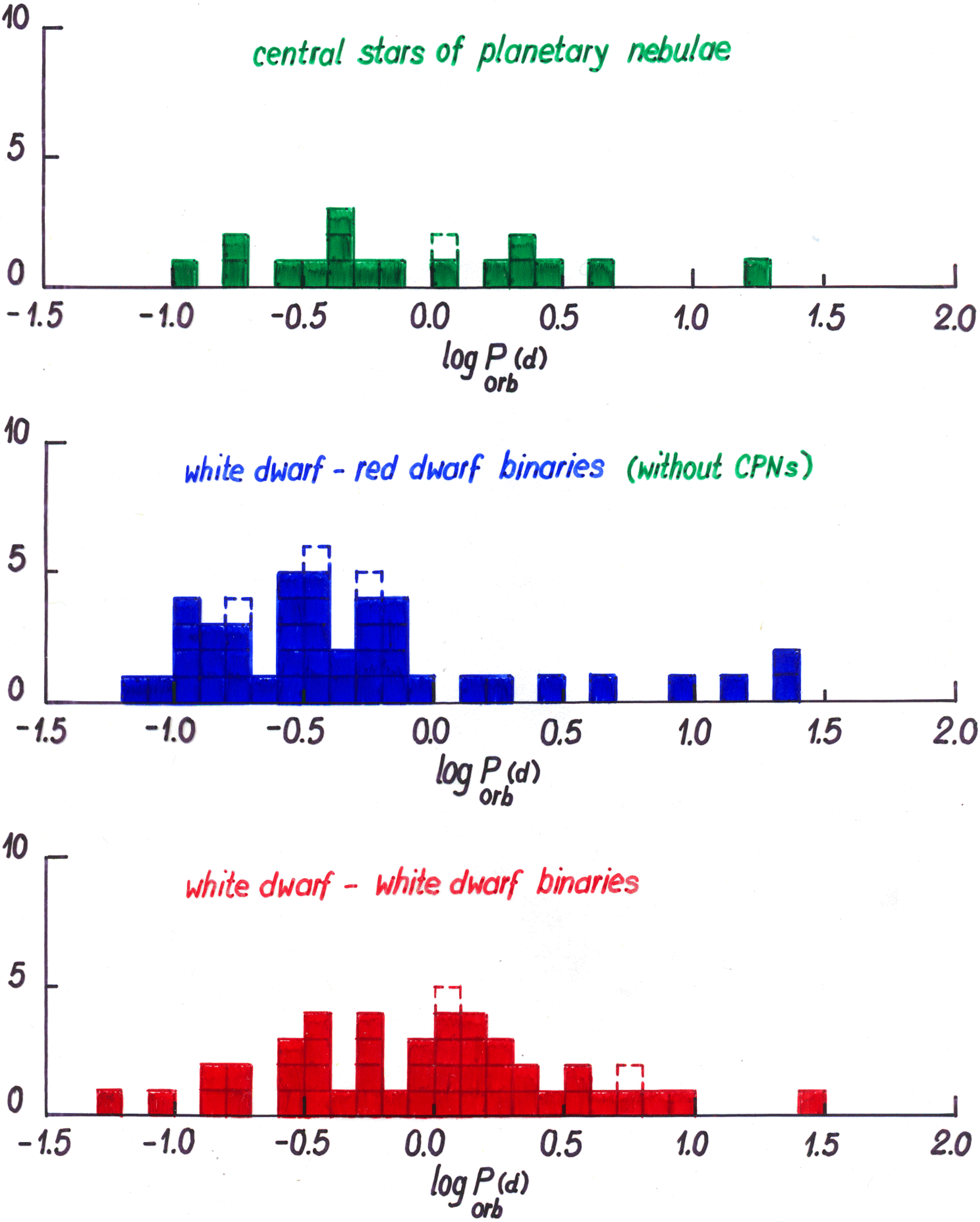
Fig 6

V477 Lyr = central star of the planetary nebula Abell 46

(Pollaco, D.L., Bell, S.A.: 1994, Monthly Notices Roy. Astron. Soc. 267, 452)



