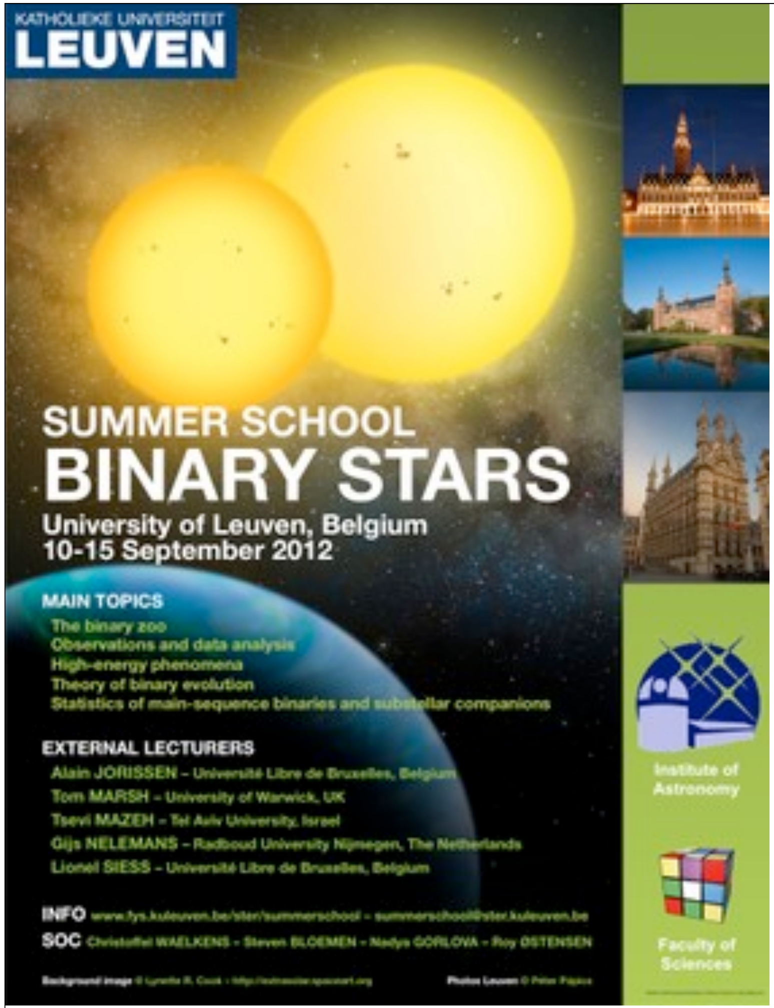

KATHOLIEKE UNIVERSITEIT
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SUMMER SCHOOL
BINARY STARS
University of Leuven, Belgium
10-15 September 2012

MAIN TOPICS
- The binary zoo
- Observations and data analysis
- High-energy phenomena
- Theory of binary evolution
- Statistics of main-sequence binaries and substellar companions

EXTERNAL LECTURERS
- Alain JORISSEN – Université Libre de Bruxelles, Belgium
- Tom MARSH – University of Warwick, UK
- Tsevi MAZEH – Tel Aviv University, Israel
- Gijs NELEMANS – Radboud University Nijmegen, The Netherlands
- Lionel SIESS – Université Libre de Bruxelles, Belgium

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SOC Christoffel WAELKENS – Steven BLOEMEN – Nadya GORLOVA – Roy ØSTENSEN

The binary zoo

Alain Jorissen

Institut d'Astronomie et d'Astrophysique

UNIVERSITÉ LIBRE DE BRUXELLES,
UNIVERSITÉ D'EUROPE
ULB

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INFO
SOC

Institute of Astronomy

Faculty of Sciences

The binary zoo

Inventaire

Une pierre
deux maisons
trois ruines
quatre: fossoyeurs
un jardin
des fleurs

un raton laveur

une douzaine d'huîtres un citron un pain
un rayon de soleil
une lame de fond
six musiciens
une porte avec son paillasson
un monsieur décoré de la légion d'honneur

un autre raton laveur

J. Prévert

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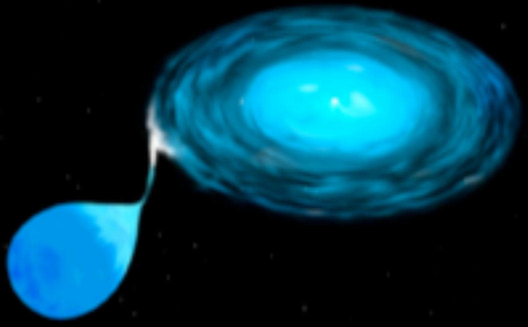
The binary zoo

Inventaire

RS CVn
W UMa
Ba
DQ Her
S (no Tc)
metal-deficient post-AGB
CH

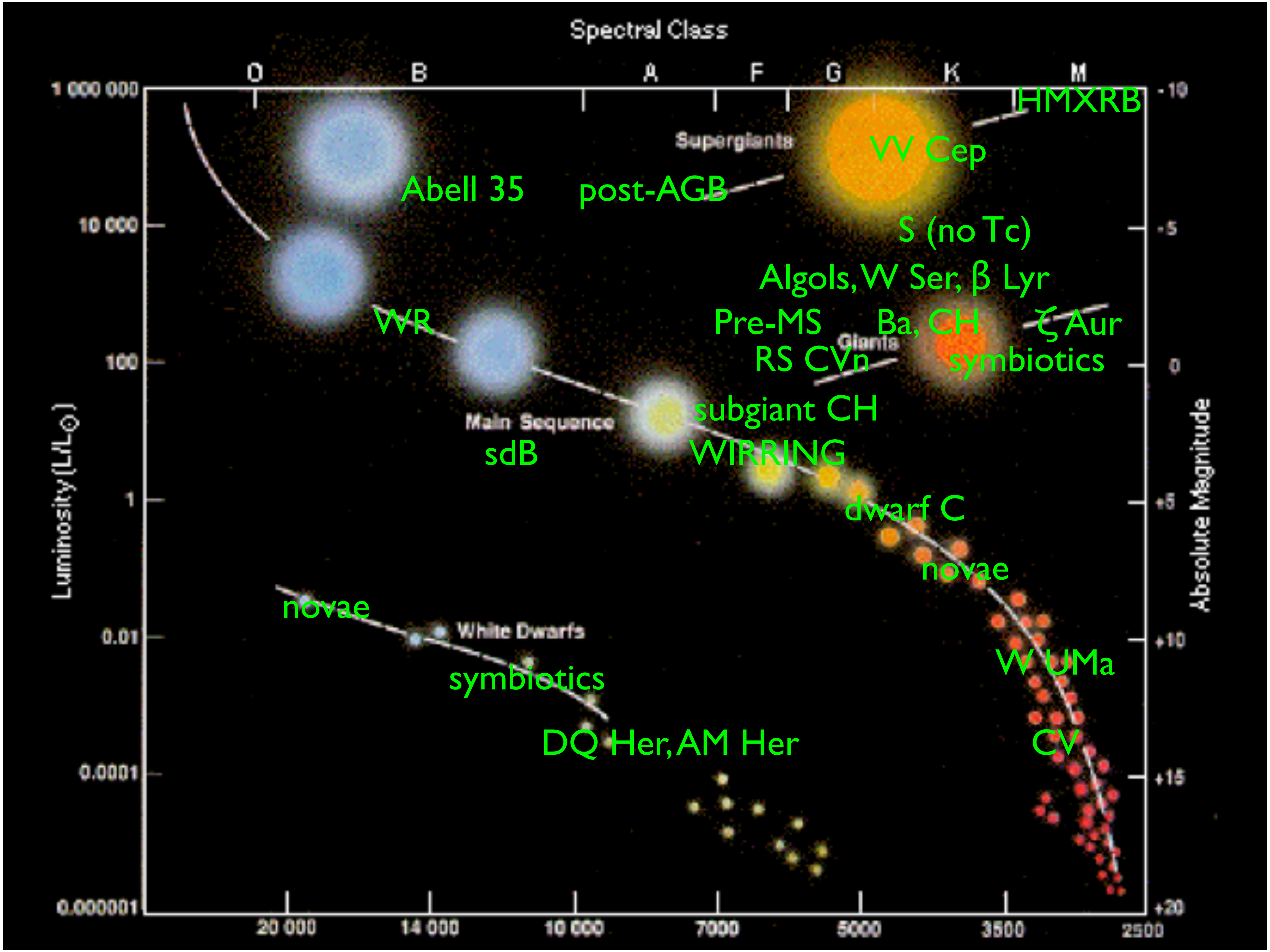
one Algol



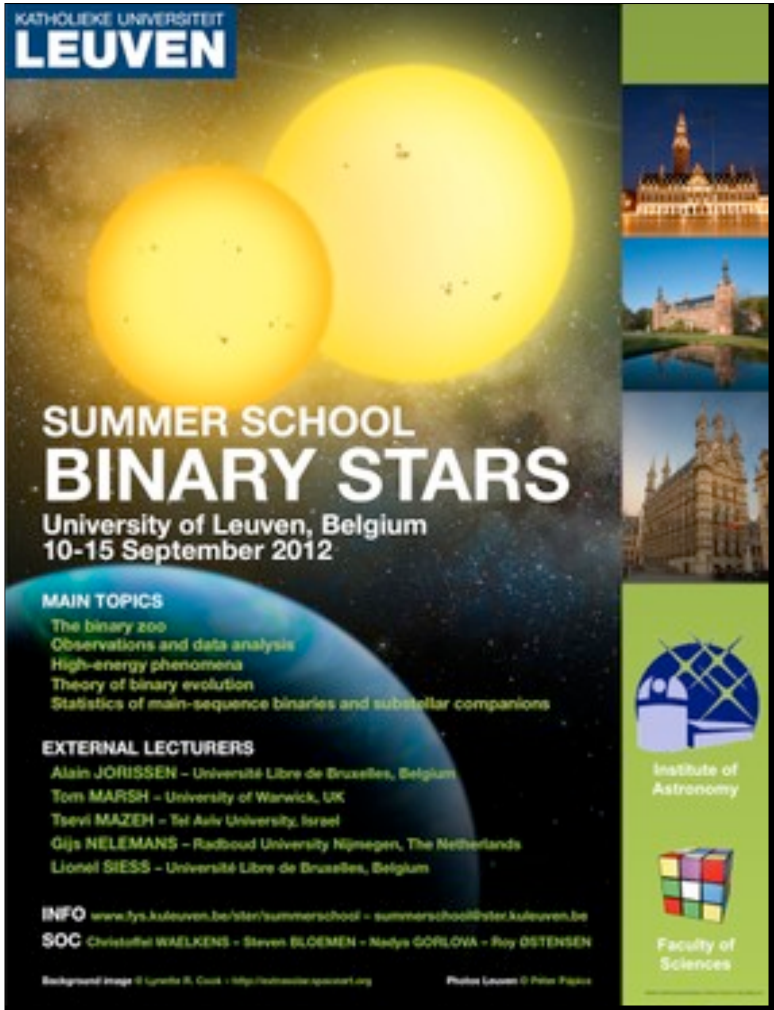
CEMPs
LMXRB
novae
SNIa
symbiotics

A. Jorissen

and another Algol


Spectral Class
O
B
A
F
G
K
M
1 000 000
10 000
100
1
0.01
0.0001
0.000001
-10
-5
0
+5
+10
+15
+20
Luminosity (L/L$_\odot$)
Absolute Magnitude
20 000
14 000
10 000
7000
5000
3500
2500
HMXRB
Supergiants
VV Cep
Abell 35
post-AGB
S (no Tc)
Algols, W Ser, β Lyr
WR
Pre-MS
Ba, CH
ζ Aur
Giants
RS CVn
symbiotics
Main Sequence
subgiant CH
sdB
WIRRING
dwarf C
novae
novae
White Dwarfs
symbiotics
W UMa
DQ Her, AM Her
CV

The binary zoo



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Conducting line :

Classification of binary stars

i) Mass transfer
ii) Evolutionary stage
iii) Observational properties

The binary zoo

Classification of binary stars:

There are three possible ways to classify binary stars, based on:

i) Mass transfer	[→ Lionel Siess, Gijs Nelemans]
ii) Evolutionary stage	[→ Lionel Siess]
iii)Observational properties	[→ Tom Marsh, Tsevi Mazeh]

The binary zoo

Classification of binary stars:

There are three possible ways to classify binary stars, based on:

i) Mass transfer [→ Lionel Siess, Gijs Nelemans]
ii) Evolutionary stage [→ Lionel Siess]
iii)Observational properties [→ Tom Marsh, Tsevi Mazeh]

Knowing the location of the binary in all 3 schemes often is the goal of binary-star research !

= The ‘guiding line’ for my 5 lectures ...

The binary zoo

Classification of binary stars

Contents

i) **Mass transfer classes: detached, semi-detached, contact**
(W UMa)

Technical intermezzi about Roche lobes, mass-radius exponents, mass-transfer rates (Bondi-Hoyle), time scales (adiabatic, thermal, nuclear), stability of mass transfer **[→ Lionel Siess]**

ii) **Evolutionary-stage classes**

Two examples: - post-AGB stars
- Barium stars *Technical intermezzo : Heavy-element synthesis*

Eggleton's classification: evolutionary class and mass transfer modes A, B, C
Important diagnostics of mass transfer modes: (a) eccentricity - period diagrams
(b) mass-function distributions
→ constraints on companion masses
→ The Algol paradox
(Algols, β Lyr, SV Cen/ W Ser)

The binary zoo

Classification of binary stars

Contents

iii) Observational-property classes [→ Tsevi Mazeh, Tom Marsh]

Technical intermezzo : Orbital elements

visual/interferometric, astrometric, spectroscopic (SB1, SB2)

Technical intermezzo : Masses

difficulties with spectroscopy : - the case of binaries involving long-period variables
- MACHO : the puzzle of sequence D (all ellipsoidal?)

photometric: (a) geometry (eclipses: Algols - β Lyr, ζ Aur - VV Cep, ellipsoidal : W UMa)
(b) dust (sequence D?, ε Aur)
(c) spots (RS CVn)
confusion between RS CVn and pre-main sequence binaries (e - P again)
(d) eruptive: [→ Tom Marsh]
(d.1) novae : MS + WD (slow mass accretion)
(d.2) dwarf novae and cataclysmic variables [→ T. Marsh, G. Nelemans]
MS + WD (fast mass accretion, accretion disk, magnetic field or not)
DQ Her, AM Her
(d.3) symbiotics: giant + WD
(d.4) SNIa : WD + WD (?)

(e) X -rays : HMXRB (neutron stars, black holes), LMXRB = CV [→ G. Nelemans]

The binary zoo

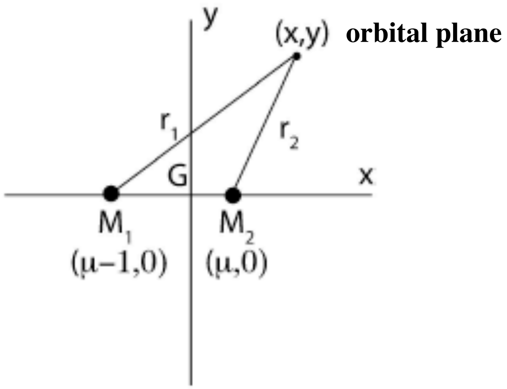
Classification of binary stars

i) **Mass transfer**

A technical parenthesis first about Roche lobes

Roche lobe (I)

The Roche model (E. Roche 1820–1883) of a binary system:



- two point masses
- circular orbits
- synchronous rotation with the orbital motion (so-called ’corotation’).

→ binary system at rest in a frame corotating with the orbital motion.

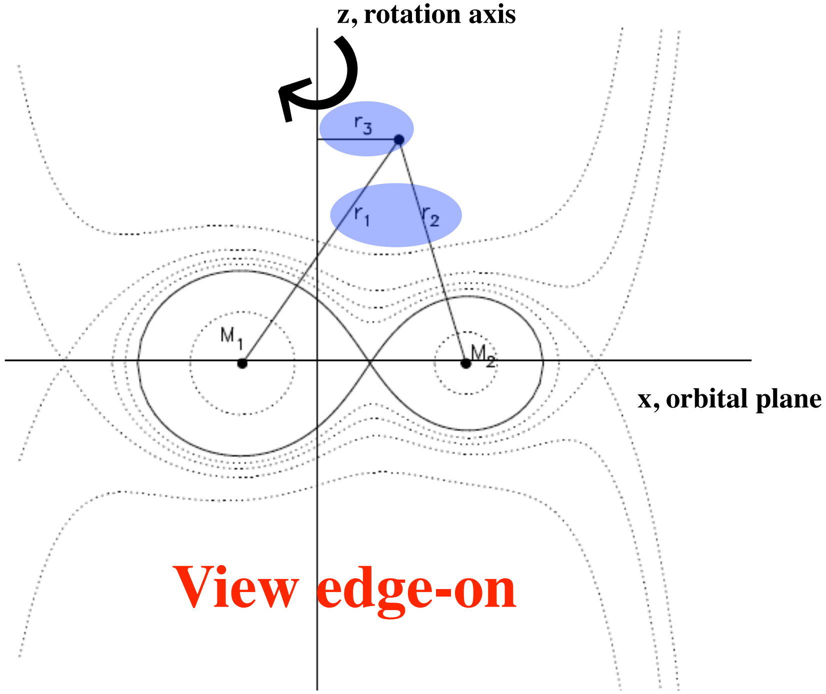
In this frame, define effective equipotential surfaces for the gravitational potential corrected for centrifugal effects :

$$\Phi = -\frac{\mu}{r_1} - \frac{1-\mu}{r_2} - \frac{r_3^2}{2} = \text{constant}$$

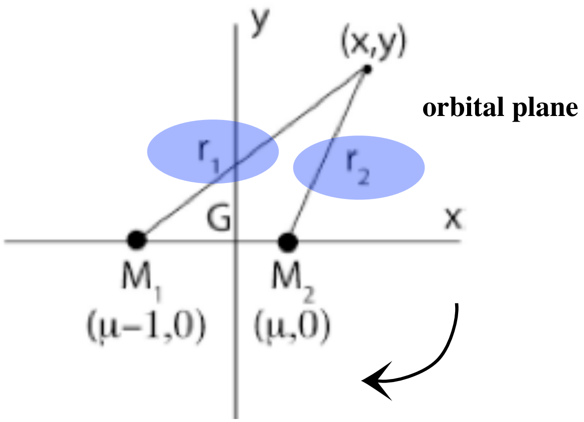
$$\text{with} \quad \mu = \frac{M_1}{M_1 + M_2}$$

in units where the orbital period and separation are taken as unit time and distance, and total mass as unit mass.

Roche lobe (II)

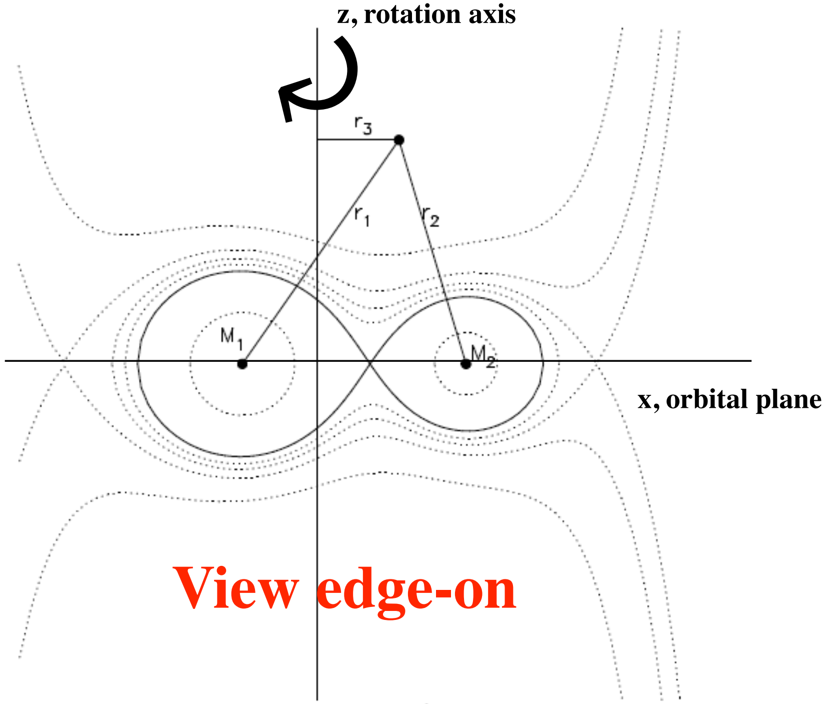


View edge-on

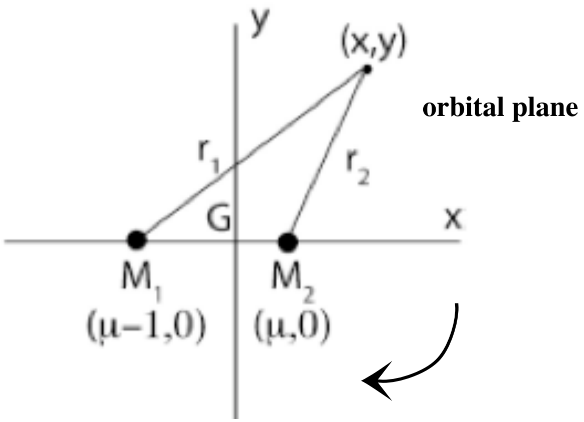


View face-on

Roche lobe (III)



View edge-on



View face-on

$$\Phi = -\frac{\mu}{r_1} - \frac{1-\mu}{r_2} - \frac{r_3^2}{2} = \text{constant}$$

with $\mu = \dfrac{M_1}{M_1 + M_2}$

$$r_1 = \left[\left(x - (\mu - 1) \right)^2 + y^2 + z^2 \right]^{1/2}$$

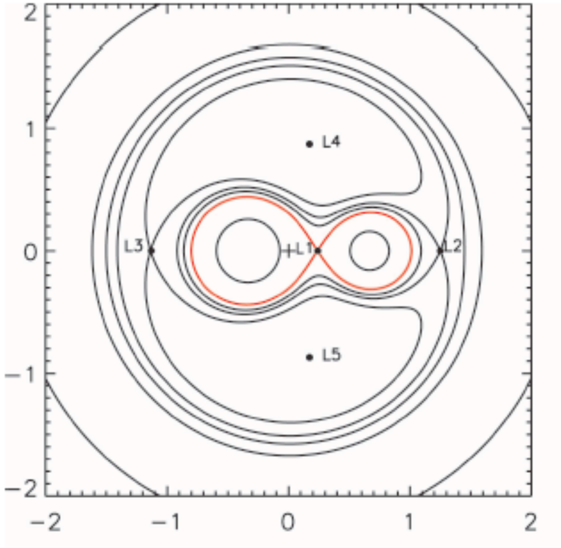
$$r_2 = \left[\left(x - \mu \right)^2 + y^2 + z^2 \right]^{1/2}$$

$$r_3 = \left[x^2 + y^2 \right]^{1/2}$$

in units where the orbital period and separation are taken as unit time and distance, and total mass as unit mass.