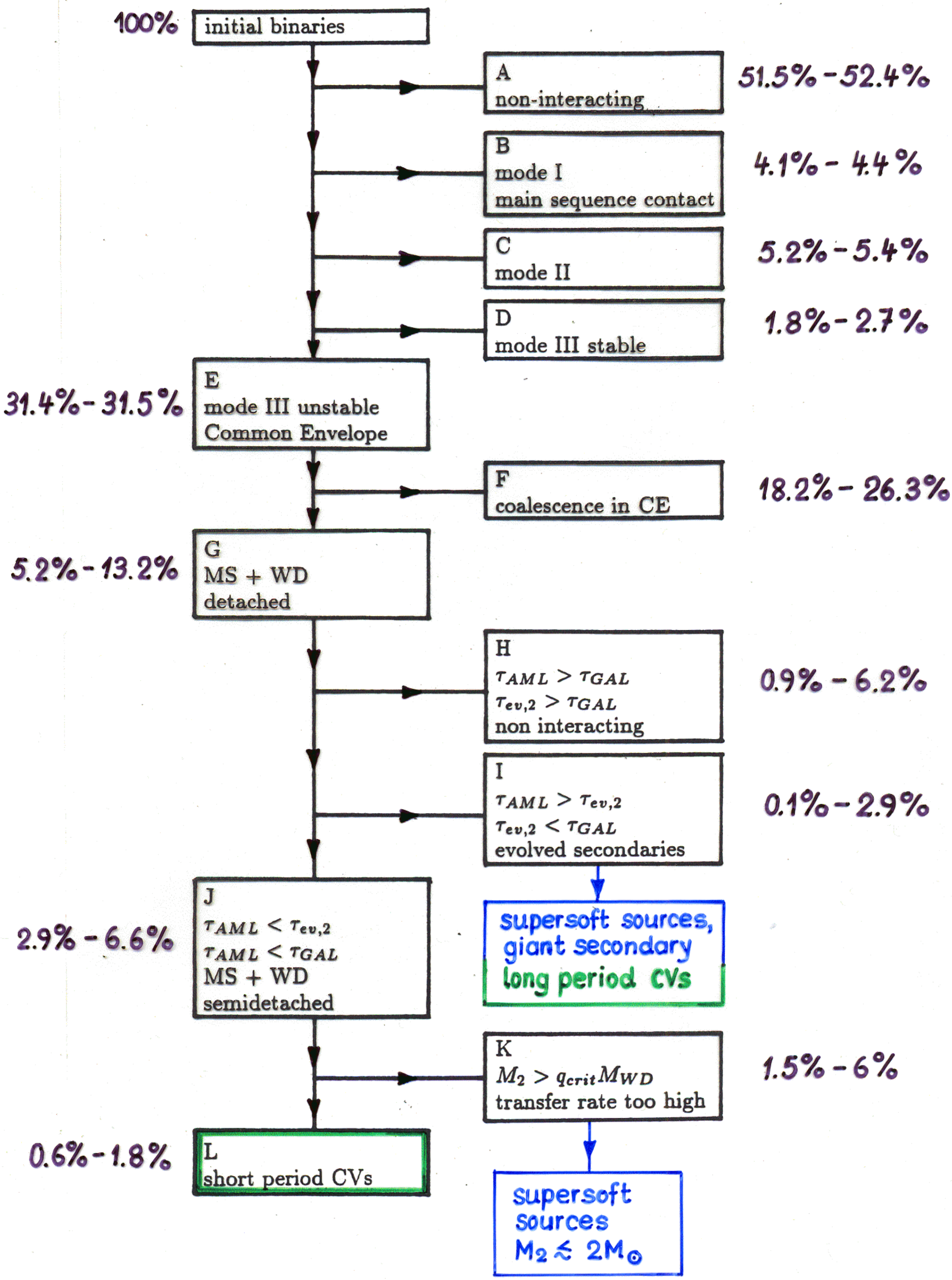
Short-period detached binaries containing a white dwarf



source : Ritter & Kolb (2001, rel. 7.7, Oct. 2006)

Schematic representation of evolutionary routes of binary evolution

(after de Kool, M.: 1992, Astron. Astrophys. 261, 188)



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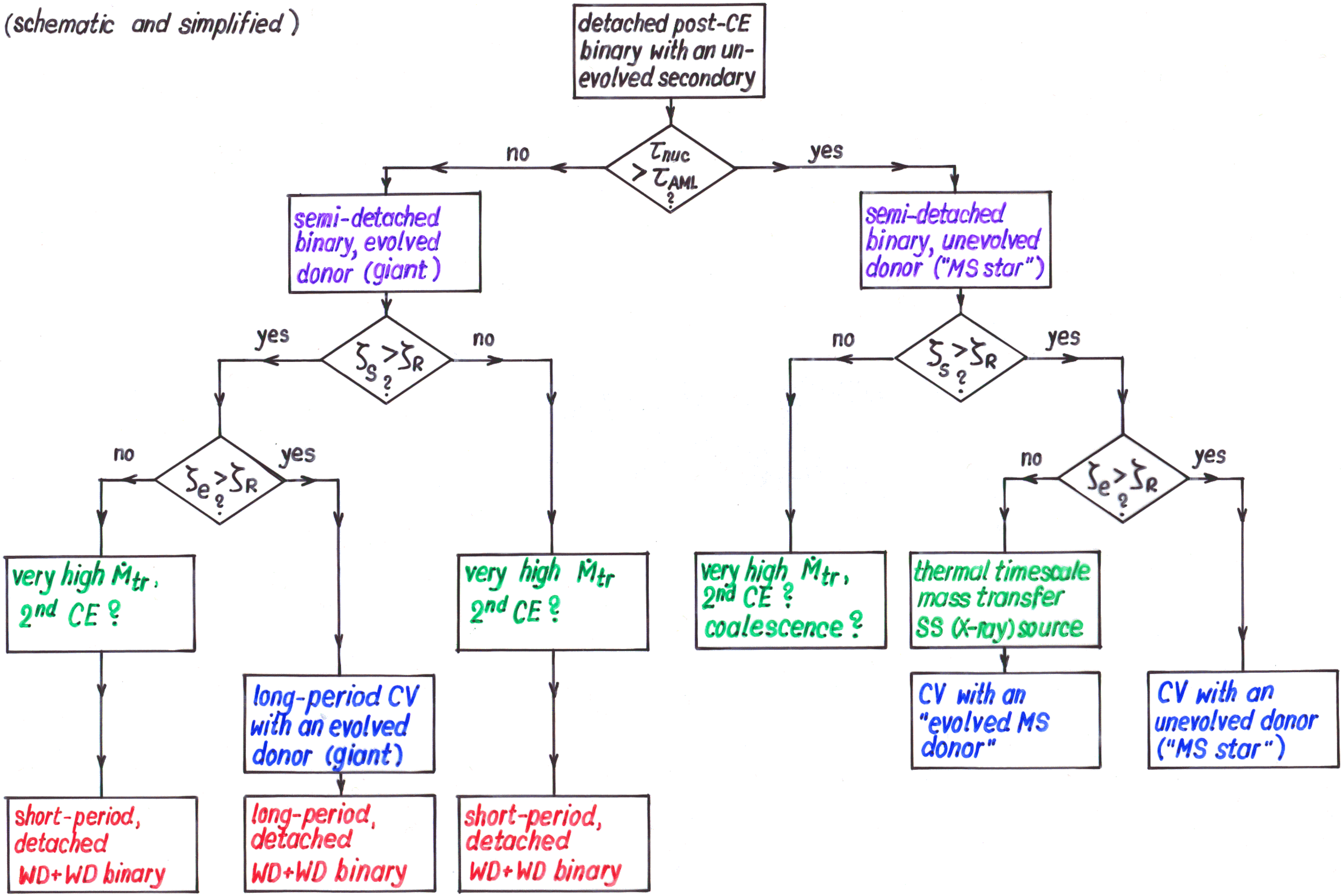
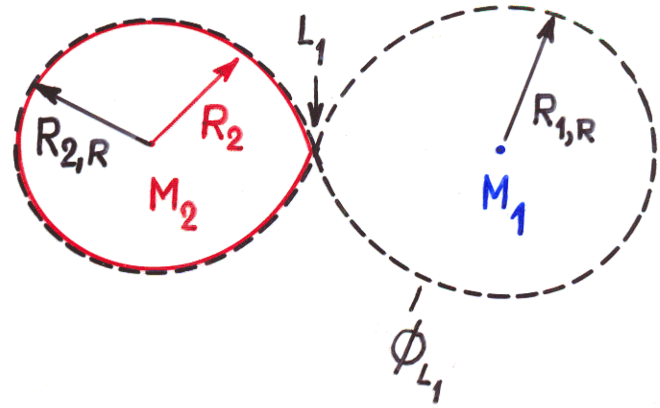
Evolution of post-CE binaries