Roche lobe (IV)

Critical surfaces whose intersection with the orbital plane form a figure eight = Roche lobes



$$R_{R,2}/a = \begin{cases} 0.38 + 0.2 \log q, & 0.5 \leq q \leq 20, \\ 0.462 \left(\frac{q}{1+q}\right)^{1/3}, & 0 < q < 0.5, \end{cases}$$

where $q = M_2/M_1$,
and a is the orbital separation.

asymmetric !

Paczynski 1971, ARA&A 9, 183

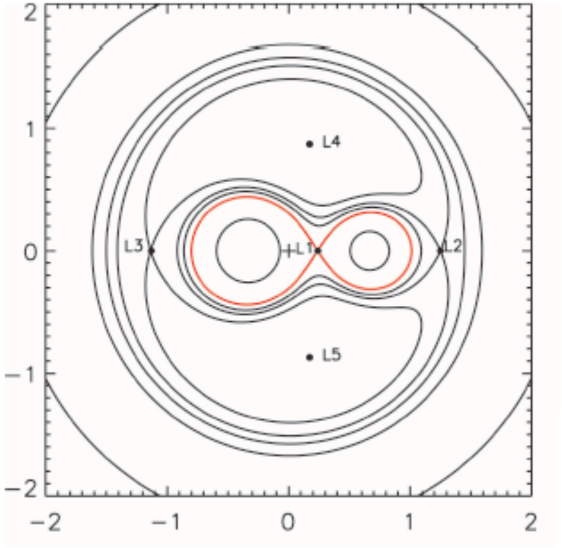
An alternative expression, valid for all q, is

$$R_{R,2}/a = \frac{0.49\ q^{2/3}}{0.6\ q^{2/3} + \ln(1 + q^{1/3})}.$$

Eggleton, 1983, ApJ 268, 368

Roche lobe (IV)

Critical surfaces whose intersection with the orbital plane form a figure eight = Roche lobes



$$R_{R,2}/a = \begin{cases} 0.38 + 0.2 \log q, & 0.5 \le q \le 20, \\ 0.462 \left(\frac{q}{1+q}\right)^{1/3}, & 0 < q < 0.5, \end{cases}$$

where $q = M_2/M_1$,
and a is the orbital separation.

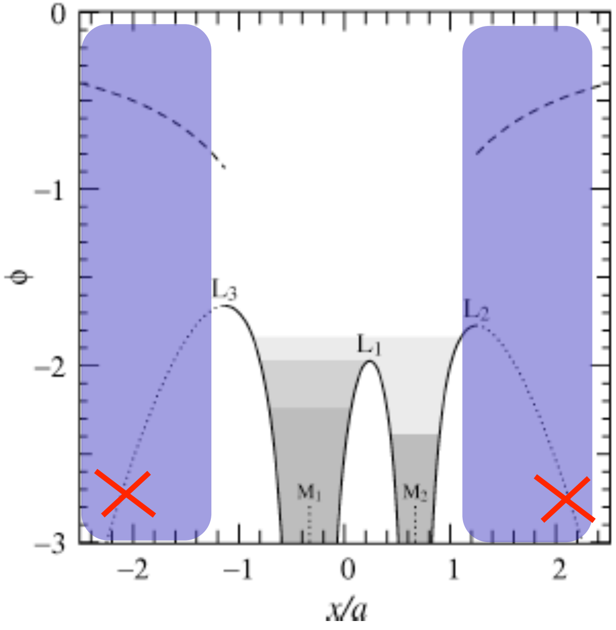
Paczynski 1971, ARA&A 9, 183

Do not confuse radius of Roche lobe $R_{R,2}$ with distance between star(s) and L_1 :

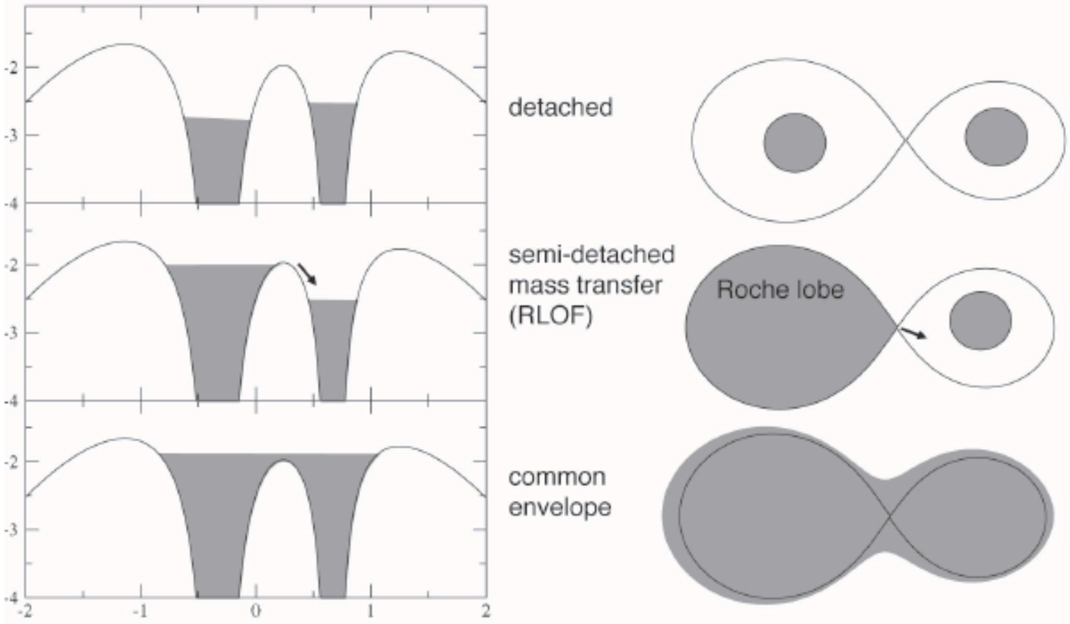
$$r(M_1 \text{to } L_1) = a\,(0.50 + 0.227 \log q)$$
$$r(M_2 \text{to } L_1) = a\,(0.50 - 0.227 \log q)$$

Roche lobe (V)

Note that co-rotation cannot be maintained outside the potential wells !



Different situations are possible:



The binary zoo

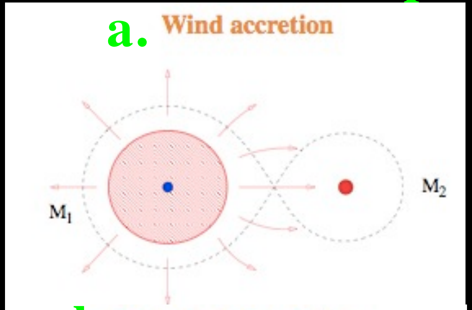
Classification of binary stars

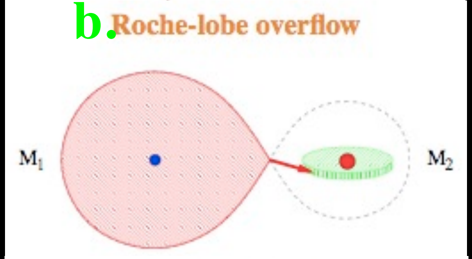
i)

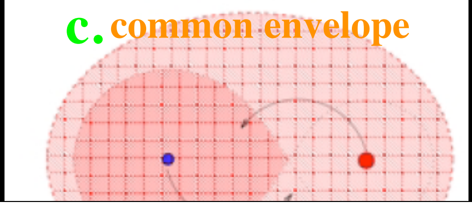
- a. Detached system
- b. Semi-detached system
- c. Contact system

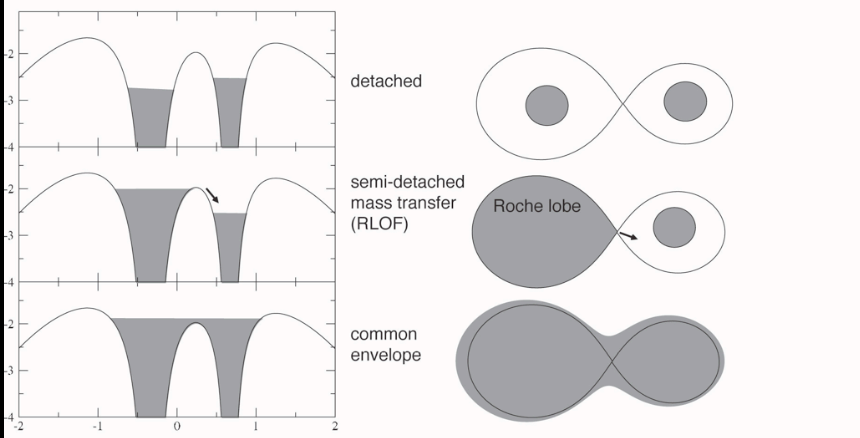
Mass transfer:

- a. wind accretion
- b. Roche-lobe overflow
- c. common envelope (transient or stationary)









The binary zoo

Classification of binary stars

i) Mass transfer

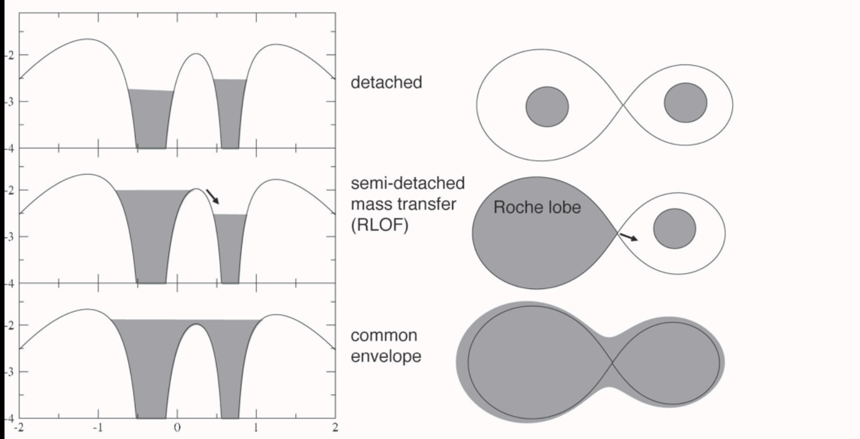
A technical parenthesis about **[→ Lionel Siess]**
mass transfer rates and their associated time scales

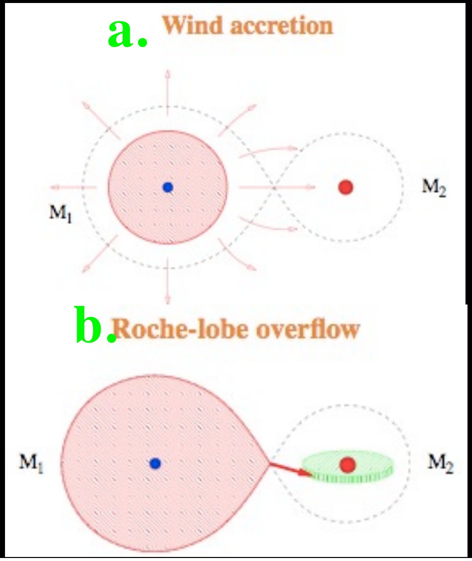
- a. Detached system
- b. Semi-detached system
- c. Contact system

→

Mass transfer:

- a. wind accretion
- b. Roche-lobe overflow



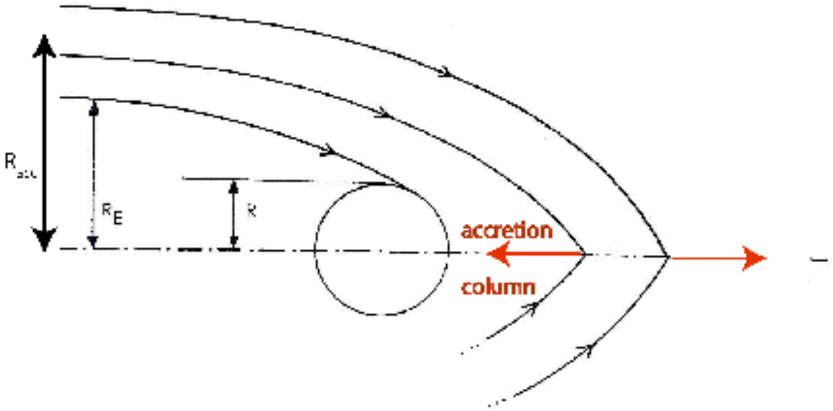


mass transfer rates

Wind accretion: $R < R_R$

1. Hoyle-Lyttleton formalism for a single star accreting matter flowing at a velocity v_∞, with gas pressure unimportant (hence cool gas):

Accretion radius: $v_\infty^2/2 = GM/R_{\mathrm{H-L}}$



Hoyle & Lyttleton 1939, Proc. Cam. Phil. Soc. 35, 405
Bondi 1952, MNRAS 114, 195
Bondi & Hoyle 1944, MNRAS 104, 273

mass transfer rates

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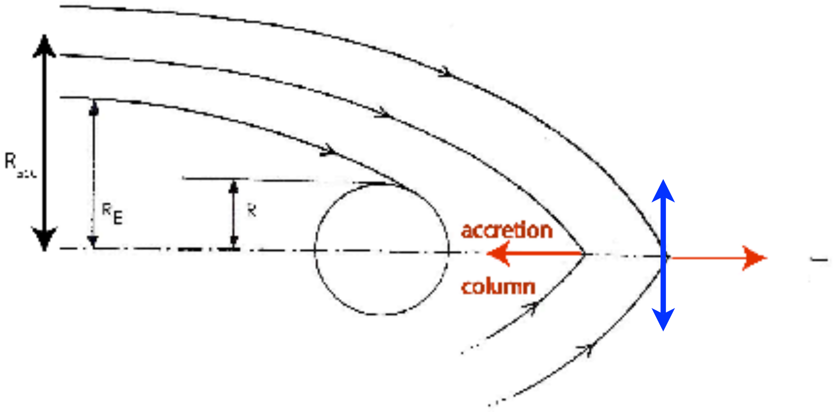
Accretion rate:
$$\dot{M}_{\mathrm{H-L}} = \pi R_{\mathrm{H-L}}^2 v_\infty \rho_\infty = 2\pi \frac{(G\,M)^2}{v_\infty^3} \rho_\infty$$



Note that there is no accretion of angular momentum because the tangential velocity components cancel out

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mass transfer rates

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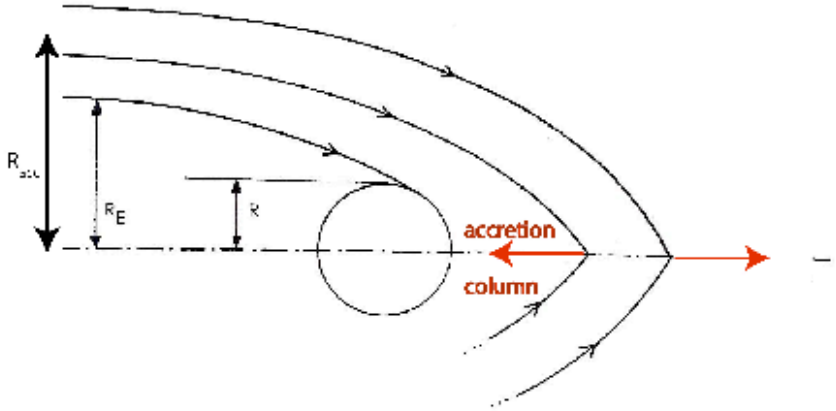

Hoyle & Lyttleton 1939, Proc. Cam. Phil. Soc. 35, 405
Bondi 1952, MNRAS 114, 195
Bondi & Hoyle 1944, MNRAS 104, 273

2. **Bondi formalism** for accretion dominated by gas pressure, with zero relative gas-star velocity:

Accretion radius: $c^2/2 = GM/R_{\mathrm{B}}$
Accretion rate: $\dot{M}_{\mathrm{B}} = \beta\,\pi R_{\mathrm{B}}^2 c \rho_\infty$

where c = sound speed, β is a parameter of order unity depending on the polytropic index of the gas.

mass transfer rates

Wind accretion: $R < R_R$

1. Hoyle-Lyttleton formalism for a single star accreting matter flowing at a velocity v_∞, with gas pressure unimportant (hence cool gas):

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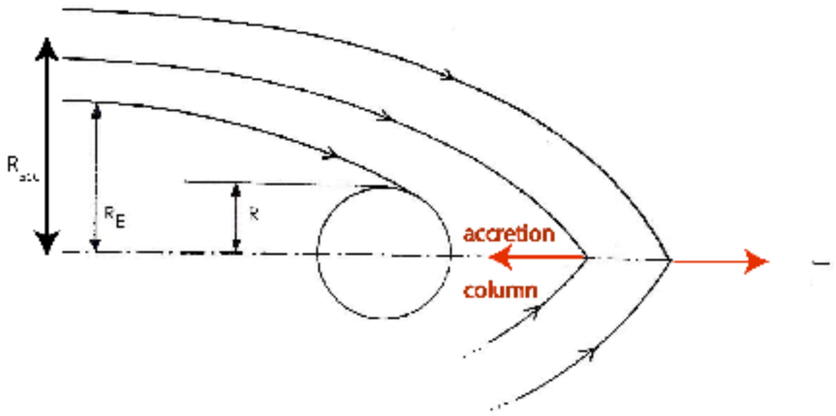
Accretion rate:

$$\dot{M}_{\mathrm{H-L}} = \pi R_{\mathrm{H-L}}^2 v_\infty \rho_\infty = 2\pi \frac{(G\,M)^2}{v_\infty^3} \rho_\infty$$



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Accretion rate: $\dot{M}_{\mathrm{B}} = \beta\,\pi R_{\mathrm{B}}^2 c \rho_\infty$

where c = sound speed, β is a parameter of order unity depending on the polytropic index of the gas.

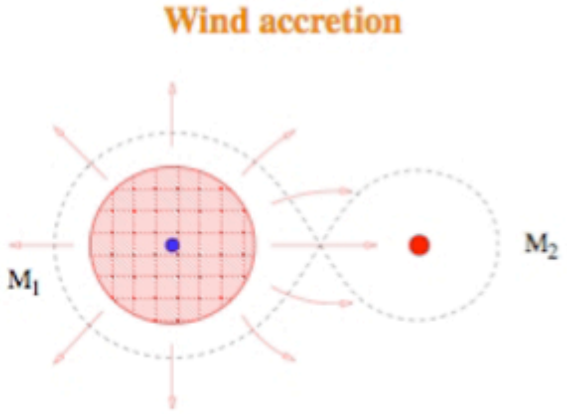
3. Bondi-Hoyle formalism is an interpolation between these two extreme cases:
Accretion rate:

$$\dot{M}_{\mathrm{B-H}} =$$

$$\beta\,\pi R_{\mathrm{H-L}}^2 v_\infty \rho_\infty \left(\frac{(v_\infty/c)^2}{1+(v_\infty/c)^2} \right)^{3/2}$$

mass transfer rates

Wind accretion: $R < R_R$



In a binary system:

- ρ_∞ from $\dot{M}_{\rm wind} = 4\pi\, r^2 \rho(r)\; v_{\rm wind}$,

with r set to a

- v_∞ replaced by $v_{\rm orb} + v_{\rm wind}$.