(schematic and simplified)



Mass transfer in a semi-detached binary



- semi-detached: here $R_2 = R_{2,R}$
  $R_1 < R_{1,R}$

- mass transfer: star 2 → star 1
  ↝ changes $M_1, M_2, R_{1,R}, R_{2,R}, R_2, a, P, \dots$

- evolution of the donor's radius $R_2 = R_2(M_2, t)$:

$$\frac{d\ln R_2}{dt} = \underbrace{\left(\frac{\partial \ln R_2}{\partial \ln M_2}\right)_s}_{=:\ \zeta_s\ =\ \text{adiabatic mass radius exponent}} \frac{d\ln M_2}{dt} + \left(\frac{\partial \ln R_2}{\partial t}\right)_{nuc} + \left(\frac{\partial \ln R_2}{\partial t}\right)_{th} \qquad (1a)$$

$$\frac{d\ln R_2}{dt} = \underbrace{\left(\frac{\partial \ln R_2}{\partial \ln M_2}\right)_e}_{=:\ \zeta_e\ =\ \text{thermal equilibrium mass radius exponent}} \frac{d\ln M_2}{dt} + \left(\frac{\partial \ln R_2}{\partial t}\right)_{nuc} \qquad (1b)$$

if the star remains near thermal equilibrium despite mass loss

- evolution of the donor's Roche radius $R_{2,R} = R_{2,R}(M_1, M_2, J)$:

$$\frac{d\ln R_{2,R}}{dt} = \underbrace{\left(\frac{\partial \ln R_{2,R}}{\partial \ln M_2}\right)_*}_{=:\ \zeta_{R,2}\ =\ \text{mass radius exponent of the Roche potential surface } \phi_{L_1}} \frac{d\ln M_2}{dt} + \left(\frac{\partial \ln R_{2,R}}{\partial t}\right)_{\dot M=0} = \zeta_{R,2}\frac{d\ln M_2}{dt} + 2\left(\frac{\partial \ln J}{\partial t}\right)_{\dot M=0} \qquad (2)$$

- stationary mass transfer if $\dot R_2 = \dot R_{2,R}$ (with $R_2 = R_{2,R}$)

(1a) + (2) ↝
$$-\dot M_2 = \frac{M_2}{\zeta_s - \zeta_{R,2}}\left\{\left(\frac{\partial \ln R_2}{\partial t}\right)_{nuc} + \left(\frac{\partial \ln R_2}{\partial t}\right)_{th} - 2\left(\frac{\partial \ln J}{\partial t}\right)_{\dot M=0}\right\} \qquad (3a)$$

(1b) + (2) ↝
$$-\dot M_2 = \frac{M_2}{\zeta_e - \zeta_{R,2}}\left\{\left(\frac{\partial \ln R_2}{\partial t}\right)_{nuc} - 2\left(\frac{\partial \ln J}{\partial t}\right)_{\dot M=0}\right\} \qquad (3b)$$

- stability criteria: adiabatic stability if $\zeta_s - \zeta_{R,2} > 0$ (4a)
  thermal stability if $\zeta_e - \zeta_{R,2} > 0$ (4b)

- ζ_s, ζ_e depend on the mass and internal structure of the donor.

Computing the long-term evolution of a semi-detached binary

▶ over most of the time mass transfer is ~ stationary, i.e. $\dot{R}_2 = \dot{R}_{2,R}$ and $R_2 = R_{2,R}$.

→

consequence of { mass loss, nuclear evolution, irradiation }

$$-\dot{M}_2 = \frac{M_2}{\zeta_S - \zeta_R}\left[\left(\frac{\partial \ln R_2}{\partial t}\right)_{nuc} + \left(\frac{\partial \ln R_2}{\partial t}\right)_{th} - 2\,\frac{\partial \ln J}{\partial t}\right]$$

systemic angular momentum loss

stellar structure
↔ evolutionary history of the donor
↔ complete history of the binary

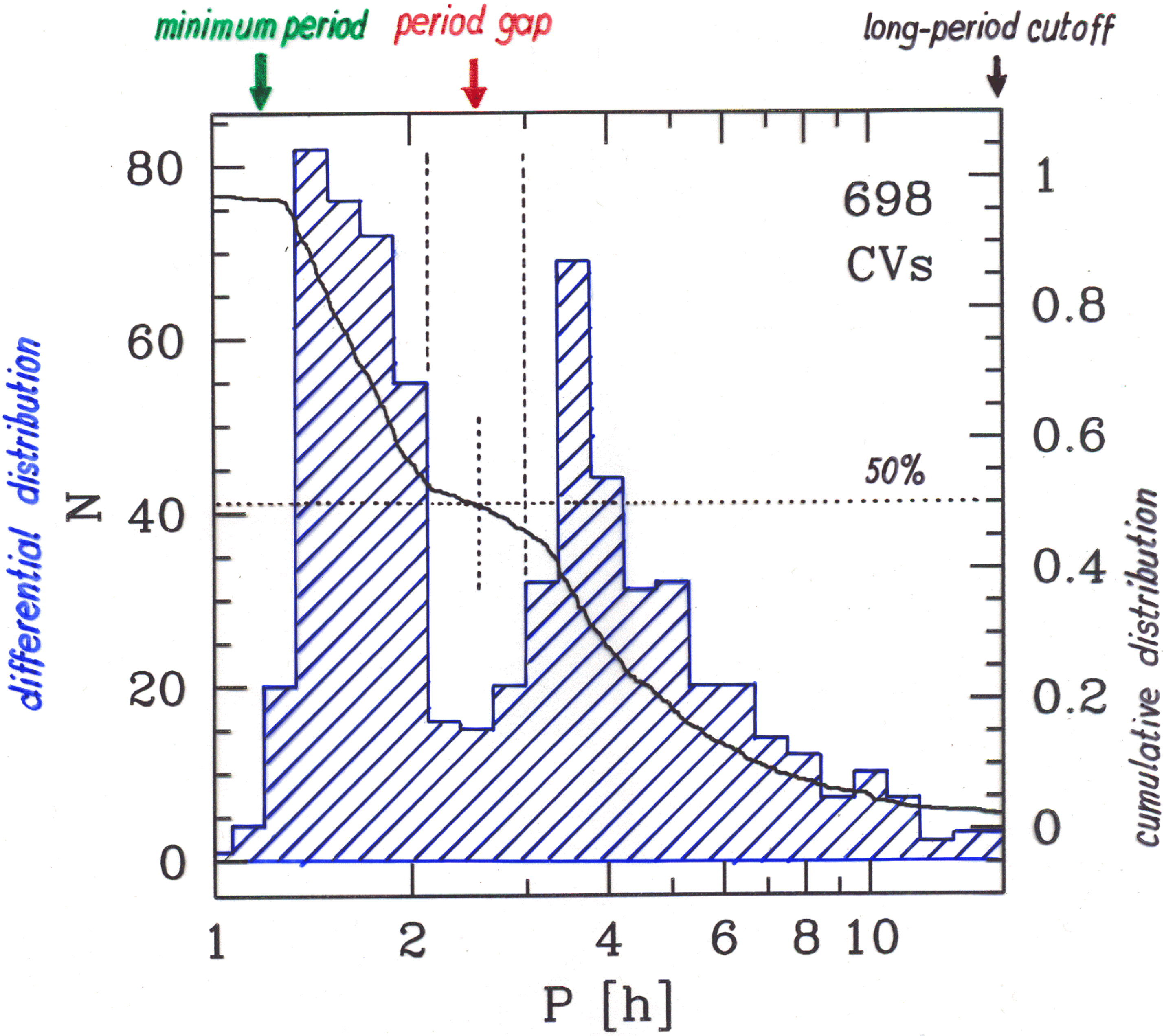
redistribution of mass and angular momentum in the system and consequential angular momentum loss (CAML)

→ Information required for computing the long-term evolution:

- complete internal structure of the donor star ↔ complete history of the binary system
- systemic angular momentum loss rate (gravitational radiation, "magnetic braking")
- model for the redistribution of mass and angular momentum in and loss of mass and angular momentum from the system (consequential angular momentum loss (CAML), i.e. ν and η)
- additional effects (irradiation of the donor, irradiation of the accretion disc, ...)