Thus:

$$\dot{M}_{\rm acc}/\dot{M}_{\rm wind} =$$

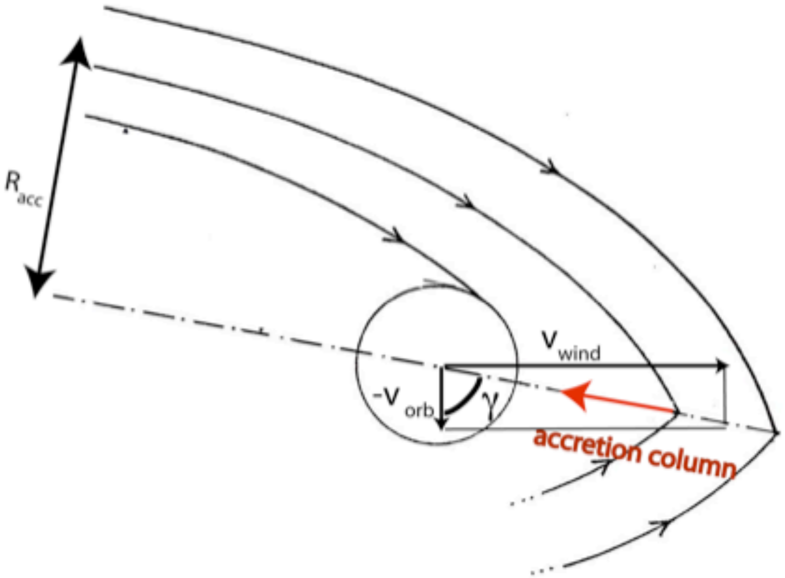
$$-2\pi\, \frac{\beta}{a^2} \left(\frac{(G\, M_{\rm acc})^2}{v_{\rm wind}^2}\right)^2 \frac{1}{[1+(v_{\rm orb}/v_{\rm wind})^2+(c/v_{\rm wind})^2]^{3/2}}$$

or using Kepler's third law:

$$\dot{M}_{\rm acc}/\dot{M}_{\rm wind} = -\beta\mu^2 \frac{k^4}{[1+k^2+(c/v_{\rm wind})^2]^{3/2}},$$

where $\mu \equiv M_{\rm accretor}/(M_{\rm accretor} + M_{\rm loser})$, $k = \dfrac{v_{\rm orb}}{v_{\rm wind}}$

Wind accretion: $R < R_R$

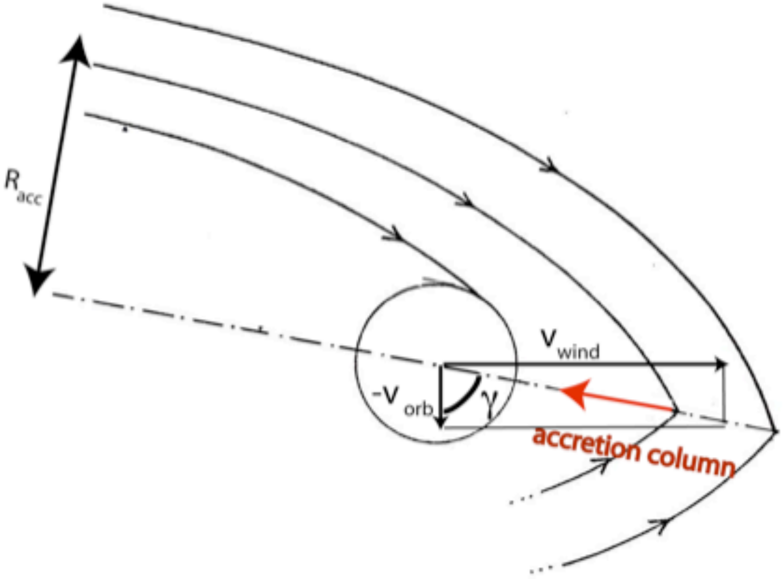


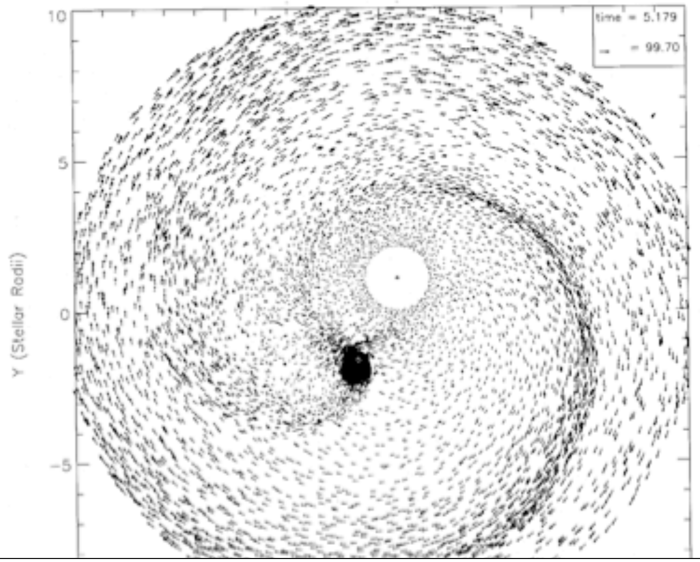
- Fast winds (binaries with OB stars): $k \equiv v_{\rm orb}/v_{\rm wind} << 1$

Accretion column, tilted by an angle $\gamma = \arctan v_{\rm wind}/v_{\rm orb}$ with respect to the orbital motion, with matter falling onto the compact star from its rear side (as viewed from the mass-losing star) with a rate $\dot{M}_{B-H}$

mass transfer rates

Wind accretion: $R < R_R$





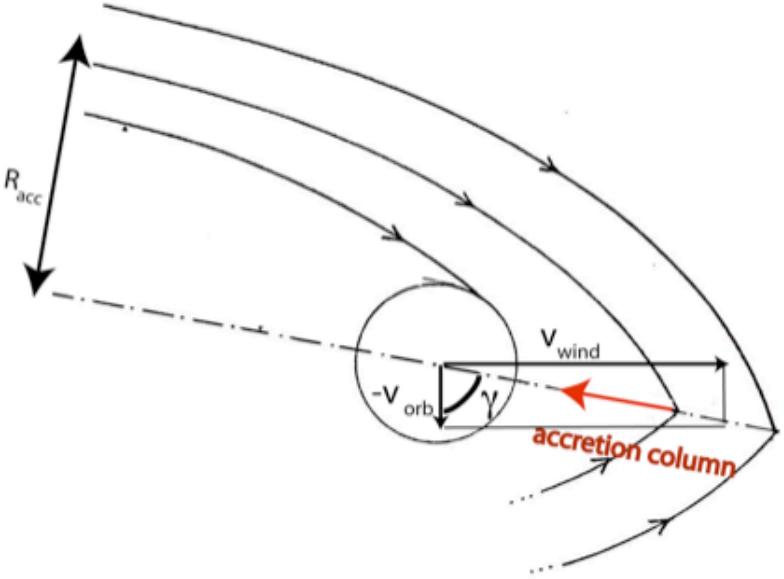
- Fast winds (binaries with OB stars):
  $k \equiv v_{\rm orb}/v_{\rm wind} << 1$

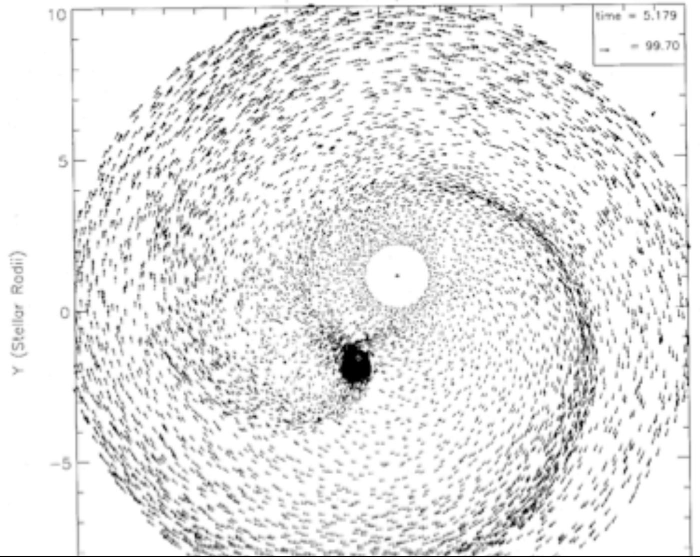
Accretion column, tilted by an angle $\gamma = \arctan v_{\rm wind}/v_{\rm orb}$ with respect to the orbital motion, with matter falling onto the compact star from its rear side (as viewed from the mass-losing star) with a rate $\dot{M}_{B-H}$

- Slow winds (detached binary systems involving an AGB star):
  $k \equiv v_{\rm orb}/v_{\rm wind} >> 1$

Accretion column distorted by Coriolis effect, must be investigated numerically.

Wind accretion: $R < R_R$





- Fast winds (binaries with OB stars):
$k \equiv v_{\rm orb}/v_{\rm wind} << 1$

Accretion column, tilted by an angle $\gamma = \arctan v_{\rm wind}/v_{\rm orb}$ with respect to the orbital motion, with matter falling onto the compact star from its rear side (as viewed from the mass-losing star) with a rate $\dot{M}_{B-H}$

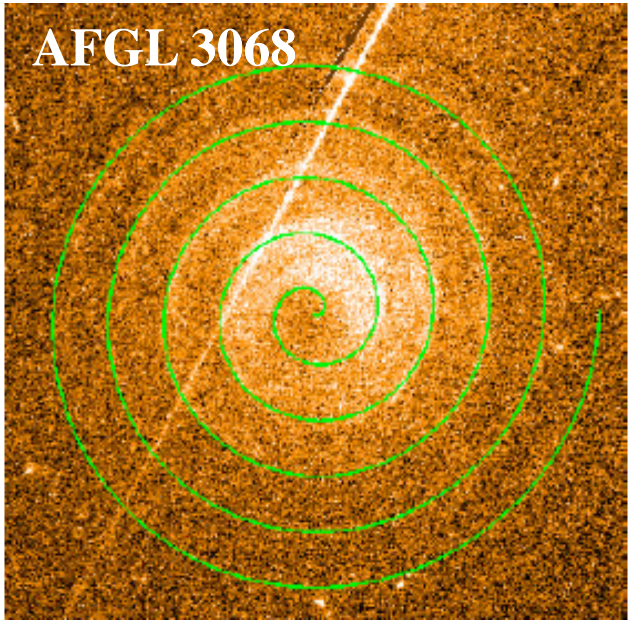
- Slow winds (detached binary systems involving an AGB star):
$k \equiv v_{\rm orb}/v_{\rm wind} >> 1$

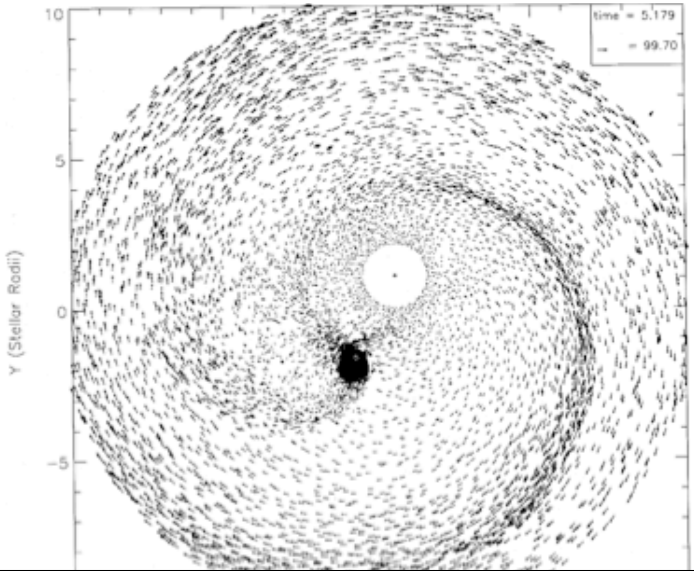
Accretion column distorted by Coriolis effect, must be investigated numerically.
Accretion rates $\leq 0.1 \dot{M}_{\rm B-H}$

Theuns & Jorissen 1993, MNRAS 265, 946
Mastrodemos & Morris 1998, ApJ 497, 303
Folini & Walder 2000, Ap&SS 274, 189
Nagae et al. 2004, A&A 419, 335
Jahanara et al., 2005, A&A 441, 589

mass transfer rates

Wind accretion: $R < R_R$





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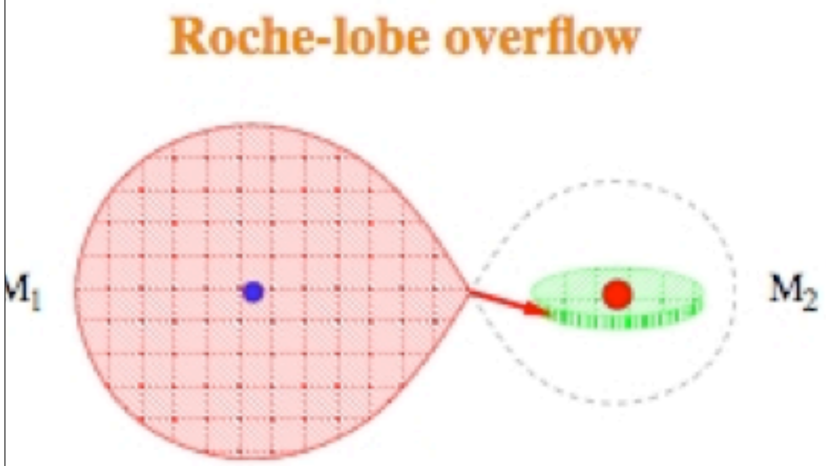
Mastrodemos & Morris 1998, ApJ 497, 303
Folini & Walder 2000, Ap&SS 274, 189
Nagae et al. 2004, A&A 419, 335
Jahanara et al., 2005, A&A 441, 589

‘Spiral arm’ feature has been observed in some binary systems: AFGL 3068, R Scl

mass transfer rates

RLOF : $R = R_R$

conservative mass transfer $\dot{M}_{\mathrm{acc}} = \dot{M}_{\mathrm{RLOF}}$



$\dot{M}_{\mathrm{RLOF}}$ is limited by the flow compression through the inner Lagrangian point, where it flows at sound speed with a rate:

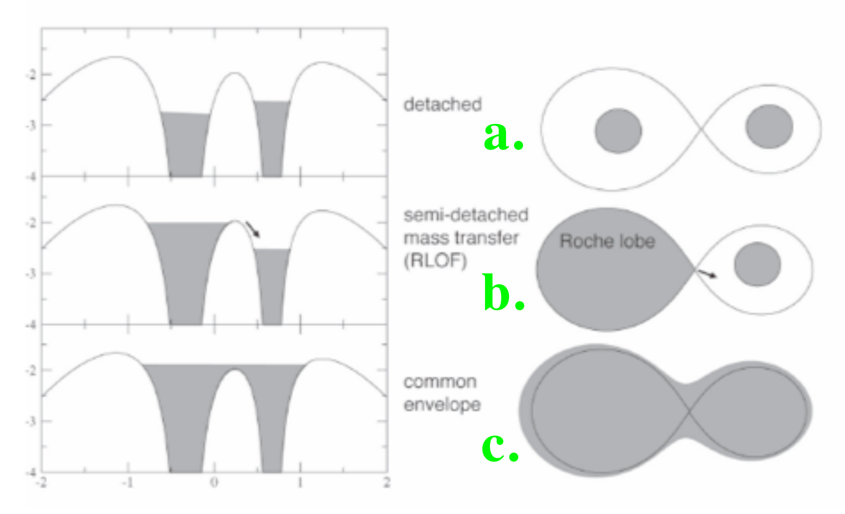
$$-\dot{M}_{\mathrm{RLOF}} = \dot{M}_{\mathrm{loser}} e^{\left(\frac{-(R_R - R)}{H_P}\right)},$$

where H_P is the pressure scale height in the mass-donor star, $\dot{M}_{\mathrm{loser}}$ is a characteristic mass-loss rate of the donor.

Lubow & Shu 1975, ApJ 198, 383
Ritter 1988, A&A 202, 93
Kolb & Ritter 1990, A&A 236, 385

The binary zoo

Classification of binary stars:



i) Mass transfer

a. Detached system

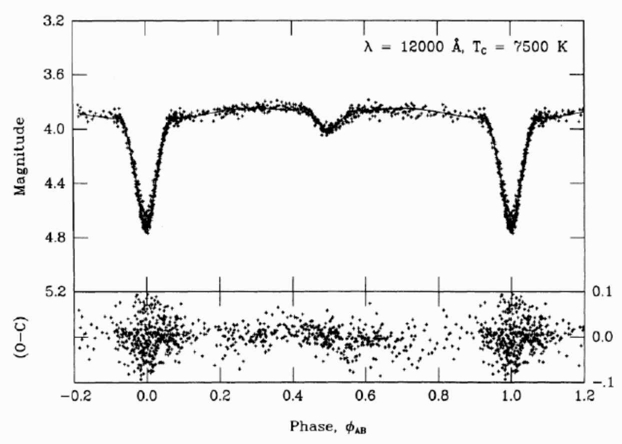
b. Semi-detached system

c. Contact system

ii) Observational properties

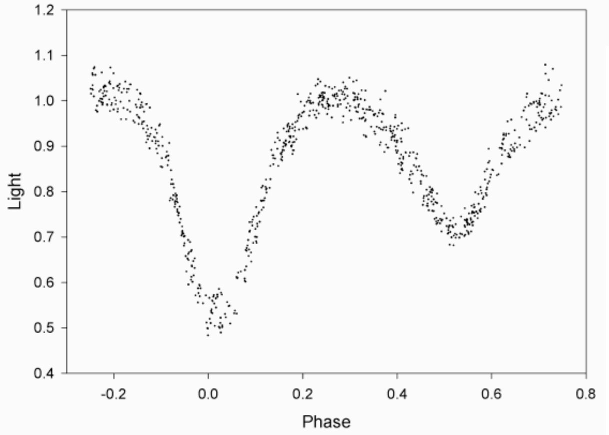
photometric binary [eclipses]

a. Detached system



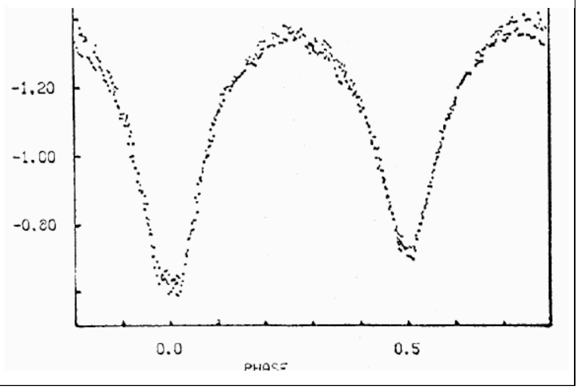
b. Semi-detached system

β Lyr



c. Contact system

W UMa



The binary zoo

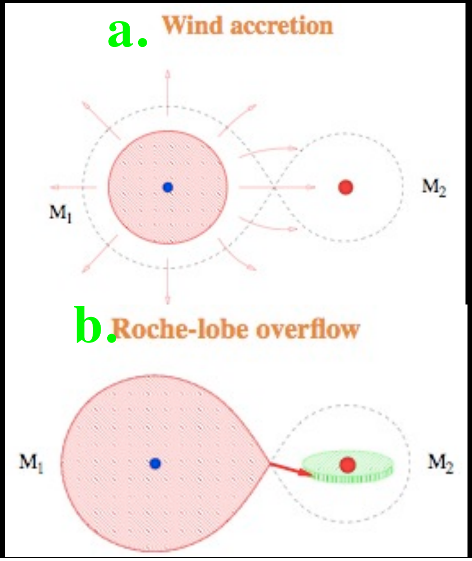
Classification of binary stars:

There are three possible ways to classify binary stars, based on:

i) Mass transfer:

- a. Detached system
- b. Semi-detached system
- c. Contact system

- a. wind accretion
- b. Roche-lobe overflow



ii) Observational properties

- a. photometric binary Ex: Algols
- b. X-ray binary Ex: Algols
- c. [peculiar] ‘abundance’ binary Ex: Algols (CNO)

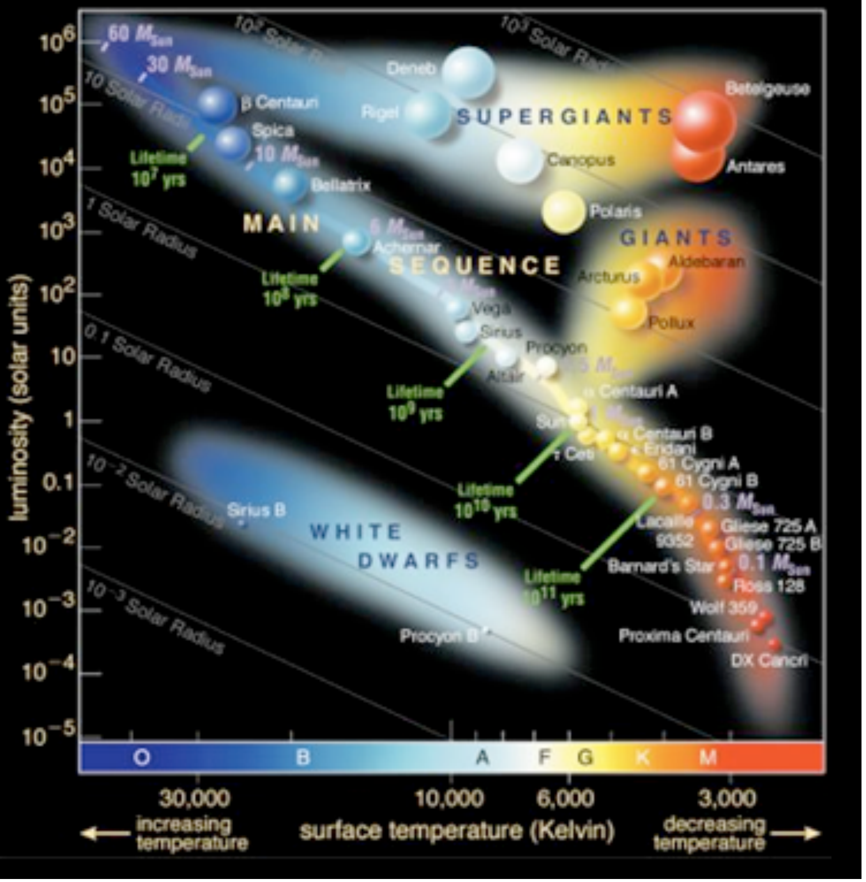
iii) Evolutionary stage

The binary zoo

Classification of binary stars:

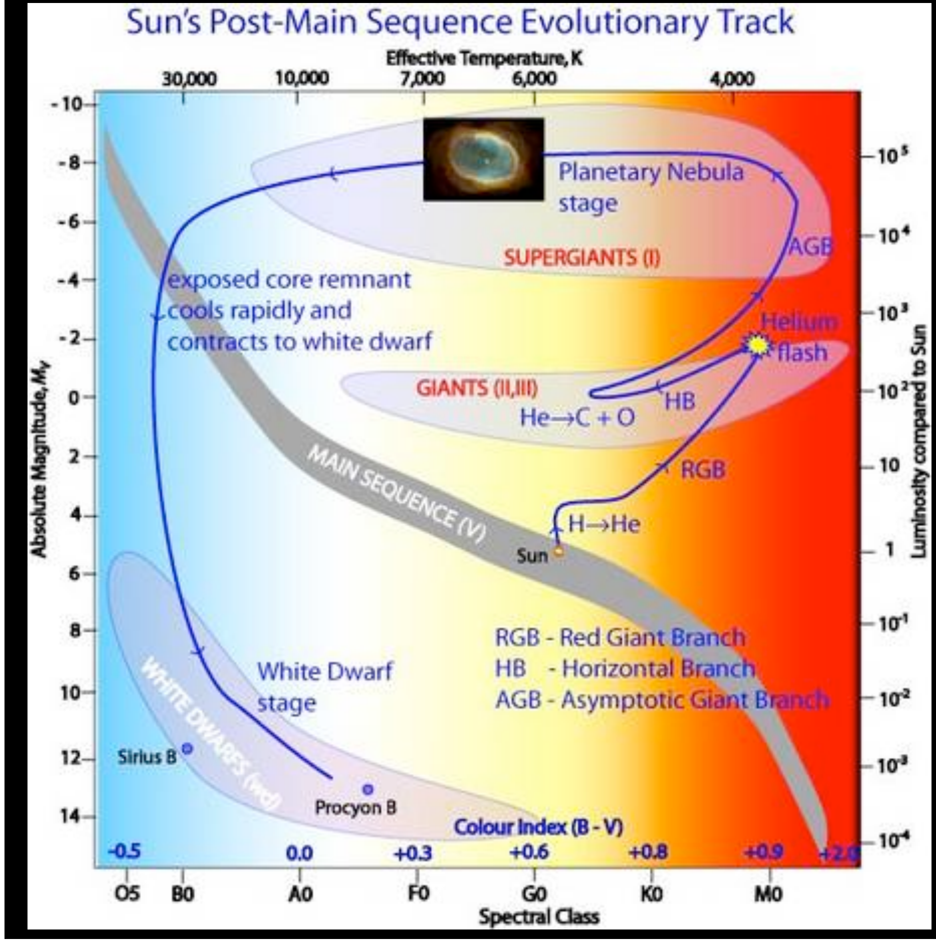
There are three possible ways to classify binary stars, based on:

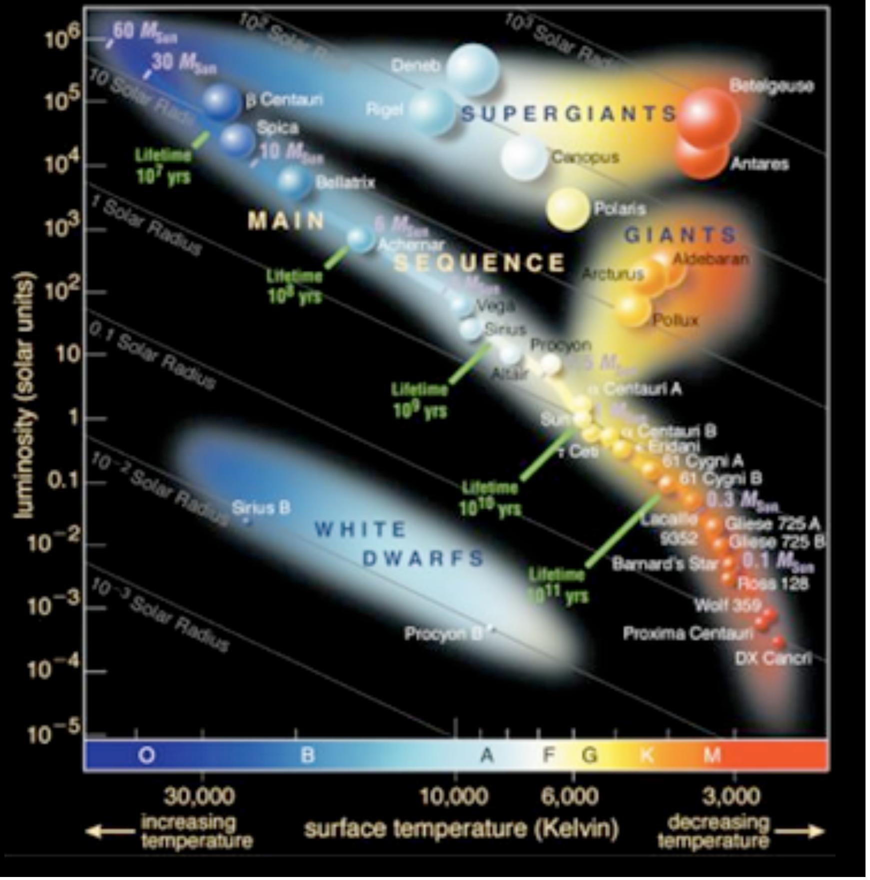
iii) Evolutionary stage



There are three possible ways to classify binary stars, based on:

iii) Evolutionary stages, connected through stellar-evolution tracks [→ Siess]

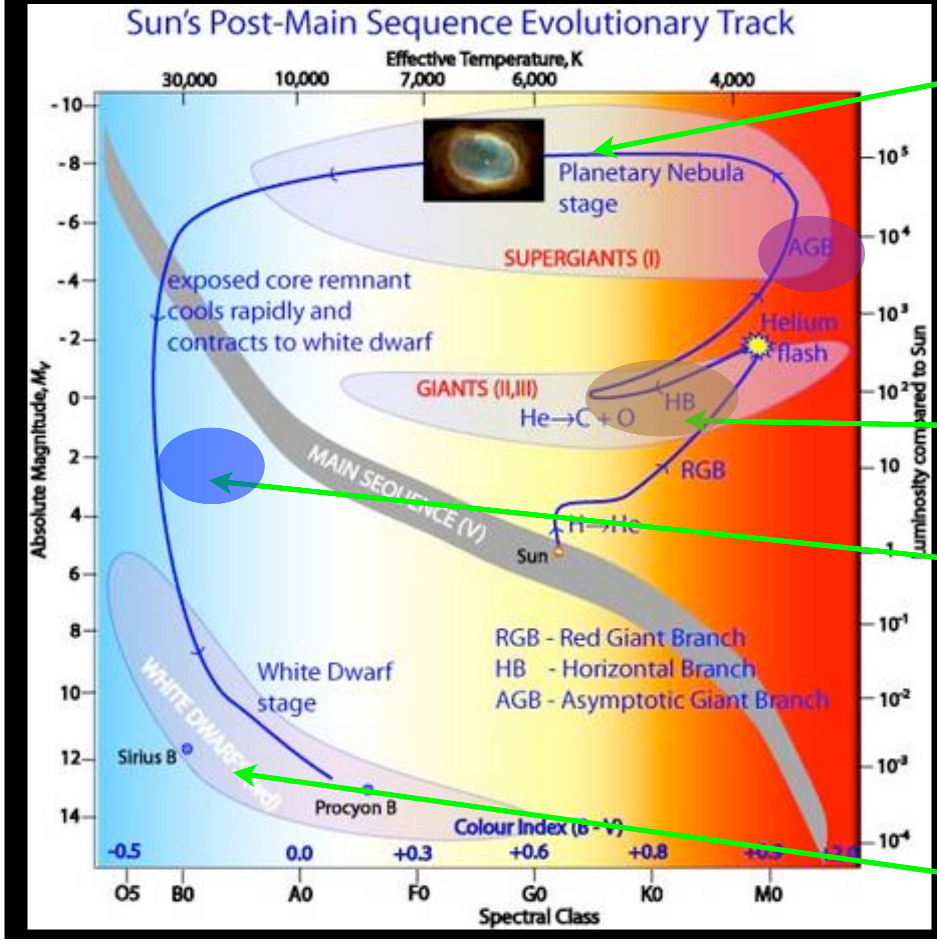

Sun's Post-Main Sequence Evolutionary Track



There are three possible ways to classify binary stars, based on:

iii) Evolutionary stage

A few examples of binaries defined by their evolutionary stages



[peculiar] 'abundance' binary:

- metal-depleted post-AGB star

- K giant with strong barium lines
[= Barium star]

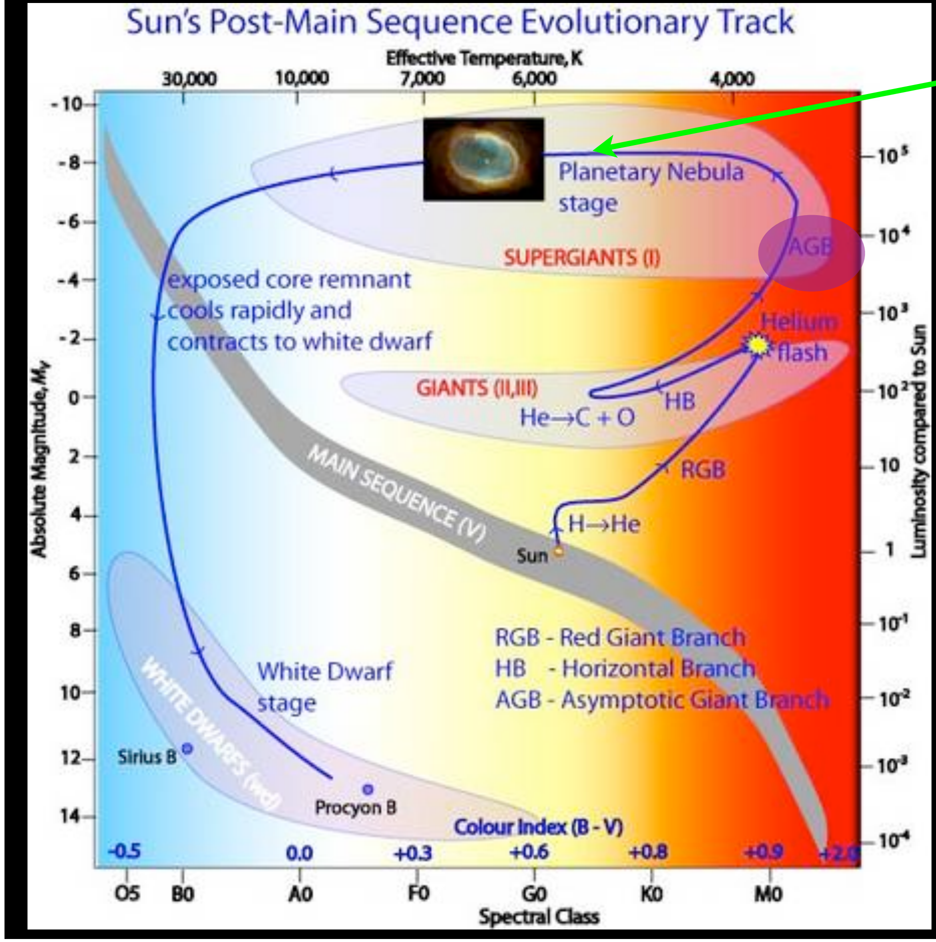
- sdB

- binary with compact companion
(BH, WD) [→ Nelemans]

iii) Evolutionary stage

[peculiar] ‘abundance’ **binary:**

- metal-depleted post-AGB star



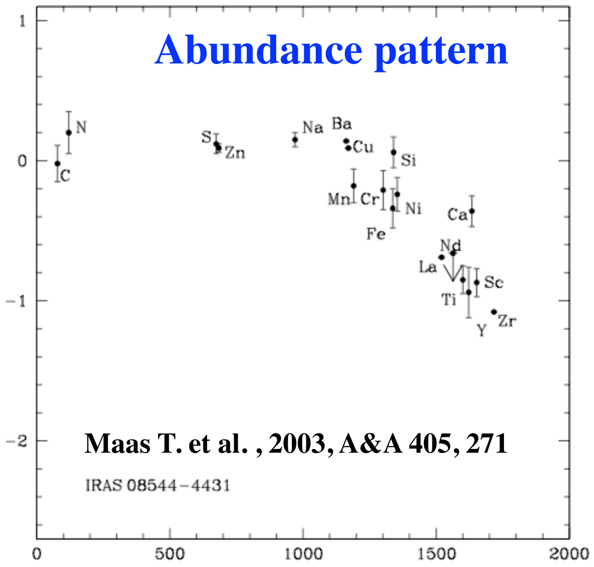
post-AGB stars

[peculiar] ‘abundance’ binary:
- metal-depleted post-AGB star

Plus the correlation with the post-AGB nature

Four correlated observational properties :

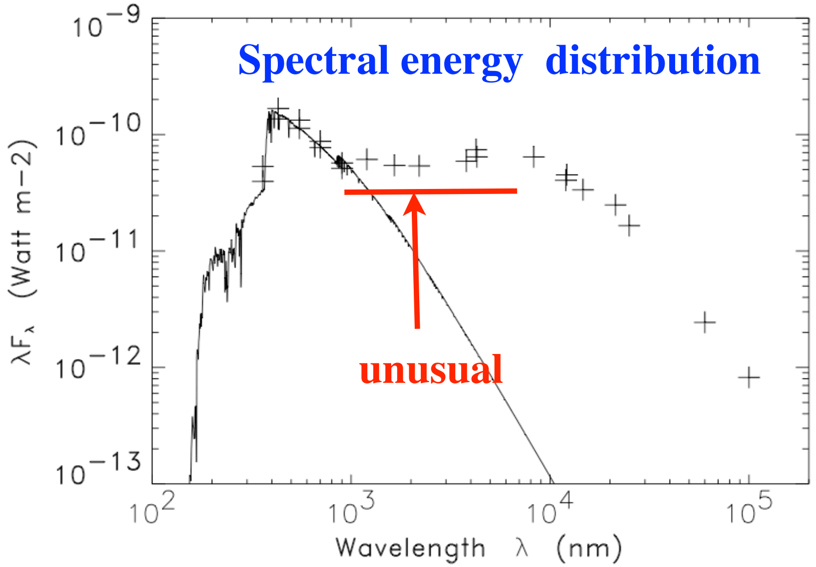
[el / H] =
log { N(el)/N(H) }



Abundance pattern

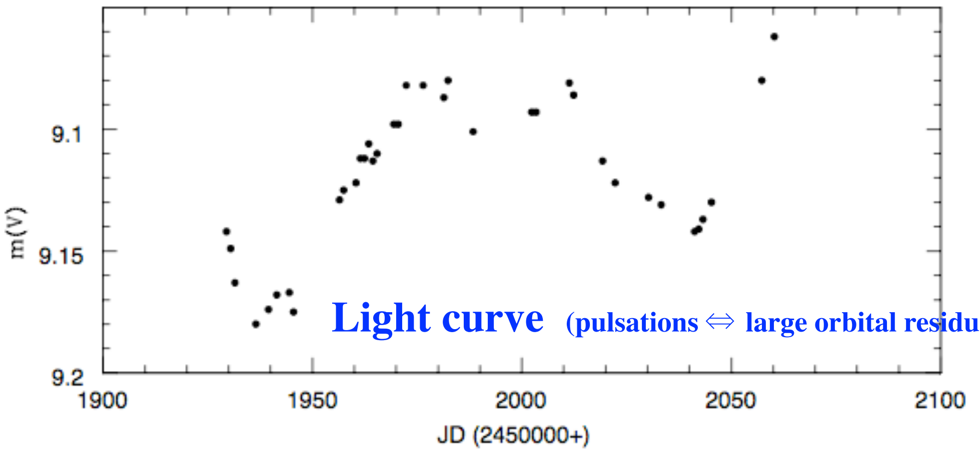
Maas T. et al. , 2003, A&A 405, 271

condensation temperature (K)

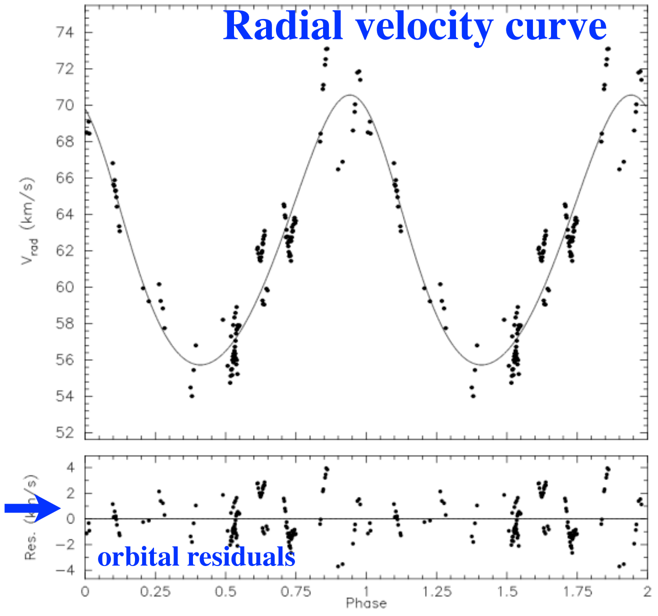


Spectral energy distribution

unusual



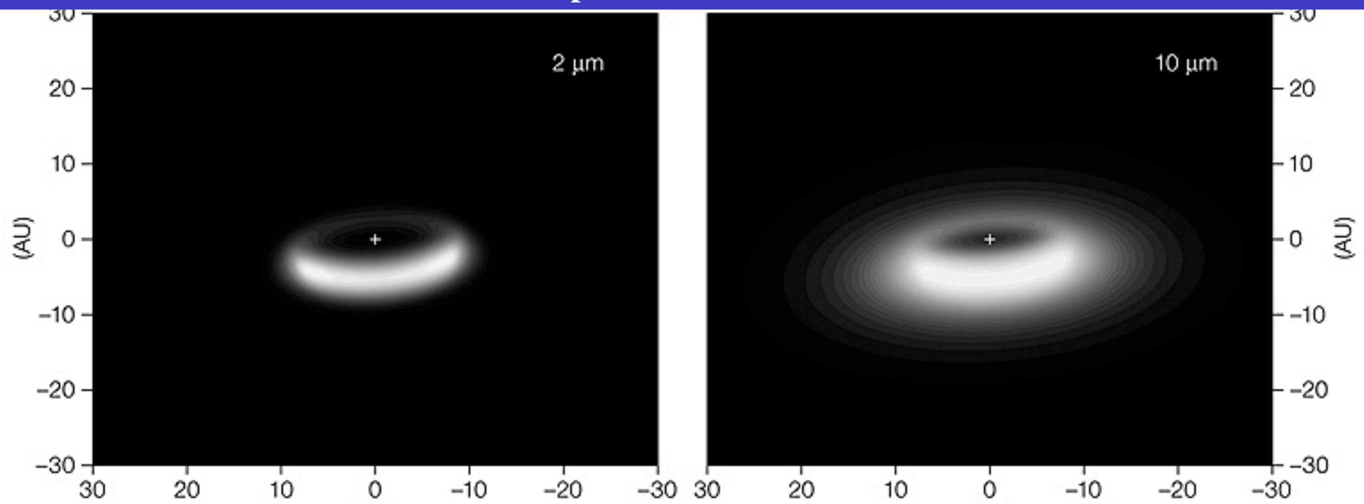
Light curve (pulsations ⇔ large orbital residuals)



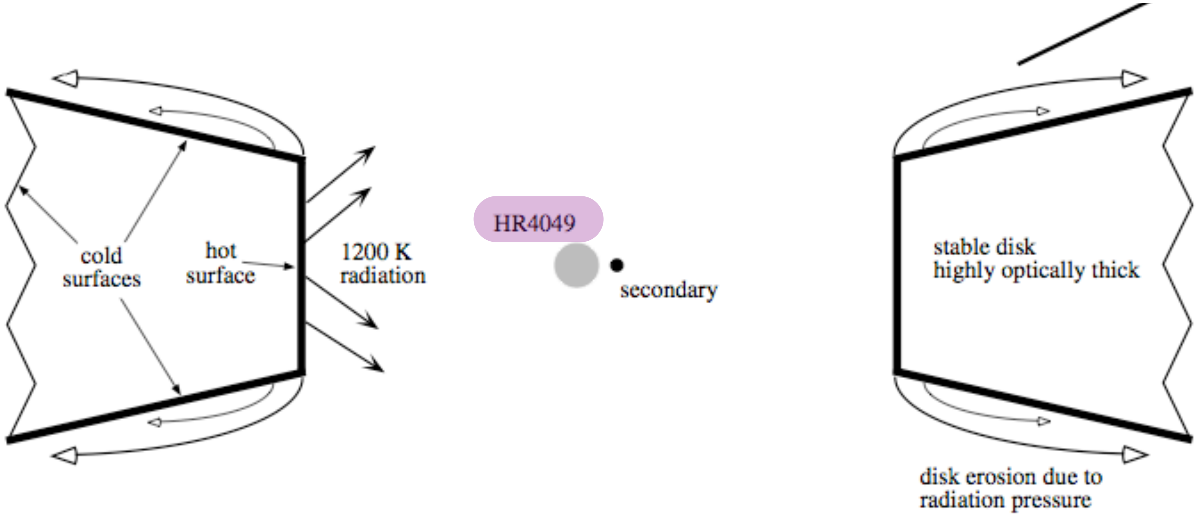
Radial velocity curve

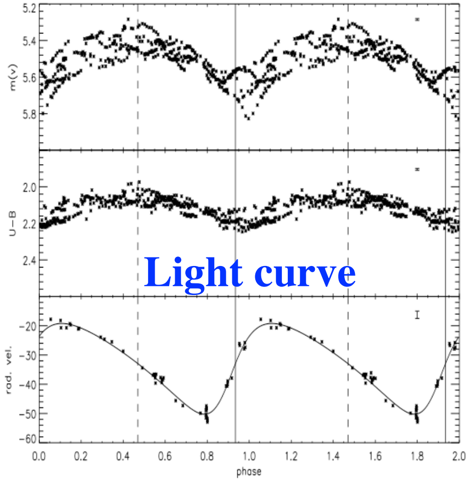
orbital residuals

post-AGB stars



The circumbinary disc accounts:
- **for the peculiar spectral energy distribution (warm dust is stored in the inner part of the disc)**
- **for the depletion pattern (re-accretion of refractory-depleted gas)**
- **for the orbital modulation of the light curve (in the absence of pulsations)**
- **for the orbital properties (eccentricity - period diagram ; "eccentricity pumping")**