Distribution of observed orbital periods of cataclysmic binaries

Source: Ritter, H., Kolb, U. 2008, http://www.mpa-garching.mpg.de/RKcat/

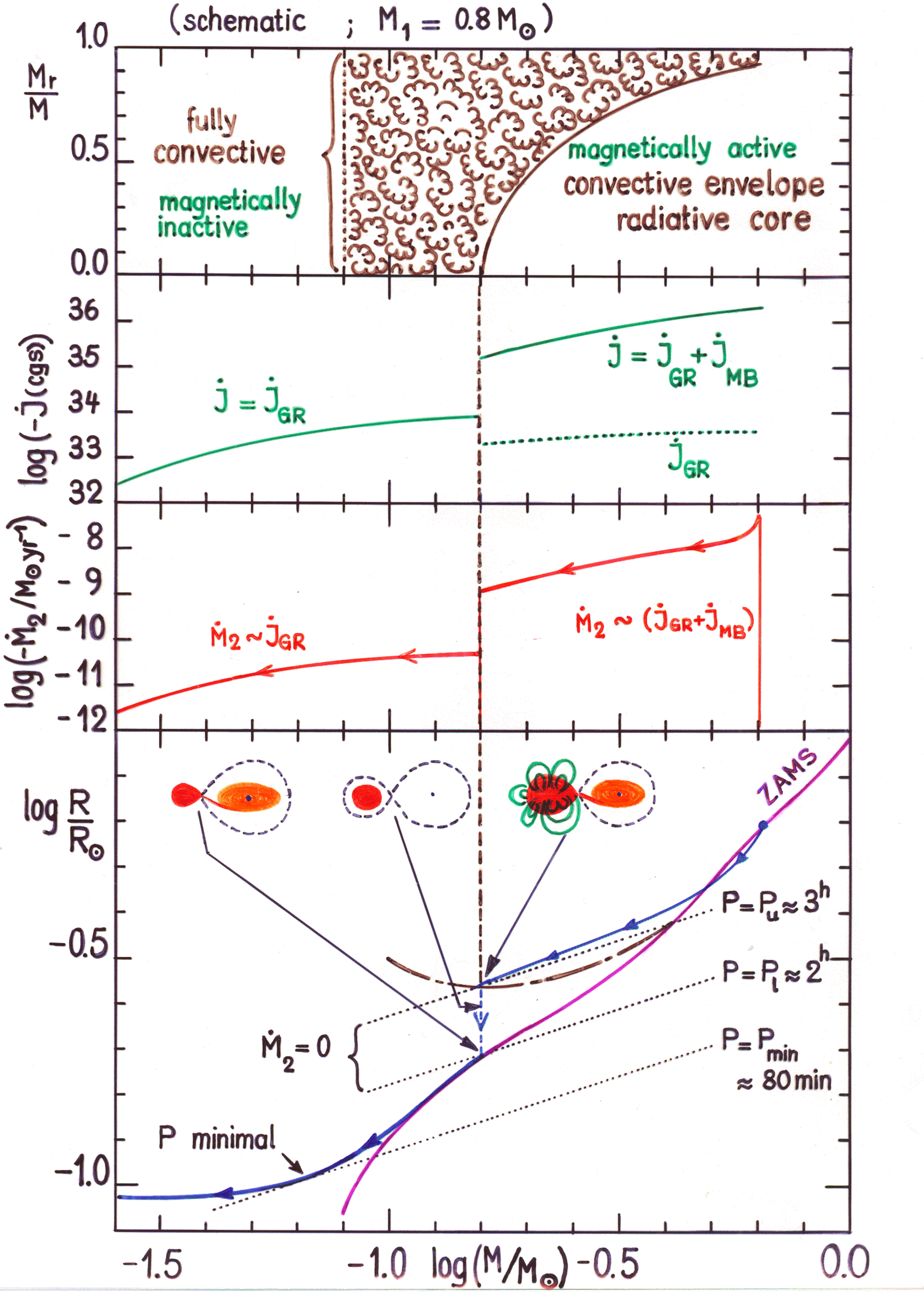


$P_{min} \approx 78$ min

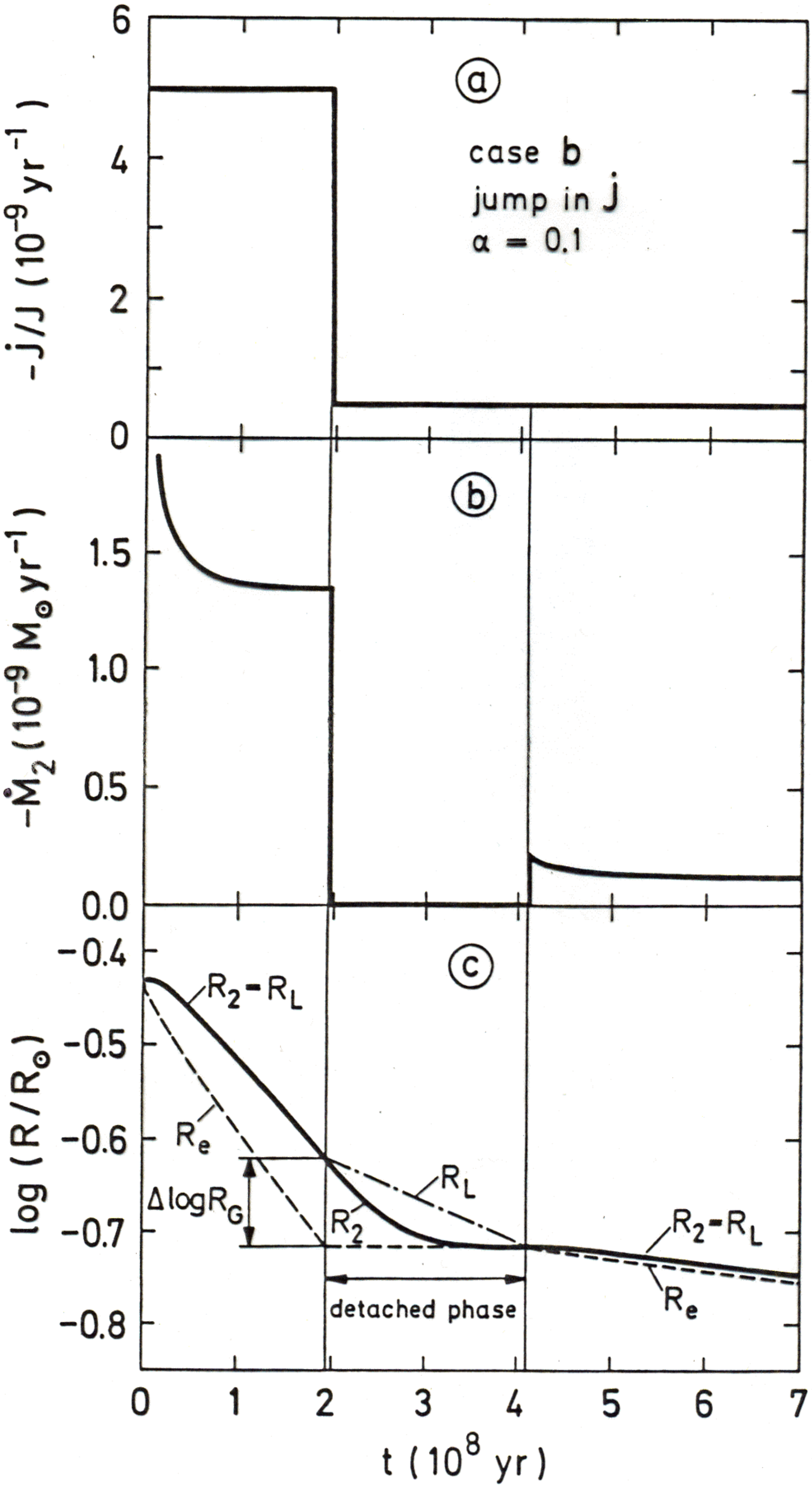
$2^h \lesssim P_{gap} \lesssim 3^h$

$P_{cutoff} \approx 16^h$

SECULAR EVOLUTION OF A CATACLYSMIC BINARY



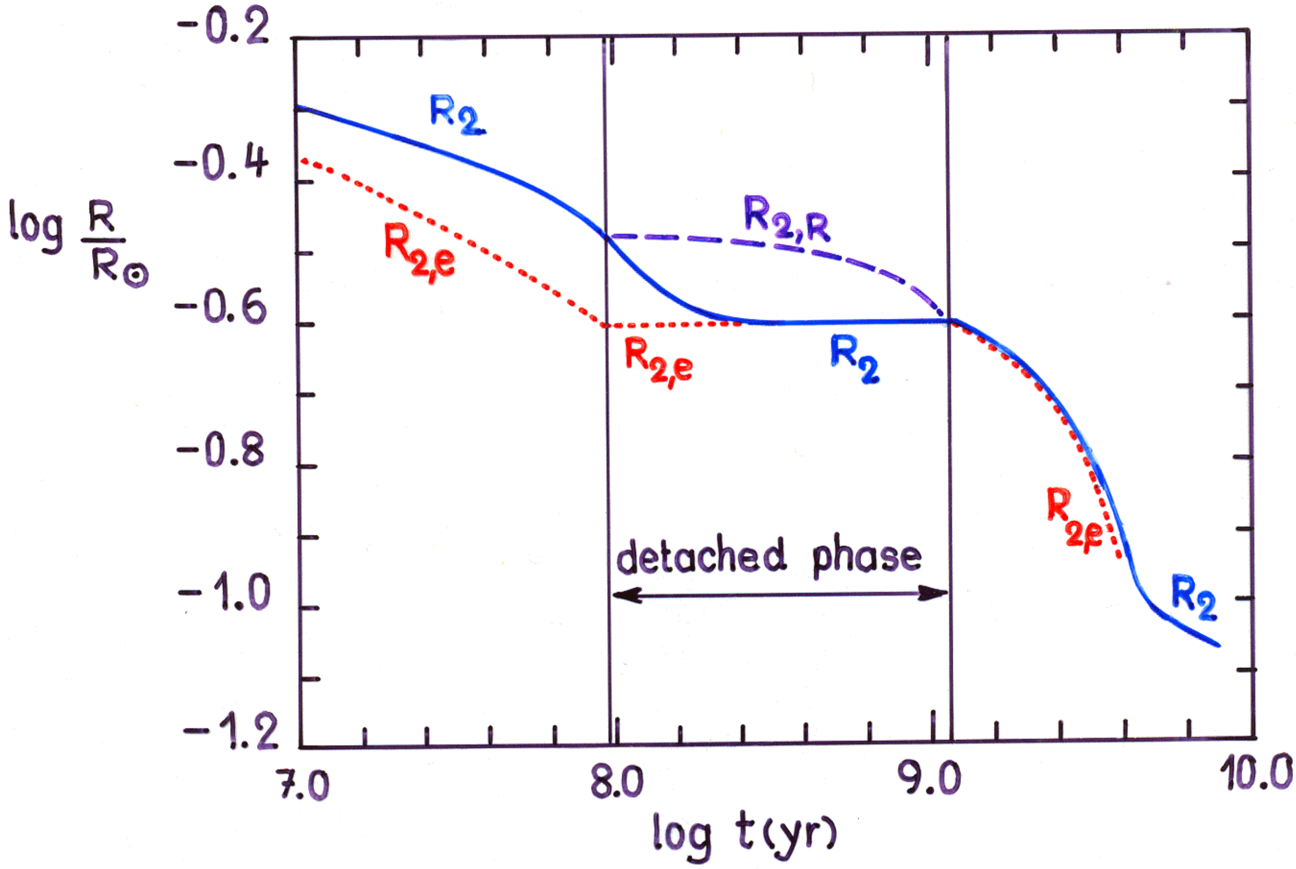
S/CVs/23



Spruit and Ritter (1983)

Secular evolution of cataclysmic binaries (Kolb 1992)

(Sequence S6)