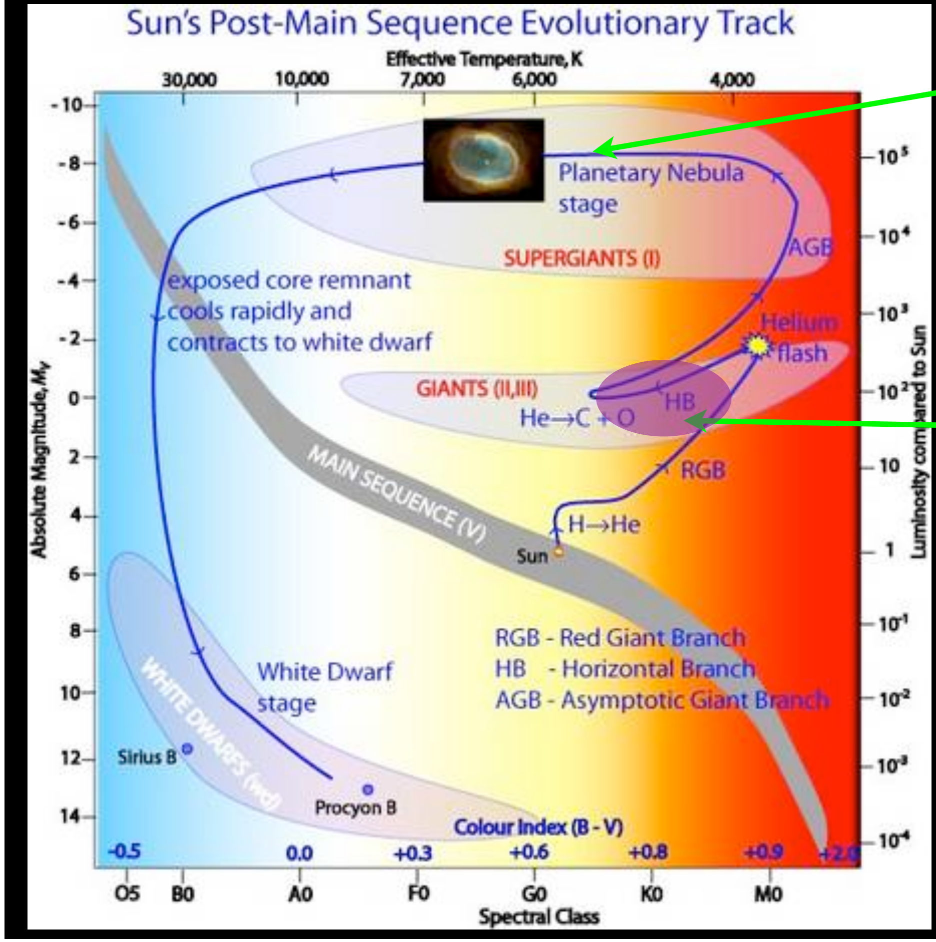




Light curve

There are three possible ways to classify binary stars, based on:

iii) Evolutionary stage



[peculiar] 'abundance' binary:

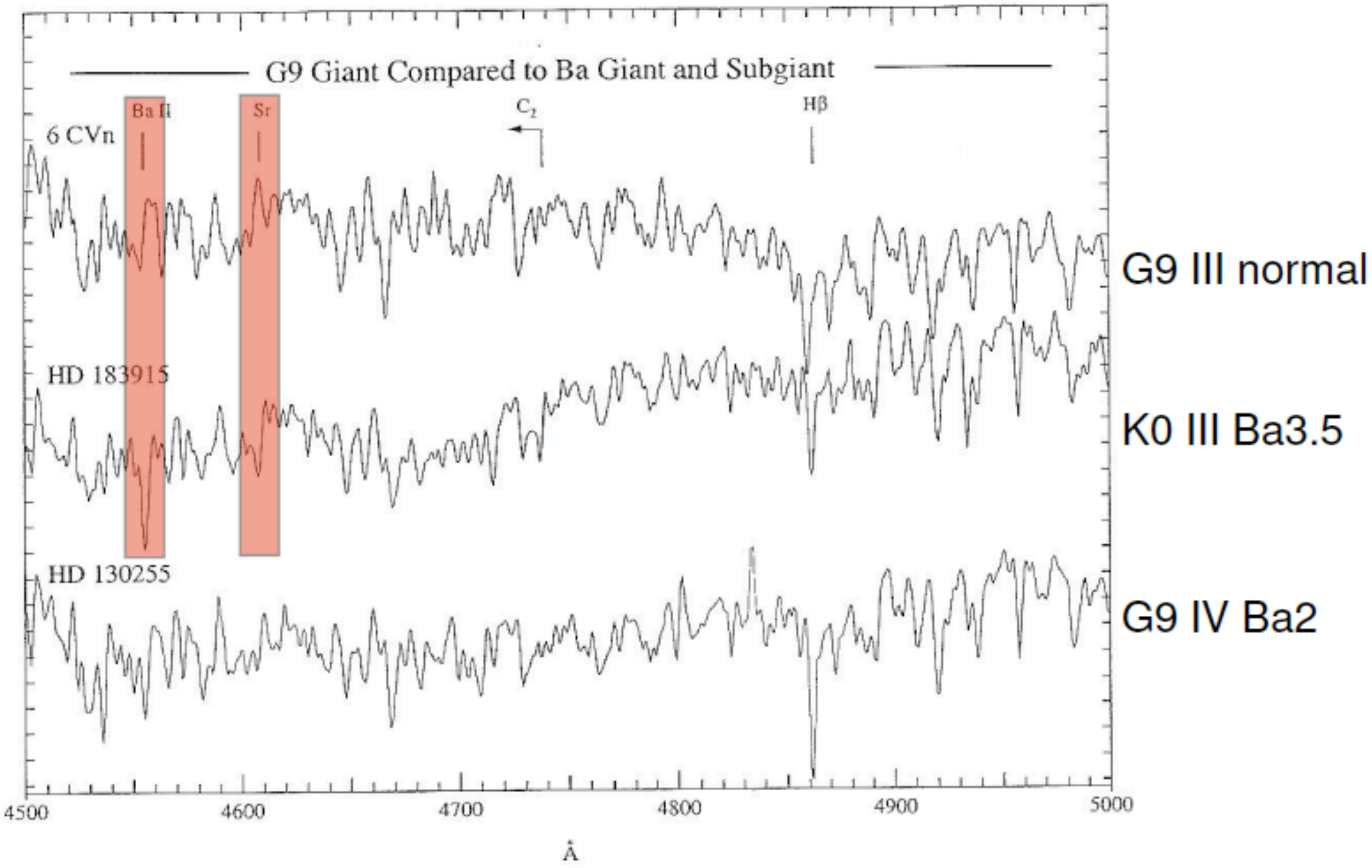
- metal-depleted post-AGB star

- K giant with strong barium lines

[= Barium star]

Barium stars

Ba stars: A class of chemically-peculiar giants known since the 50's



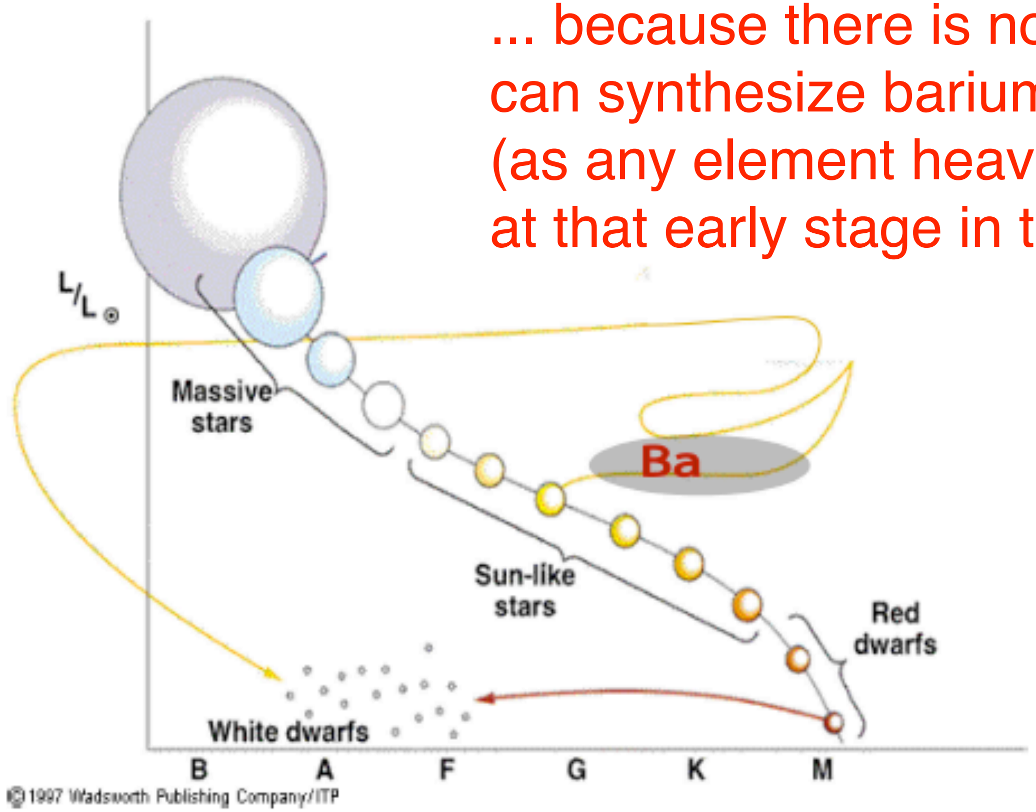
Barnbaum (1996), ApJS 105, 419

Barium stars

Ba stars: A class of chemically-peculiar giants known since the 50's

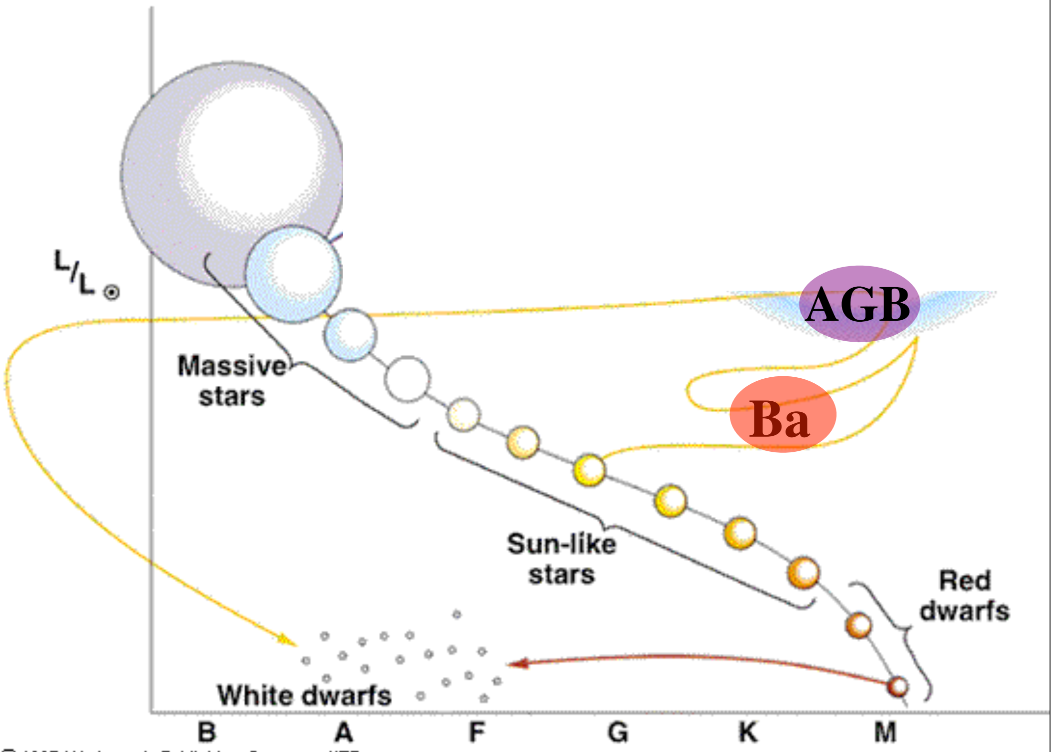
Chemical peculiarities attributed to mass transfer...

... because there is no way a star can synthesize barium
(as any element heavier than Fe)
at that early stage in the evolution



Barium stars

Synthesis of He-burning nucleosynthesis products:
12C, 19F, s-process elements (Sr, Ba, Tc, Pb...)



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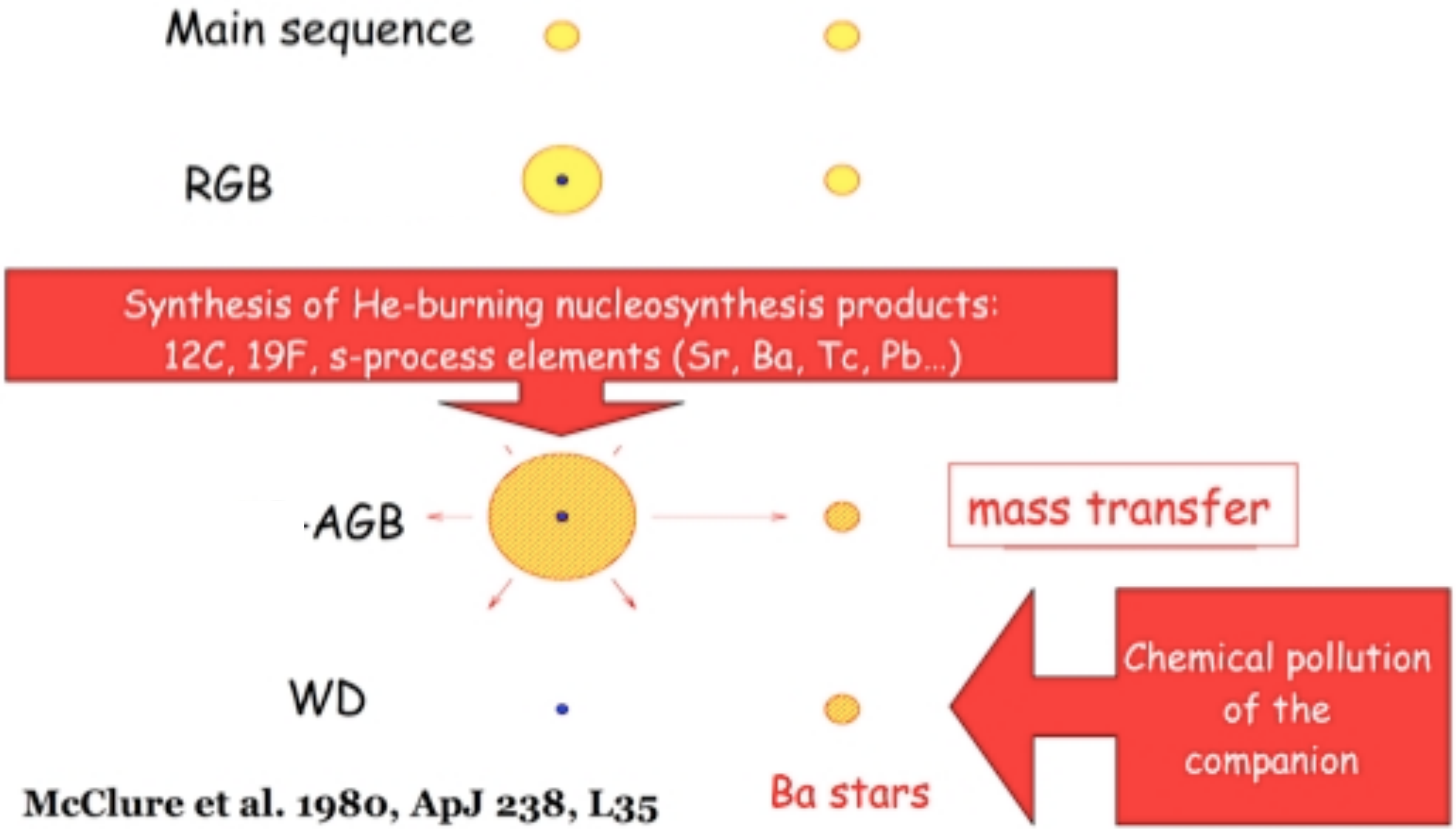
Barium stars

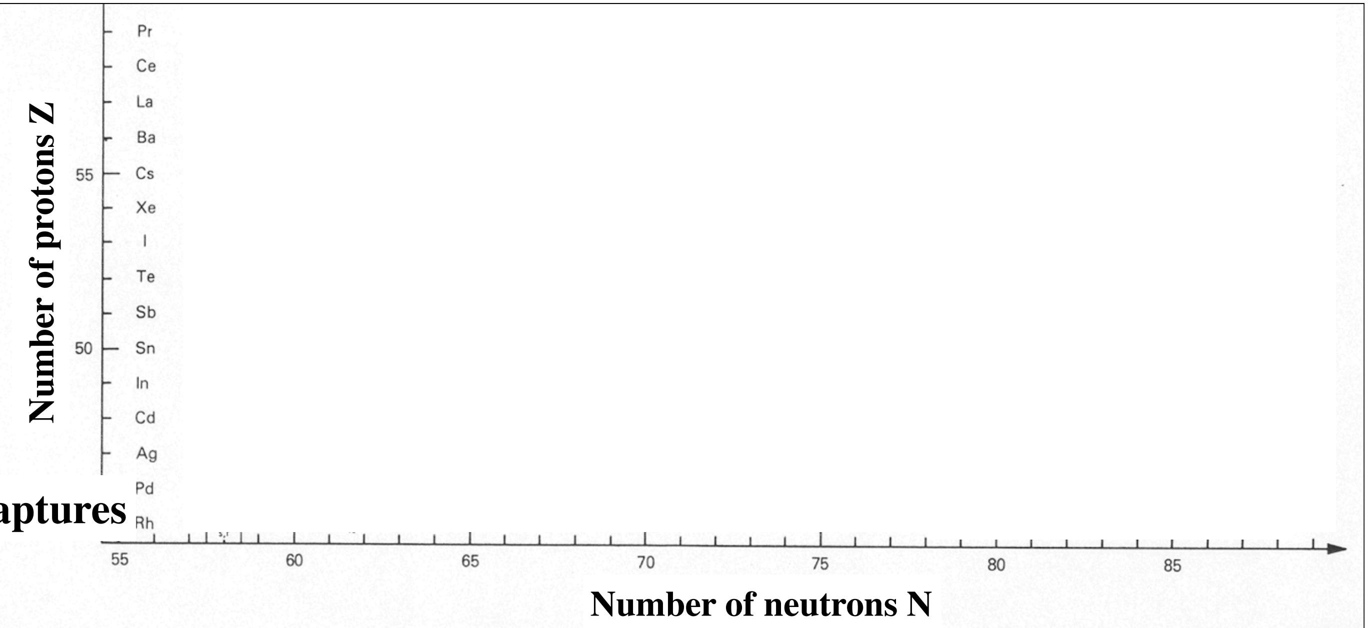
A technical parenthesis about the synthesis of heavy elements

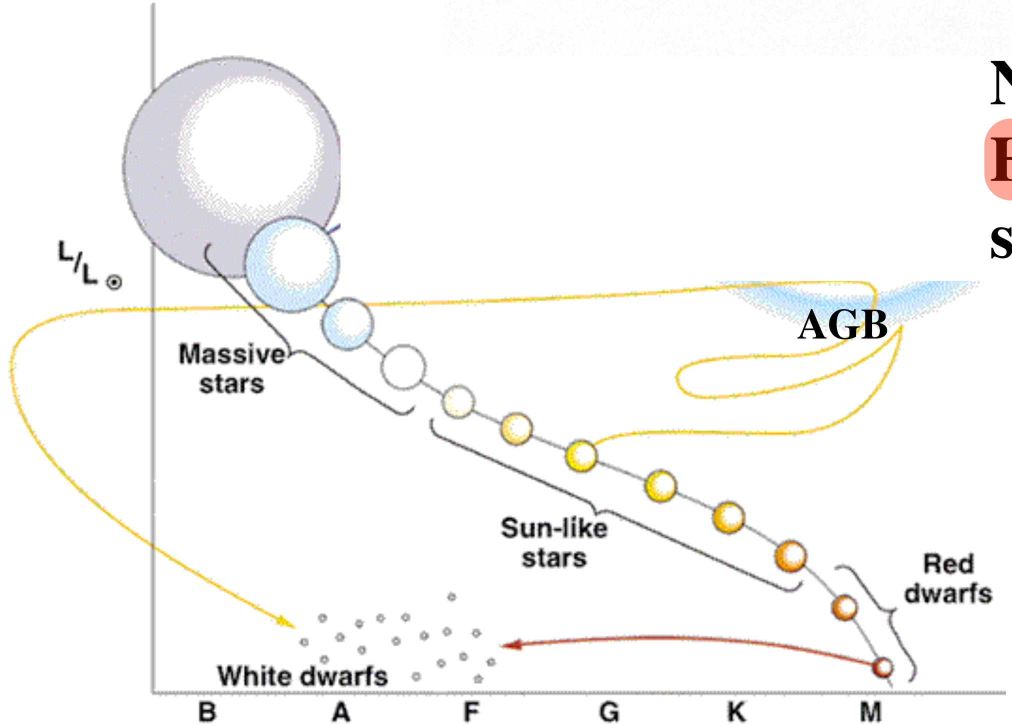


McClure et al. 1980, ApJ 238, L35

A technical parenthesis about the synthesis of heavy elements

= a chain of neutron captures





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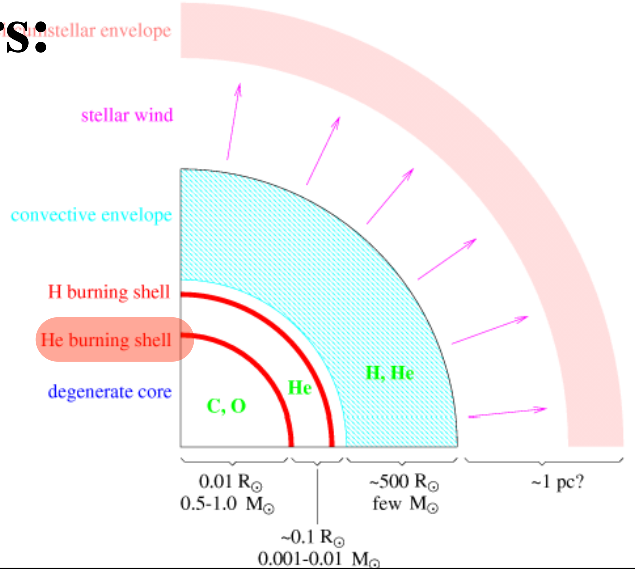
Neutrons are produced in the **He-burning shell** of AGB stars:



A technical parenthesis about the synthesis of heavy elements

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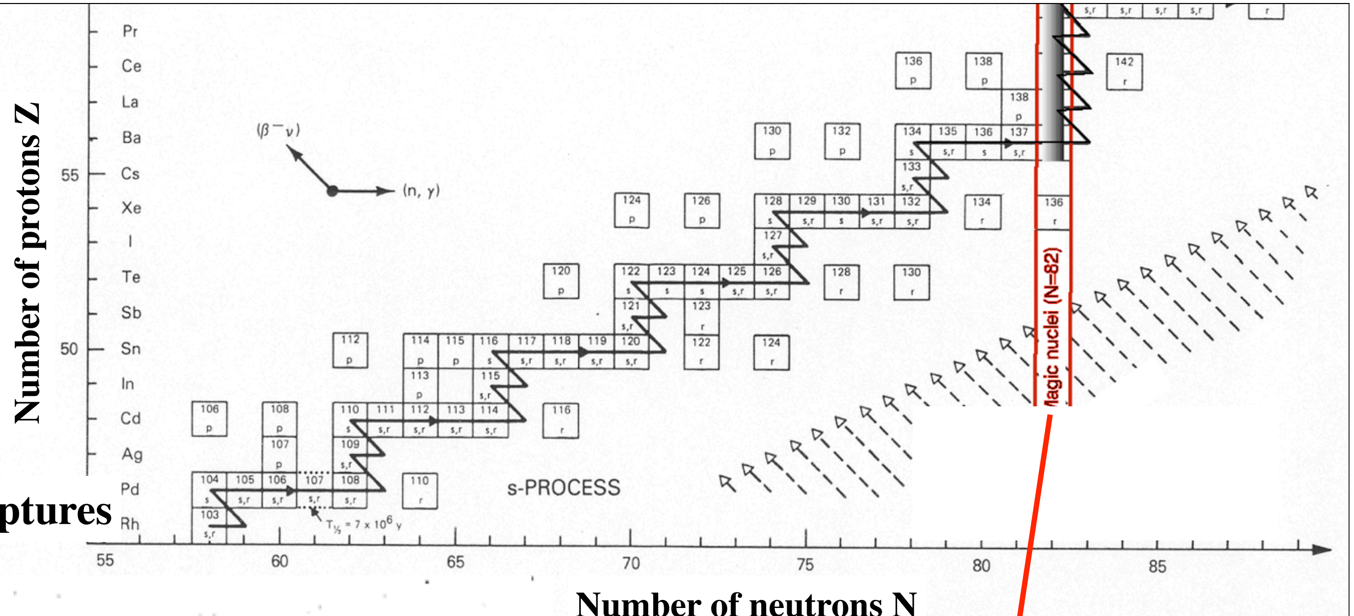
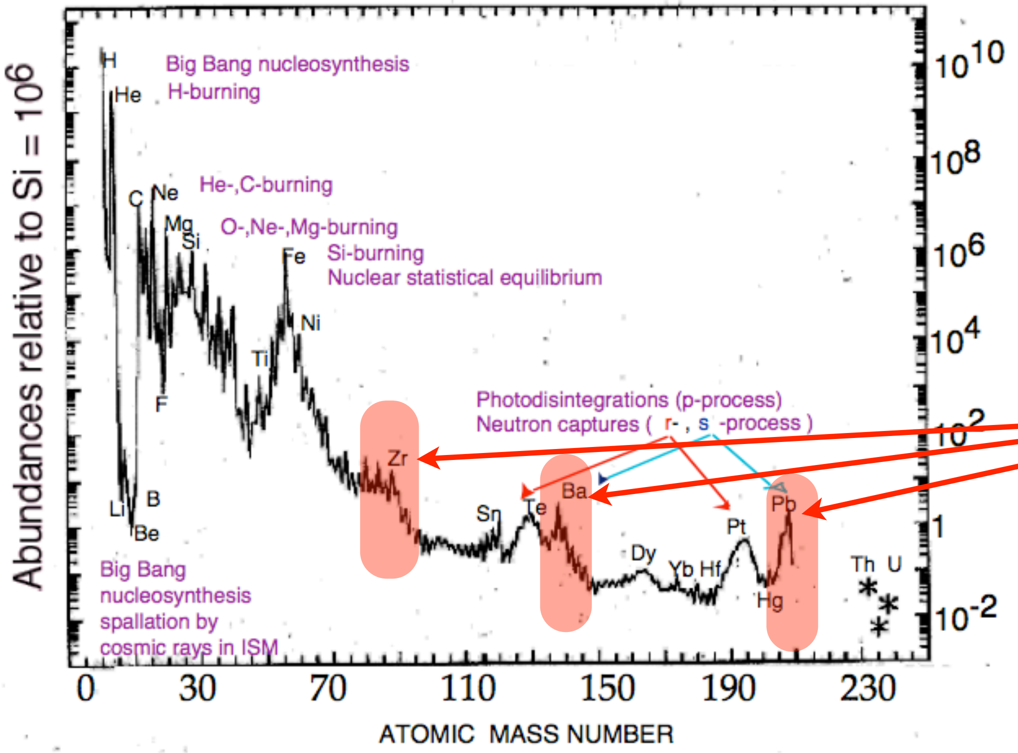


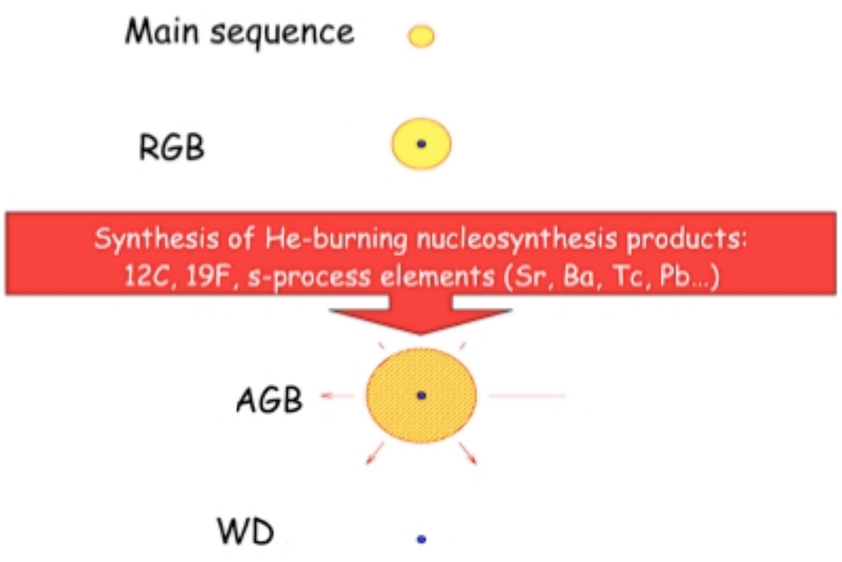


Nuclei with closed neutron shell (“magic nuclei”)

Small cross section

→ piles up

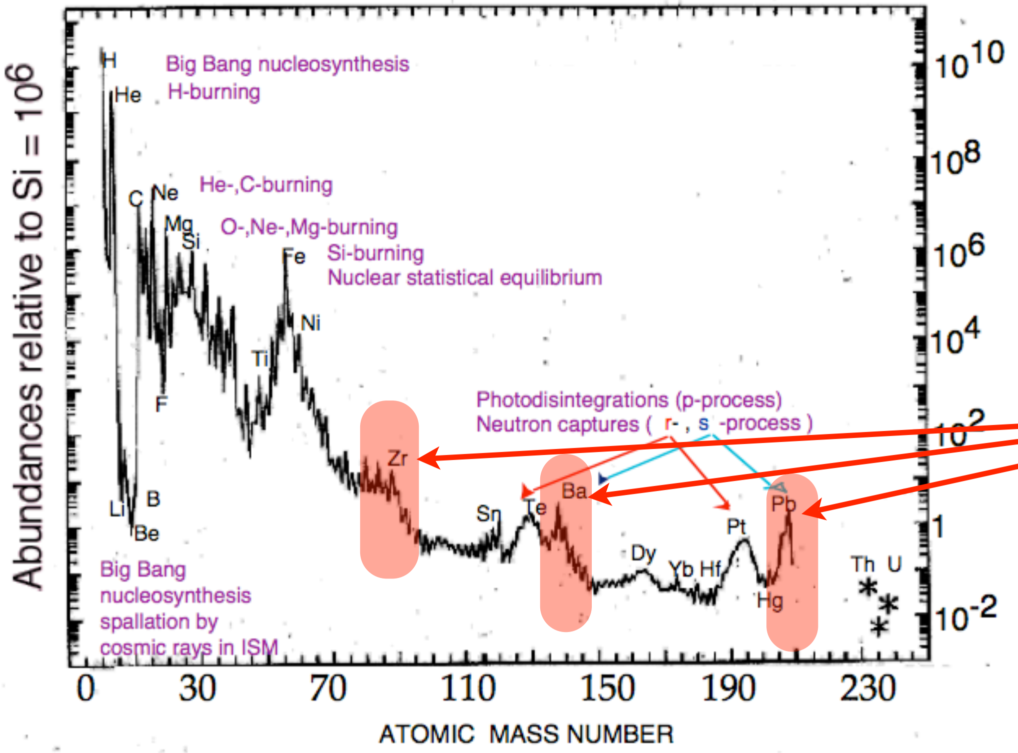
→ abundance peaks



Hence AGB stars become enriched in heavy elements, e.g. Zr

For instance, S stars = AGB stars

→ **ZrO bands in S stars**



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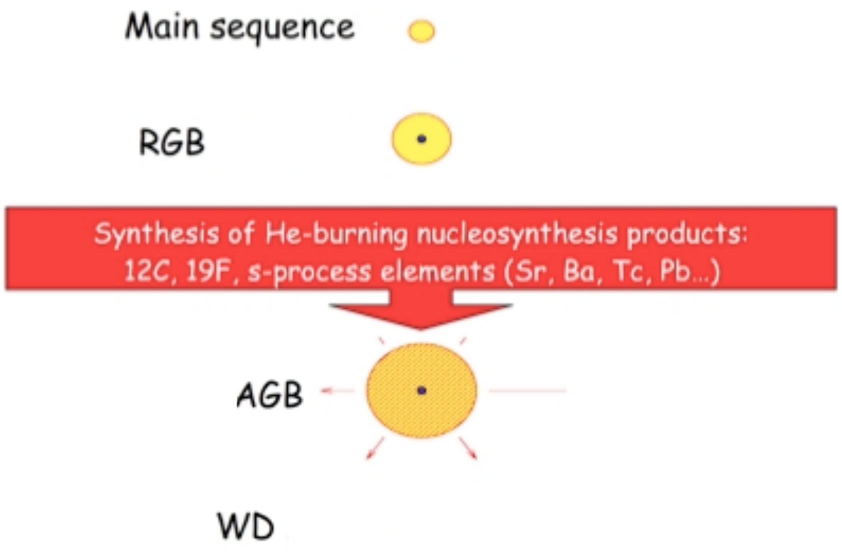

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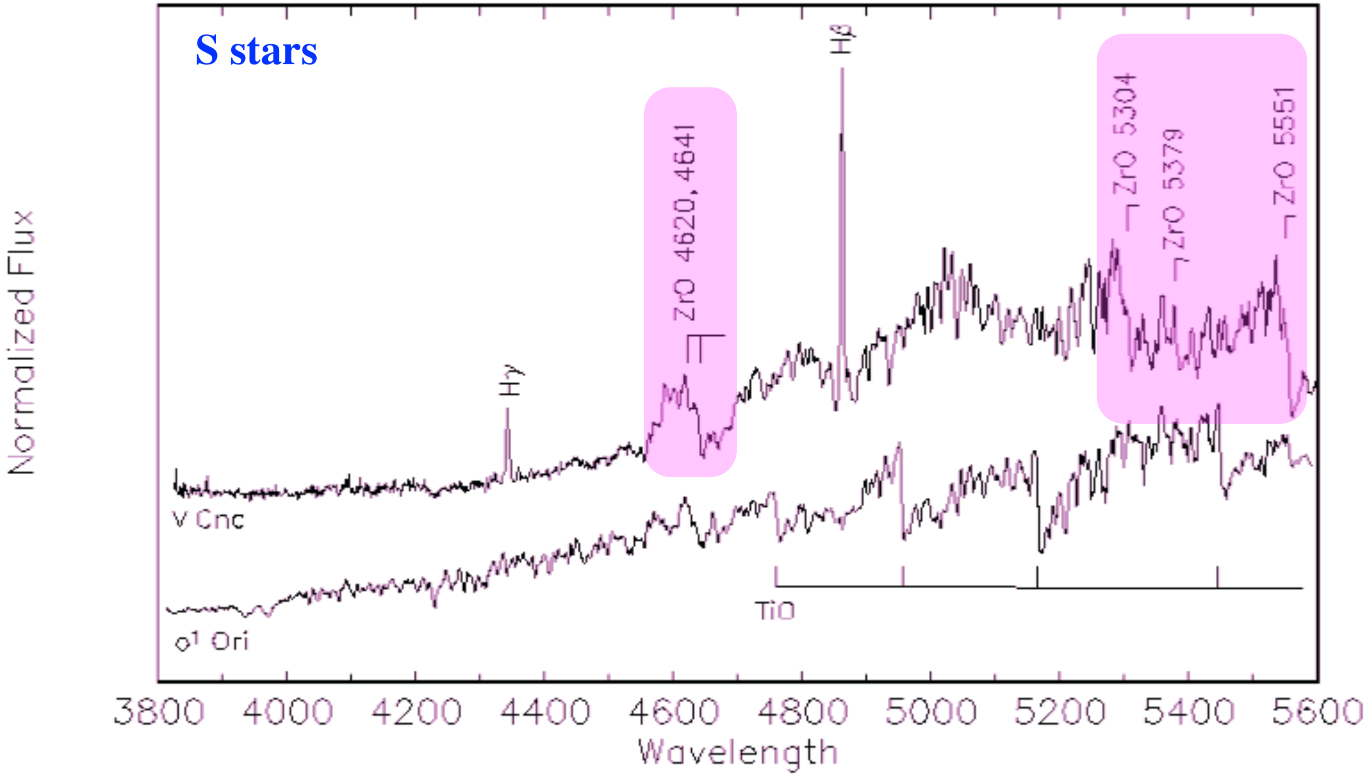
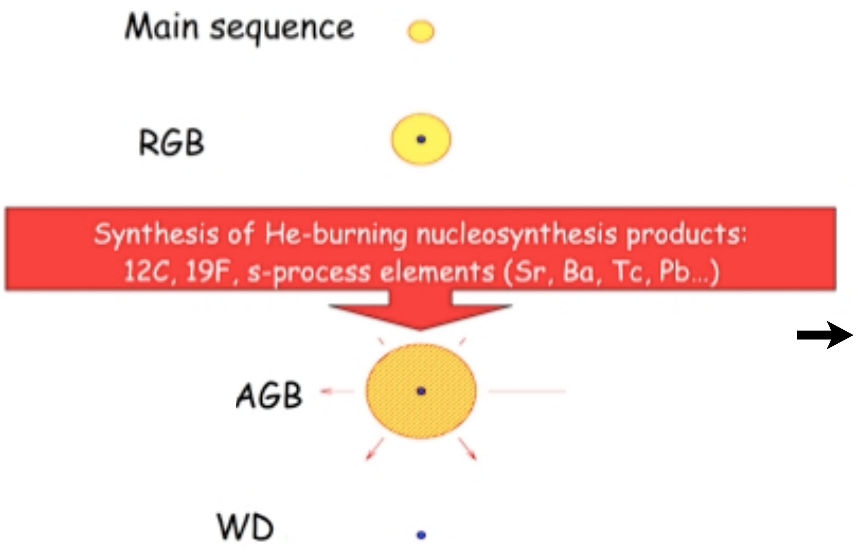




Synthesis of He-burning nucleosynthesis products:
12C, 19F, s-process elements (Sr, Ba, Tc, Pb...)

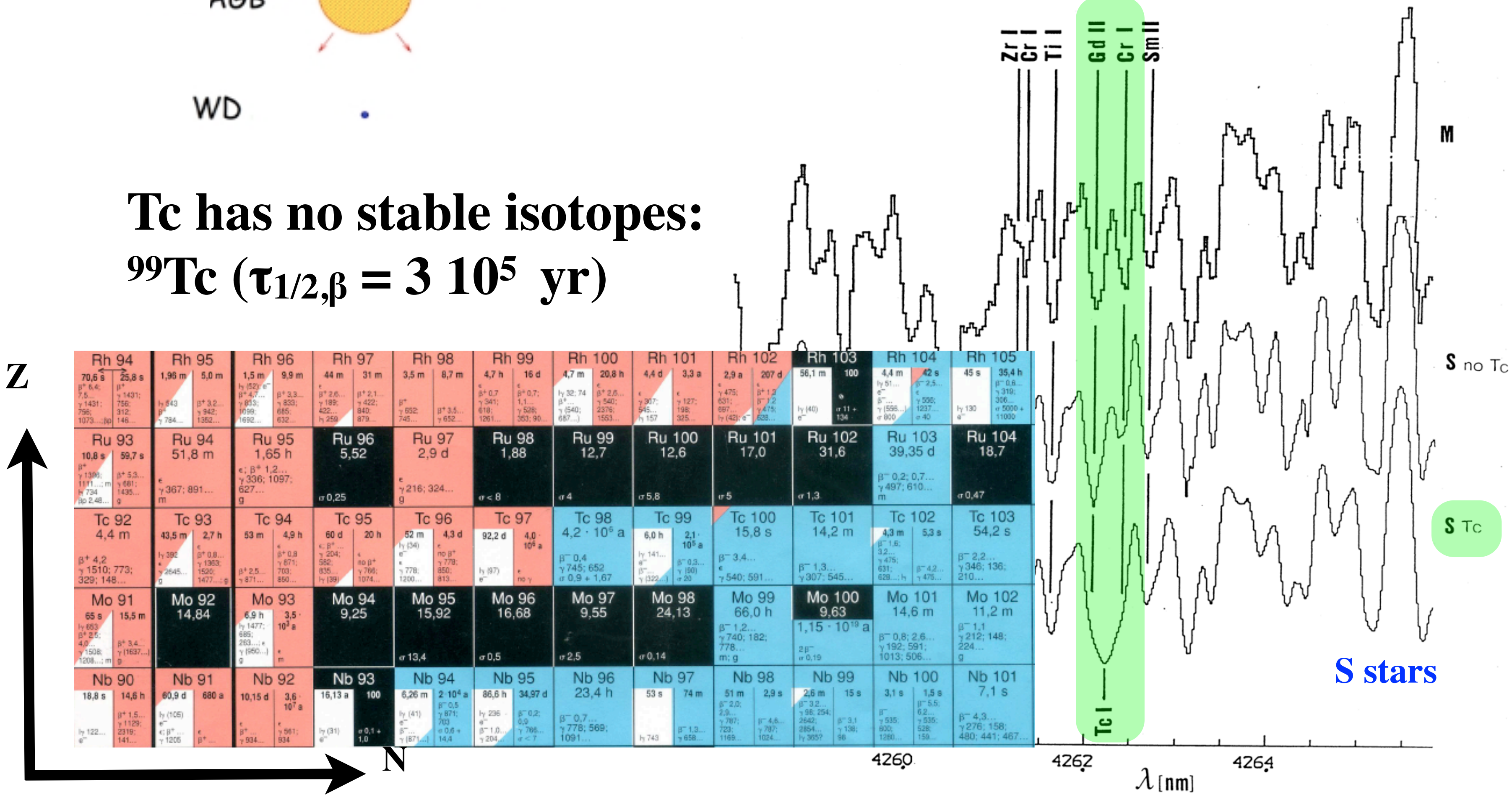
Hence AGB stars become enriched in heavy elements, e.g. Zr

For instance, S stars = AGB stars

→ ZrO bands and Tc lines in S stars

Tc has no stable isotopes:

^{99}Tc ($\tau_{1/2,\beta}$ = 3 10^5 yr)



Rh 94 70,6 s 25,8 s	Rh 95 1,96 m 5,0 m	Rh 96 1,5 m 9,9 m	Rh 97 44 m 31 m	Rh 98 3,5 m 8,7 m	Rh 99 4,7 h 16 d	Rh 100 4,7 m 20,8 h	Rh 101 4,4 d 3,3 a	Rh 102 2,9 a 207 d	Rh 103 56,1 m 100	Rh 104 4,4 m 42 s	Rh 105 45 s 35,4 h
Ru 93 10,8 s 59,7 s	Ru 94 51,8 m	Ru 95 1,65 h	Ru 96 5,52 σ 0,25	Ru 97 2,9 d	Ru 98 1,88 σ < 8	Ru 99 12,7 σ 4	Ru 100 12,6 σ 5,8	Ru 101 17,0 σ 5	Ru 102 31,6 σ 1,3	Ru 103 39,35 d	Ru 104 18,7 σ 0,47
Tc 92 4,4 m	Tc 93 43,5 m 2,7 h	Tc 94 53 m 4,9 h	Tc 95 60 d 20 h	Tc 96 52 m 4,3 d	Tc 97 92,2 d 4,0 · 10^6 a	Tc 98 4,2 · 10^6 a	Tc 99 6,0 h 2,1 · 10^5 a	Tc 100 15,8 s	Tc 101 14,2 m	Tc 102 4,3 m 5,3 s	Tc 103 54,2 s
Mo 91 65 s 15,5 m	Mo 92 14,84	Mo 93 6,9 h 3,5 · 10^3 a	Mo 94 9,25	Mo 95 15,92 σ 13,4	Mo 96 16,68 σ 0,5	Mo 97 9,55 σ 2,5	Mo 98 24,13 σ 0,14	Mo 99 66,0 h	Mo 100 9,63 1,15 · 10^{19} a	Mo 101 14,6 m	Mo 102 11,2 m
Nb 90 18,8 s 14,6 h	Nb 91 60,9 d 680 a	Nb 92 10,15 d 3,6 · 10^7 a	Nb 93 16,13 a 100	Nb 94 6,26 m 2 · 10^4 a	Nb 95 86,6 h 34,97 d	Nb 96 23,4 h	Nb 97 53 s 74 m	Nb 98 51 m 2,9 s	Nb 99 2,6 m 15 s	Nb 100 3,1 s 1,5 s	Nb 101 7,1 s