parameters: $M_{2,i} = 0.6\,M_\odot$

$M_{1,i} = 0.7\,M_\odot$

$\dot{J}_{MB} = \dot{J}_{VZ}$, $f_{VZ} = 1$, $r_{g2} = r_{g2,tot}$

$\eta = 0$

$\nu = q^{-1}$

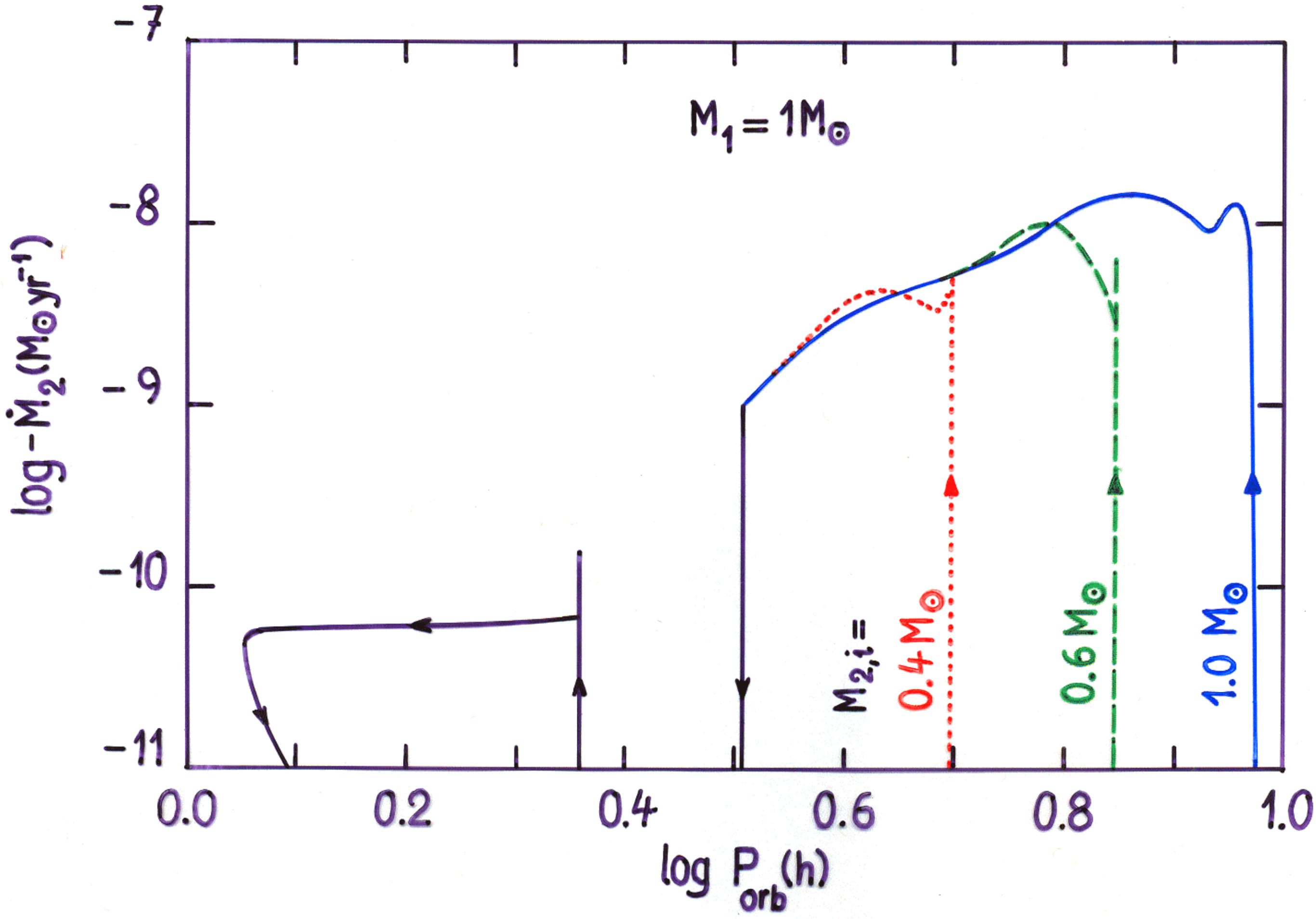
resulting properties: $M_{conv} = 0.2440\ M_\odot$

$P_u = 3.4528$ hr

$P_\ell = 2.2468$ hr

$P_{min} = 1.0840$ hr

Secular evolution of cataclysmic binaries (Kolb & Ritter 1992; Kolb 1993)



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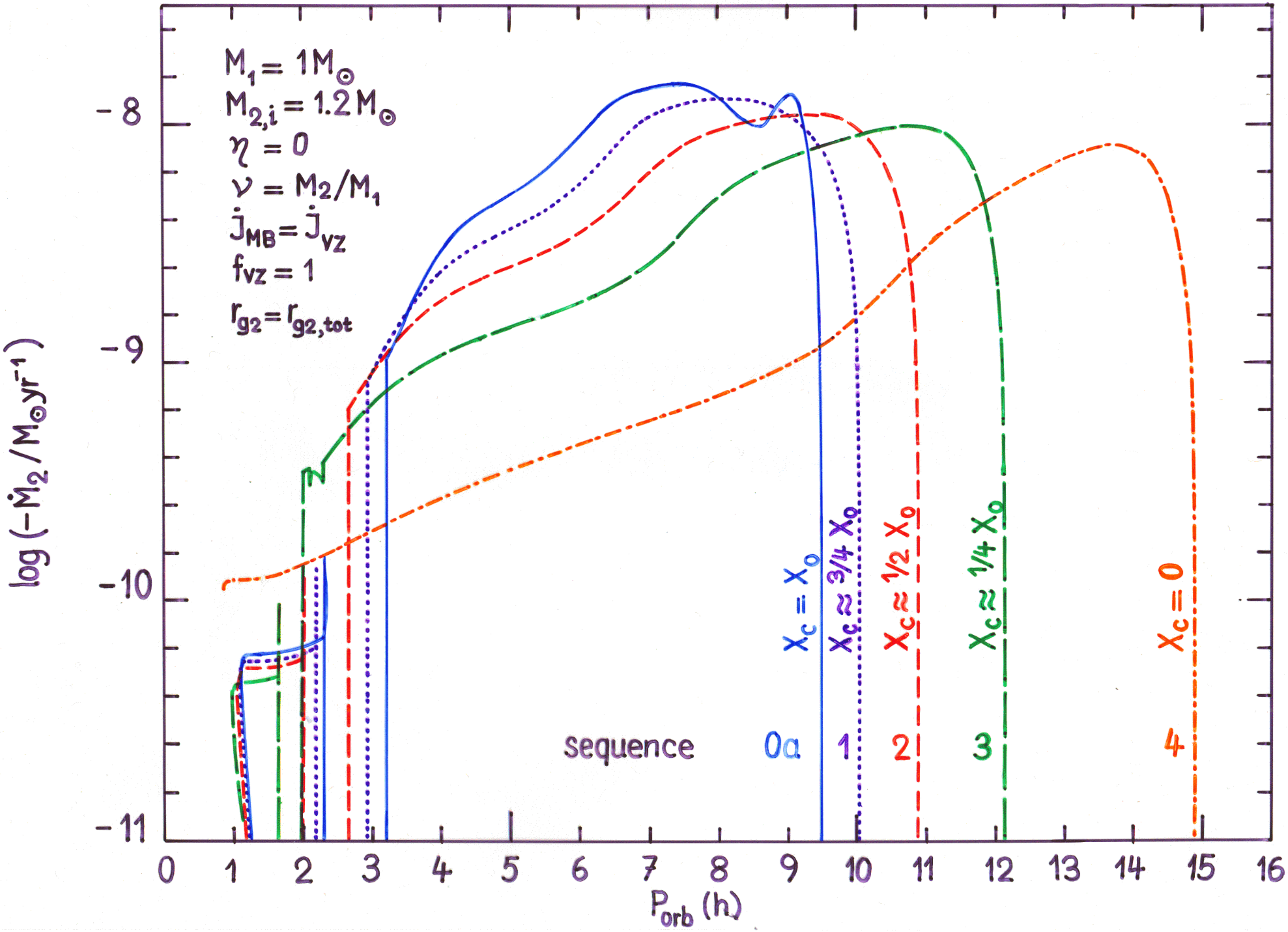
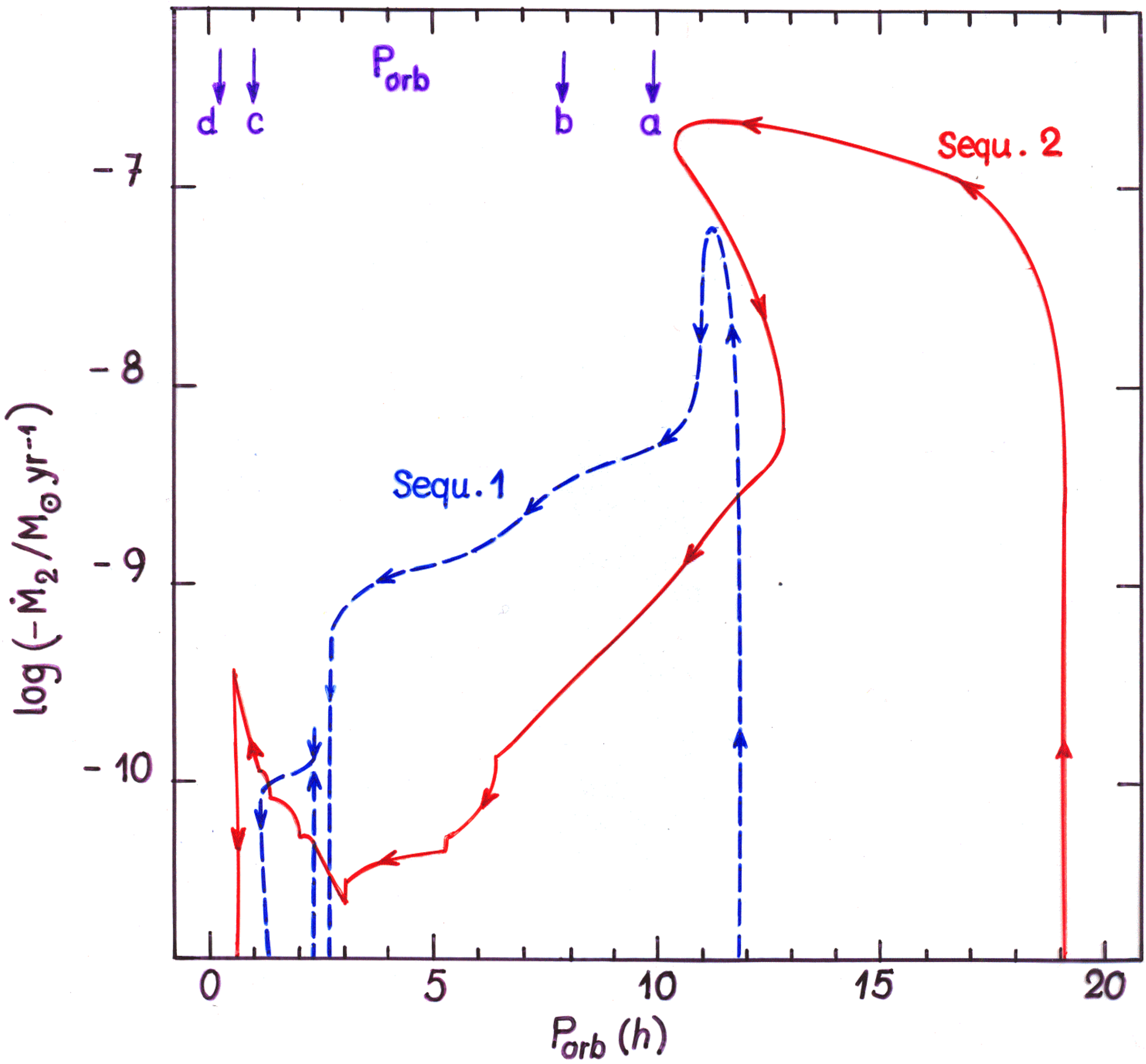
Secular evolution of cataclysmic binaries with an evolved secondary

(Ritter, H.: 1994, Mem. A. S. It. 65, 173; *computations by R. Singer*)



Thermal timescale mass transfer in CVs and LMXBs

Schenker, K., King, A.R.: 2002, ASP Conf. Ser. Vol. 261, p. 242



Initial parameters:

Sequ.	$M_{1,i}/M_\odot$	$M_{2,i}/M_\odot$	q_i	$X_{c,i}$	$P_{orb,i}$ (h)	case
1	1.4	1.6	1.143	0.56	~12	weak TTMT*
2	0.7	1.6	2.286	~0.05	~19	strong TTMT*

a ≙ AE Aqr ; b ≙ V1309 Ori ; c = V485 Cen ; d ≙ AM CVn

* TTMT = thermal timescale mass transfer