Hence AGB stars become enriched in heavy elements, e.g. Zr

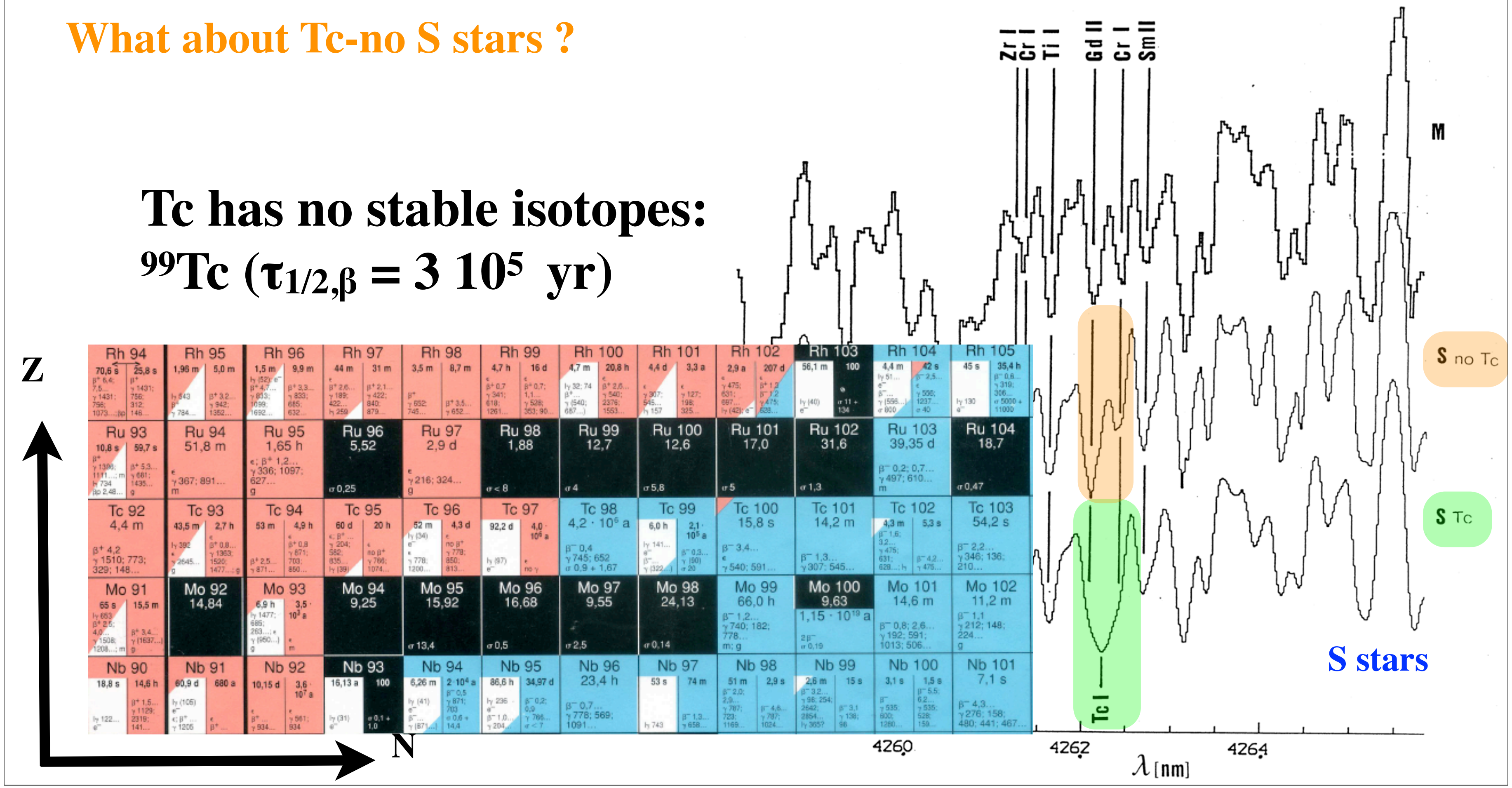
For instance, S stars = AGB stars

→ ZrO bands and Tc lines in S stars

What about Tc-no S stars ?

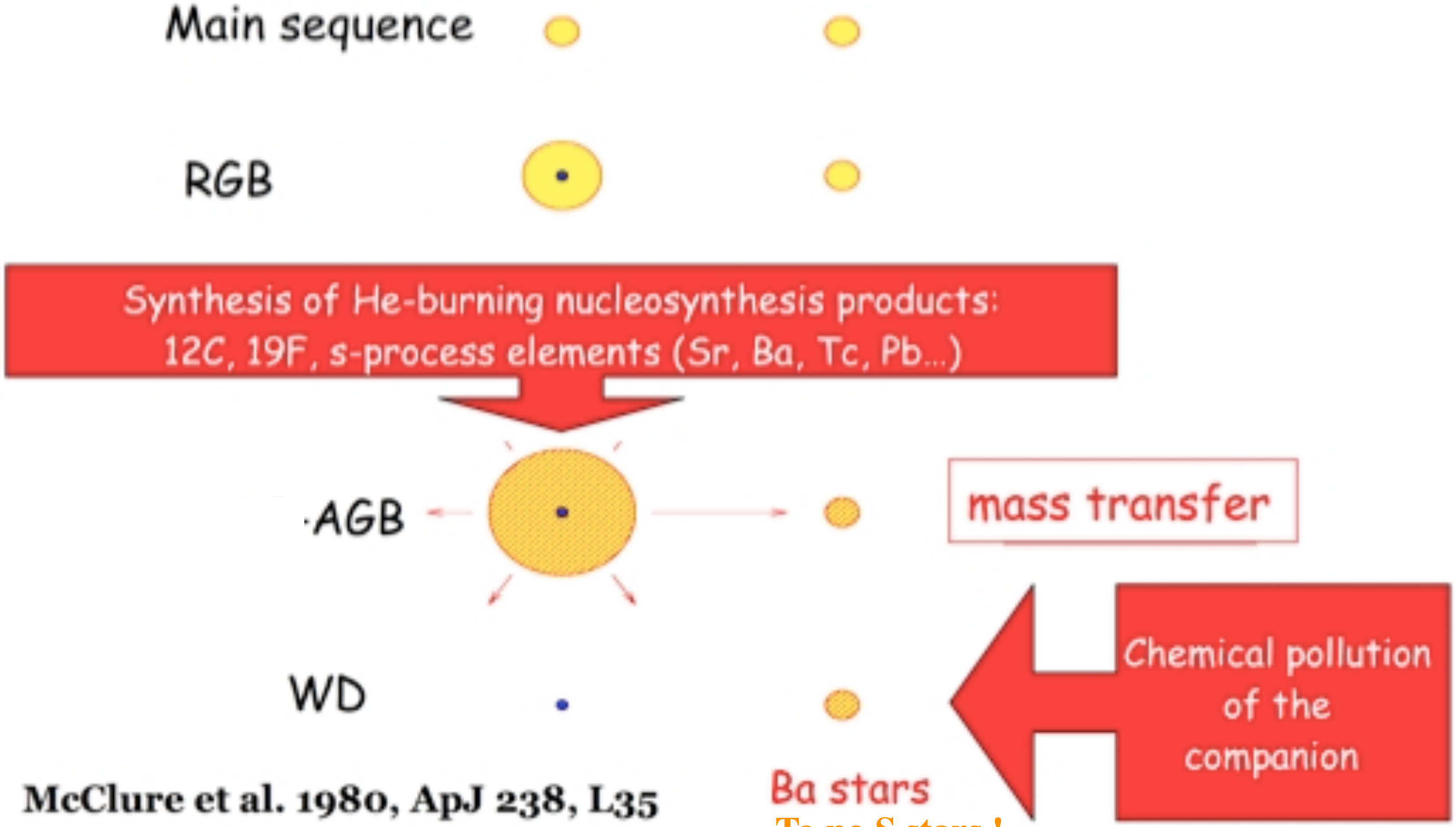
Tc has no stable isotopes:

^{99}Tc ($\tau_{1/2,\beta}$ = 3 10^5 yr)



Rh 94 70,6 s 25,8 s	Rh 95 1,96 m 5,0 m	Rh 96 1,5 m 9,9 m	Rh 97 44 m 31 m	Rh 98 3,5 m 8,7 m	Rh 99 4,7 h 16 d	Rh 100 4,7 m 20,8 h	Rh 101 4,4 d 3,3 a	Rh 102 2,9 a 207 d	Rh 103 56,1 m 100	Rh 104 4,4 m 42 s	Rh 105 45 s 35,4 h
Ru 93 10,8 s 59,7 s	Ru 94 51,8 m	Ru 95 1,65 h	Ru 96 5,52	Ru 97 2,9 d	Ru 98 1,88	Ru 99 12,7	Ru 100 12,6	Ru 101 17,0	Ru 102 31,6	Ru 103 39,35 d	Ru 104 18,7
Tc 92 4,4 m	Tc 93 43,5 m 2,7 h	Tc 94 53 m 4,9 h	Tc 95 60 d 20 h	Tc 96 52 m 4,3 d	Tc 97 92,2 d 4,0 · 10^6 a	Tc 98 4,2 · 10^5 a	Tc 99 6,0 h 2,1 · 10^5 a	Tc 100 15,8 s	Tc 101 14,2 m	Tc 102 4,3 m 5,3 s	Tc 103 54,2 s
Mo 91 65 s 15,5 m	Mo 92 14,84	Mo 93 6,9 h 3,5 · 10^3 a	Mo 94 9,25	Mo 95 15,92	Mo 96 16,68	Mo 97 9,55	Mo 98 24,13	Mo 99 66,0 h	Mo 100 9,63 1,15 · 10^{19} a	Mo 101 14,6 m	Mo 102 11,2 m
Nb 90 18,8 s 14,6 h	Nb 91 60,9 d 680 a	Nb 92 10,15 d 3,6 · 10^7 a	Nb 93 16,13 a 100	Nb 94 6,26 m 2 · 10^4 a	Nb 95 86,6 h 34,97 d	Nb 96 23,4 h	Nb 97 53 s 74 m	Nb 98 51 m 2,9 s	Nb 99 2,6 m 15 s	Nb 100 3,1 s 1,5 s	Nb 101 7,1 s

Tc-no S stars are all binaries!



Tc-no S stars !

McClure et al. 1980, ApJ 238, L35

The binary zoo

Classification of binary stars:

i) Mass transfer
ii) Observational properties
iii)Evolutionary stage

A given binary has a location in each 3 classification schemes; however, often its classification is only known in 1 or 2 schemes:

Knowing the location of a binary (family) in all 3 schemes often is the goal of binary-star research !

Nice achievements in that respect have just been discussed :
Post-AGB stars (KULeuven !)
Barium and Tc-no S stars (ULB !)

Knowing the location of a binary (family) in all 3 schemes often is the goal of binary-star research !

Often a very difficult problem...

To help this process, a complex classification scheme merging schemes *i* (D/S/C) and *iii* (Evol.) has been proposed by P. Eggleton

(Evolutionary Processes in Binary and Multiple Stars, Cambridge Univ. Press, 2001):

Knowing the location of a binary (family) in all 3 schemes often is the goal of binary-star research !

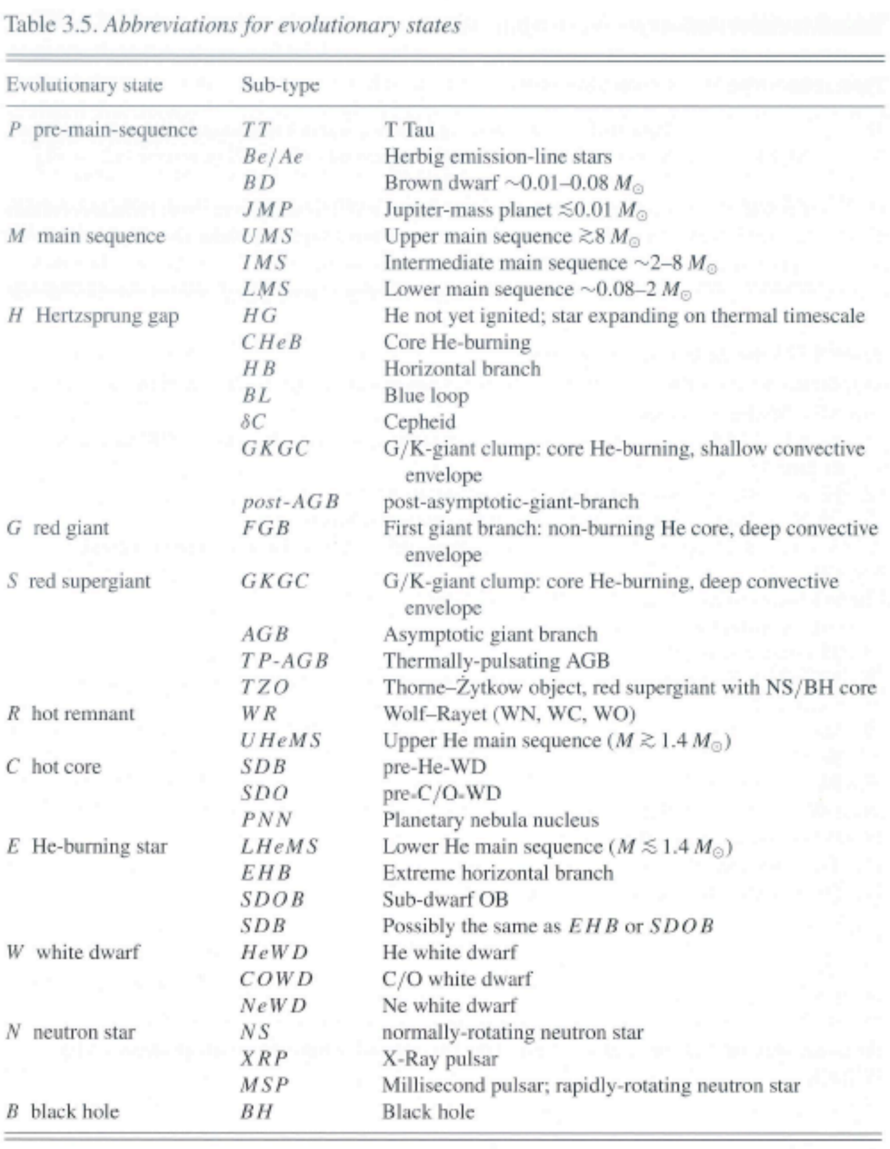


Table 3.5. *Abbreviations for evolutionary states*

Evolutionary state	Sub-type	
P pre-main-sequence	*TT*	T Tau
	Be/Ae	Herbig emission-line stars
	BD	Brown dwarf ~0.01–0.08 $M_\odot$
	JMP	Jupiter-mass planet $\lesssim$0.01 $M_\odot$
M main sequence	*UMS*	Upper main sequence $\gtrsim$8 $M_\odot$
	IMS	Intermediate main sequence ~2–8 $M_\odot$
	LMS	Lower main sequence ~0.08–2 $M_\odot$
H Hertzsprung gap	*HG*	He not yet ignited; star expanding on thermal timescale
	CHeB	Core He-burning
	HB	Horizontal branch
	BL	Blue loop
	δC	Cepheid
	GKGC	G/K-giant clump: core He-burning, shallow convective envelope
	post-AGB	post-asymptotic-giant-branch
G red giant	*FGB*	First giant branch: non-burning He core, deep convective envelope
S red supergiant	*GKGC*	G/K-giant clump: core He-burning, deep convective envelope
	AGB	Asymptotic giant branch
	TP-AGB	Thermally-pulsating AGB
	TZO	Thorne–Żytkow object, red supergiant with NS/BH core
R hot remnant	*WR*	Wolf–Rayet (WN, WC, WO)
	UHeMS	Upper He main sequence ($M \gtrsim 1.4\ M_\odot$)
C hot core	*SDB*	pre-He-WD
	SDO	pre-C/O-WD
	PNN	Planetary nebula nucleus
E He-burning star	*LHeMS*	Lower He main sequence ($M \lesssim 1.4\ M_\odot$)
	EHB	Extreme horizontal branch
	SDOB	Sub-dwarf OB
	SDB	Possibly the same as *EHB* or *SDOB*
W white dwarf	*HeWD*	He white dwarf
	COWD	C/O white dwarf
	NeWD	Ne white dwarf
N neutron star	*NS*	normally-rotating neutron star
	XRP	X-Ray pulsar
	MSP	Millisecond pulsar; rapidly-rotating neutron star
B black hole	*BH*	Black hole

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Knowing the location of a binary (family) in all 3 schemes often is the goal of binary-star research !

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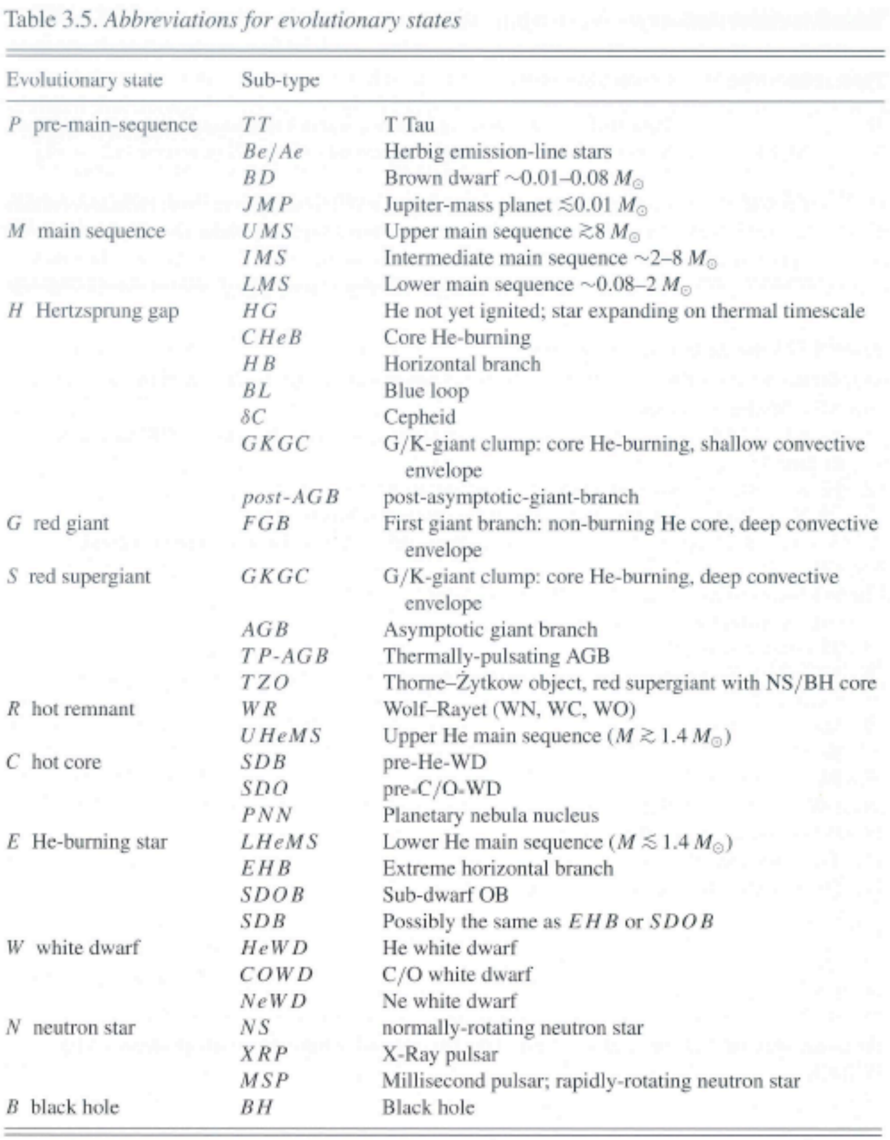

Table 3.5. *Abbreviations for evolutionary states*

Evolutionary state	Sub-type	
P pre-main-sequence	*TT*	T Tau
	Be/*Ae*	Herbig emission-line stars
	BD	Brown dwarf ~0.01–0.08 $M_\odot$
	JMP	Jupiter-mass planet $\lesssim$0.01 $M_\odot$
M main sequence	*UMS*	Upper main sequence $\gtrsim$8 $M_\odot$
	IMS	Intermediate main sequence ~2–8 $M_\odot$
	LMS	Lower main sequence ~0.08–2 $M_\odot$
H Hertzsprung gap	*HG*	He not yet ignited; star expanding on thermal timescale
	CHeB	Core He-burning
	HB	Horizontal branch
	BL	Blue loop
	δC	Cepheid
	GKGC	G/K-giant clump: core He-burning, shallow convective envelope
	post-AGB	post-asymptotic-giant-branch
G red giant	*FGB*	First giant branch: non-burning He core, deep convective envelope
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R hot remnant	*WR*	Wolf–Rayet (WN, WC, WO)
	UHeMS	Upper He main sequence ($M \gtrsim 1.4\,M_\odot$)
C hot core	*SDB*	pre-He-WD
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	PNN	Planetary nebula nucleus
E He-burning star	*LHeMS*	Lower He main sequence ($M \lesssim 1.4\,M_\odot$)
	EHB	Extreme horizontal branch
	SDOB	Sub-dwarf OB
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W white dwarf	*HeWD*	He white dwarf
	COWD	C/O white dwarf
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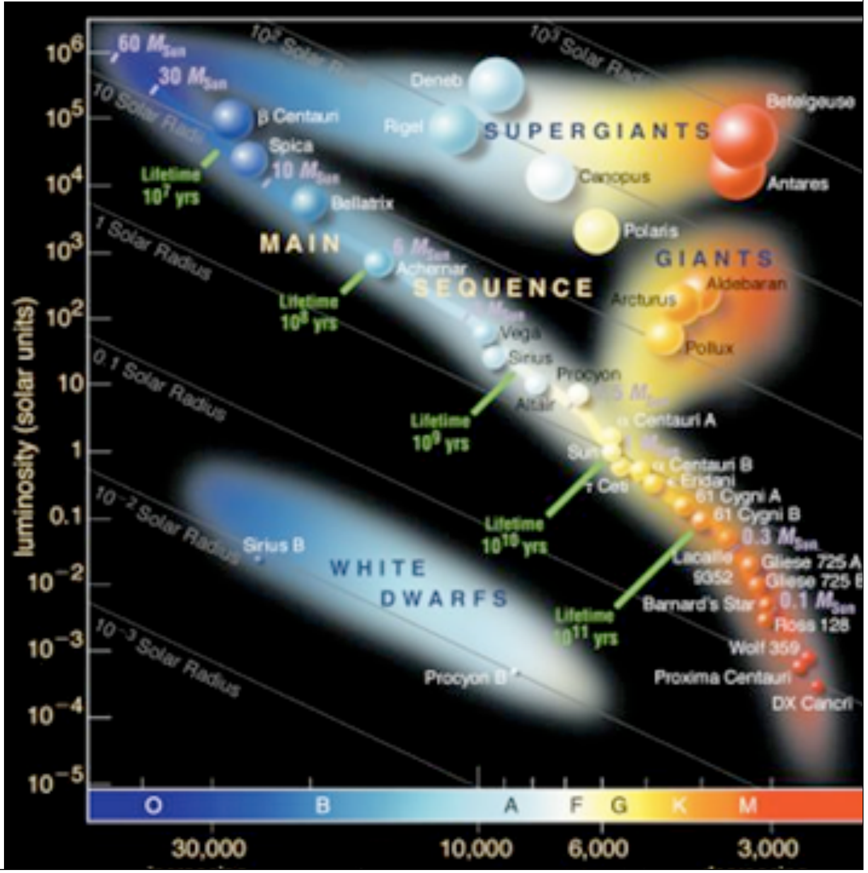

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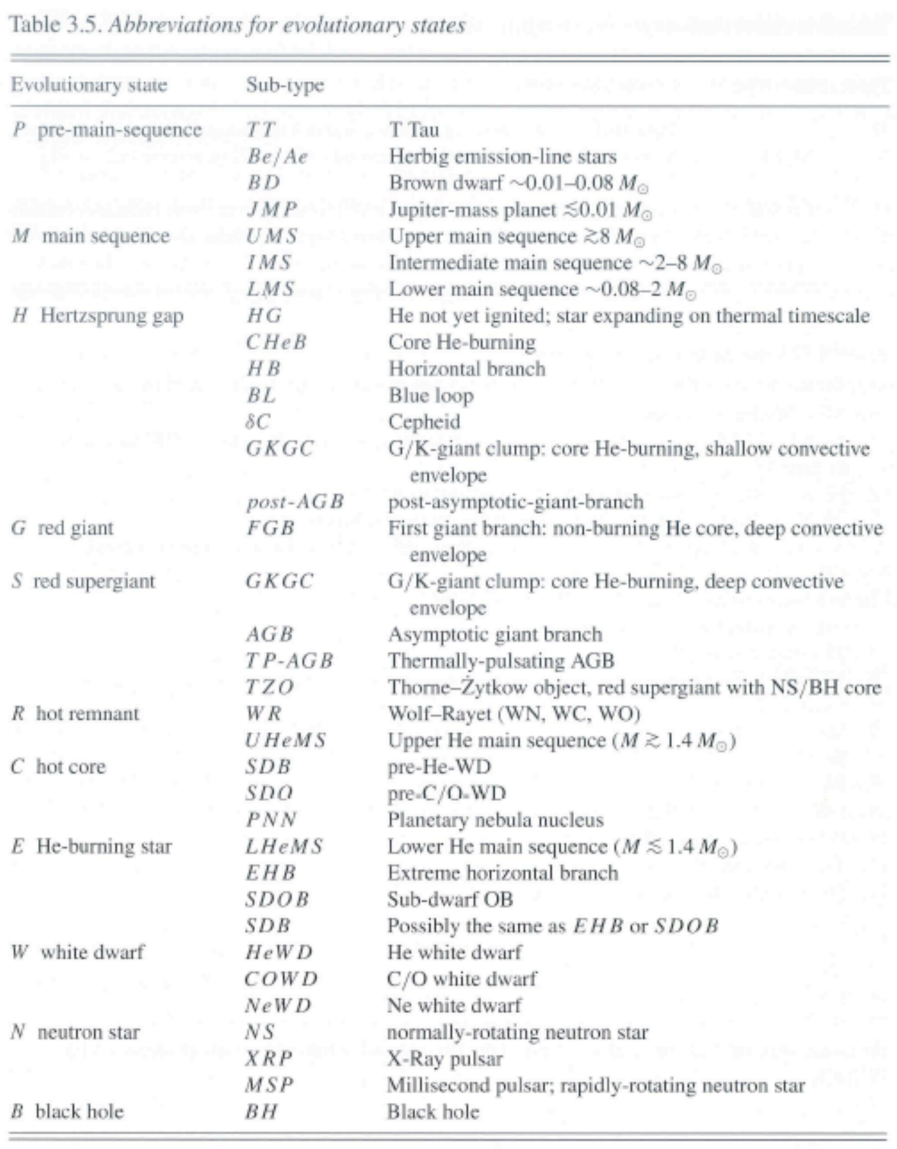

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Then, a given evolutionary path will

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- a mass-transfer mode [→ Siess]

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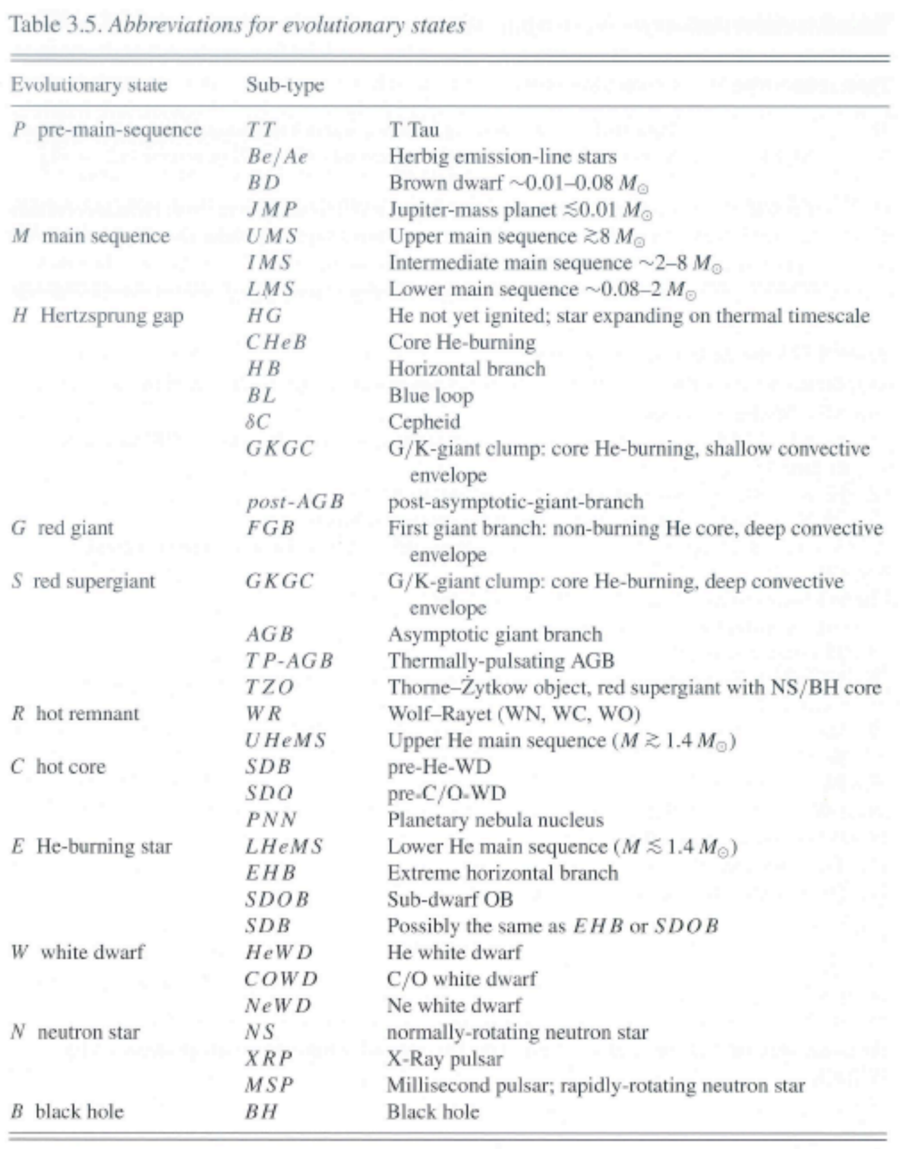

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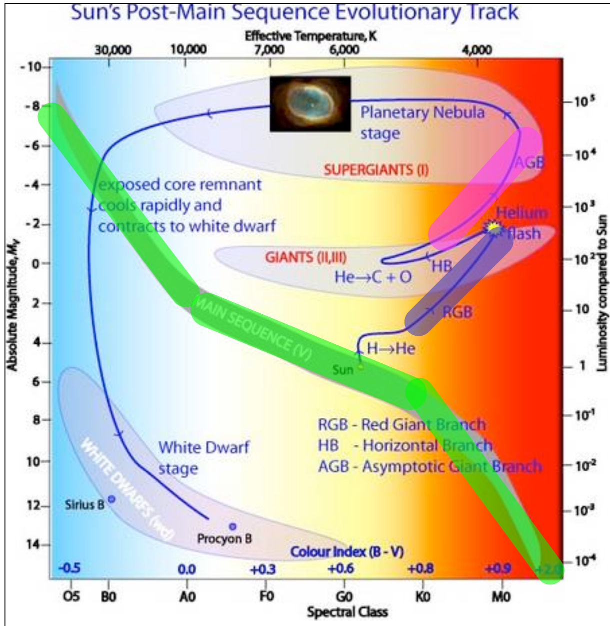
Example:

case AD = case A with Dynamic RLOF:

MMD → MMS → (M → H → G→ W)MC



Mass-transfer modes : cases A, B and C

case A = RLOF during main sequence

case B = RLOF during first giant branch

case C = RLOF during asymptotic giant branch

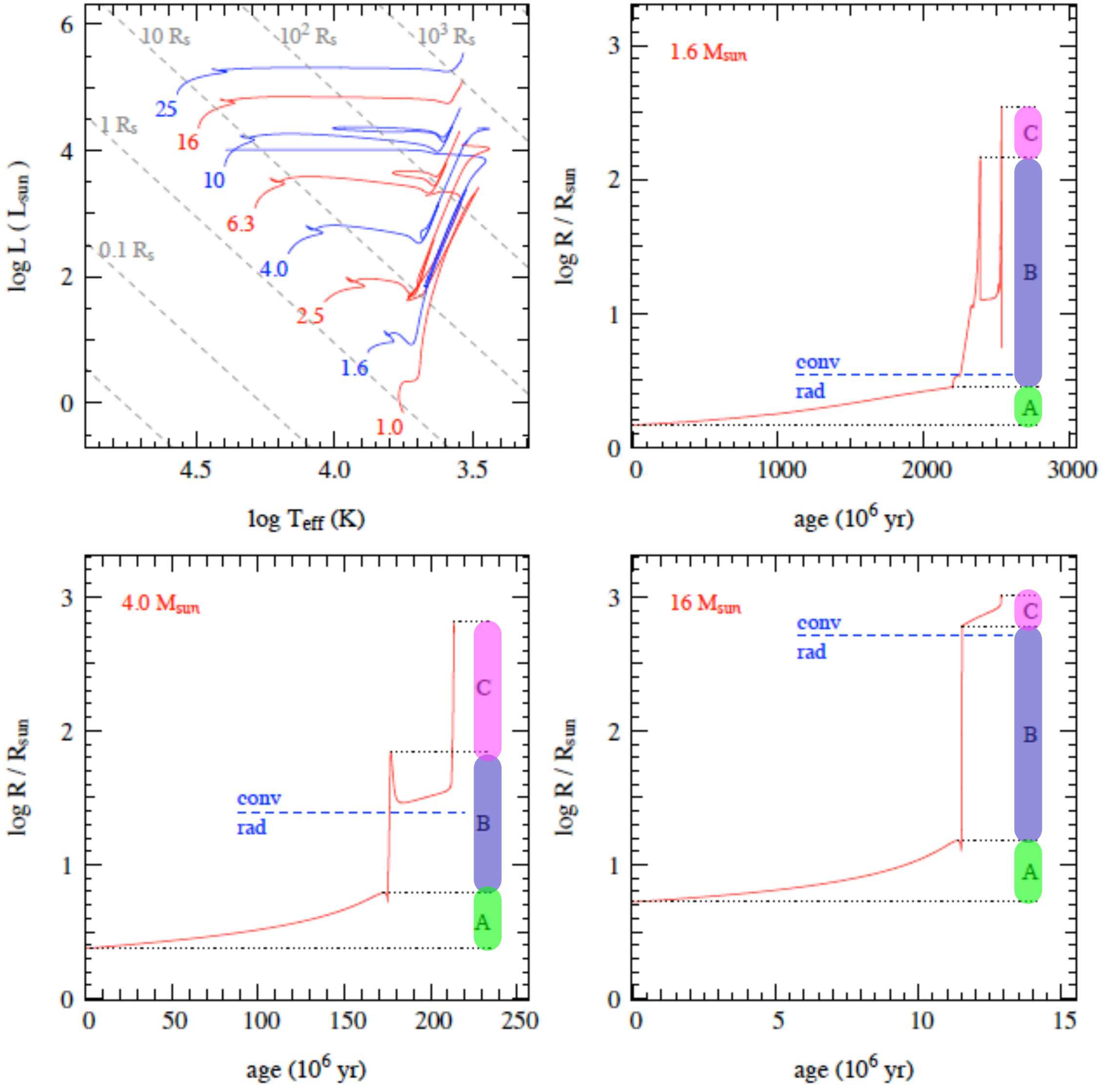


Figure 6.2. Evolution in the H-R diagram (panel a) of single stars with masses between 1.0 and 25 $M_\odot$, as indicated, together with lines of constant radii (in solar radii, dashed lines). The other panels show the variation of the radii of stars of (b) 1.6 $M_\odot$, (c) 4 $M_\odot$ and (d) 16 $M_\odot$ between the ZAMS and either the end of the AGB (1.6 and 4 $M_\odot$) or carbon burning (16 $M_\odot$). The models have been calculated for a metallicity $Z = 0.02$ and a moderate amount of overshooting. The dotted lines indicate the radii at the ZAMS, the end of the MS, the ignition of He, and the maximum radius. The dashed blue line shows the radius at which the stars develop a deep convective envelope on the giant branch.

[From O. Pols]

Then, a given evolutionary path will be characterized by :

- a mass-transfer mode

simplest ‘case A..’, ‘B..’, ‘C..’

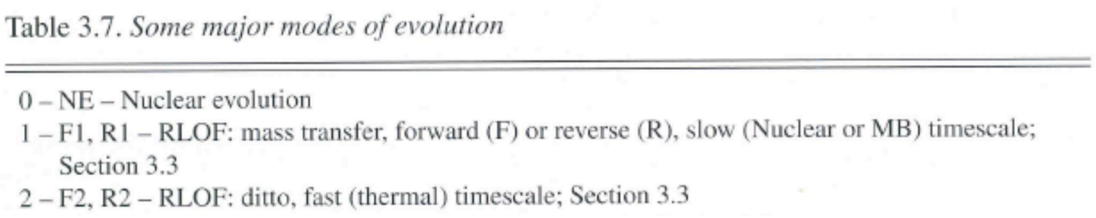


Table 3.7. *Some major modes of evolution*

0 – NE – Nuclear evolution
1 – F1, R1 – RLOF: mass transfer, forward (F) or reverse (R), slow (Nuclear or MB) timescale; Section 3.3
2 – F2, R2 – RLOF: ditto, fast (thermal) timescale; Section 3.3

} cases A, B, or C

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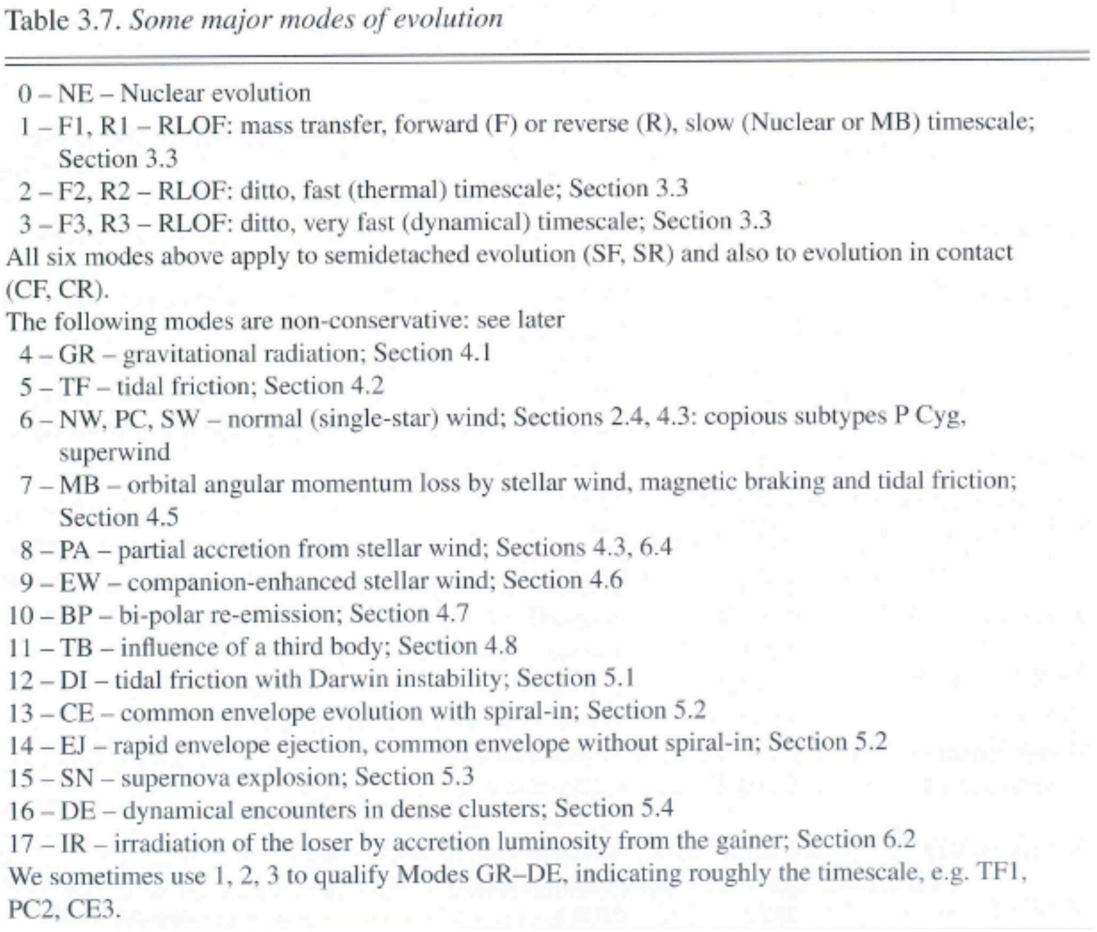
simplest 'case A..', 'B..', 'C..'

But the full picture is generally much more complex:



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1 – F1, R1 – RLOF: mass transfer, forward (F) or reverse (R), slow (Nuclear or MB) timescale; Section 3.3
2 – F2, R2 – RLOF: ditto, fast (thermal) timescale; Section 3.3
3 – F3, R3 – RLOF: ditto, very fast (dynamical) timescale; Section 3.3

} cases A, B, or C

All six modes above apply to semidetached evolution (SF, SR) and also to evolution in contact (CF, CR).

The following modes are non-conservative: see later

4 – GR – gravitational radiation; Section 4.1
5 – TF – tidal friction; Section 4.2
6 – NW, PC, SW – normal (single-star) wind; Sections 2.4, 4.3: copious subtypes P Cyg, superwind
7 – MB – orbital angular momentum loss by stellar wind, magnetic braking and tidal friction; Section 4.5
8 – PA – partial accretion from stellar wind; Sections 4.3, 6.4
9 – EW – companion-enhanced stellar wind; Section 4.6
10 – BP – bi-polar re-emission; Section 4.7
11 – TB – influence of a third body; Section 4.8
12 – DI – tidal friction with Darwin instability; Section 5.1
13 – CE – common envelope evolution with spiral-in; Section 5.2
14 – EJ – rapid envelope ejection, common envelope without spiral-in; Section 5.2
15 – SN – supernova explosion; Section 5.3
16 – DE – dynamical encounters in dense clusters; Section 5.4
17 – IR – irradiation of the loser by accretion luminosity from the gainer; Section 6.2

We sometimes use 1, 2, 3 to qualify Modes GR–DE, indicating roughly the timescale, e.g. TF1, PC2, CE3.

18 - ID - Interaction with circumbinary disc

Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer/interaction processes

Then, a given evolutionary path will be characterized by :

- a mass-transfer mode

simplest ‘case A..’, ‘B..’, ‘C..’

But the full picture is generally much more complex.

Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

because they rule the evolution of orbital elements [→ Siess] :

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Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

because they rule the evolution of orbital elements [→ Siess]:

$$\dot{a} = f_a(a, e, M, \dot{M})$$

$$\dot{P} = f_P(a, e, M, \dot{M})$$

$$\dot{e} = f_e(a, e, M, \dot{M})$$

$$\dot{M} = f_M(a, e, M)$$

$$\frac{a^3}{P^2} = M = M_1 + M_2$$

Canonical binary evolution

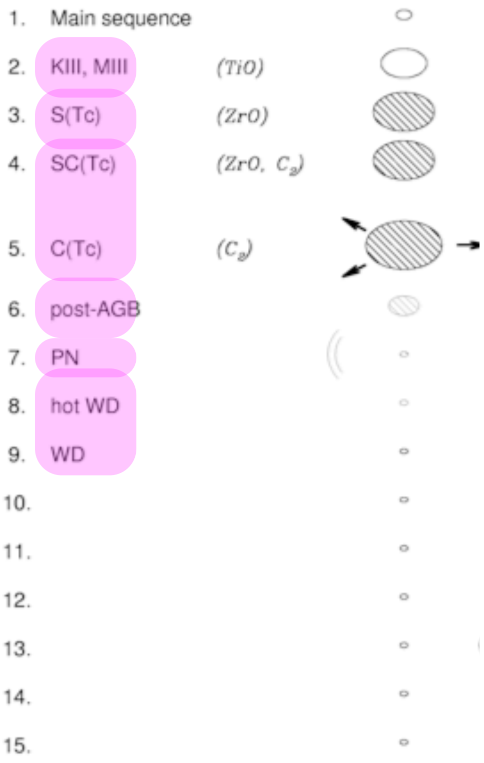
- Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS 329, 897

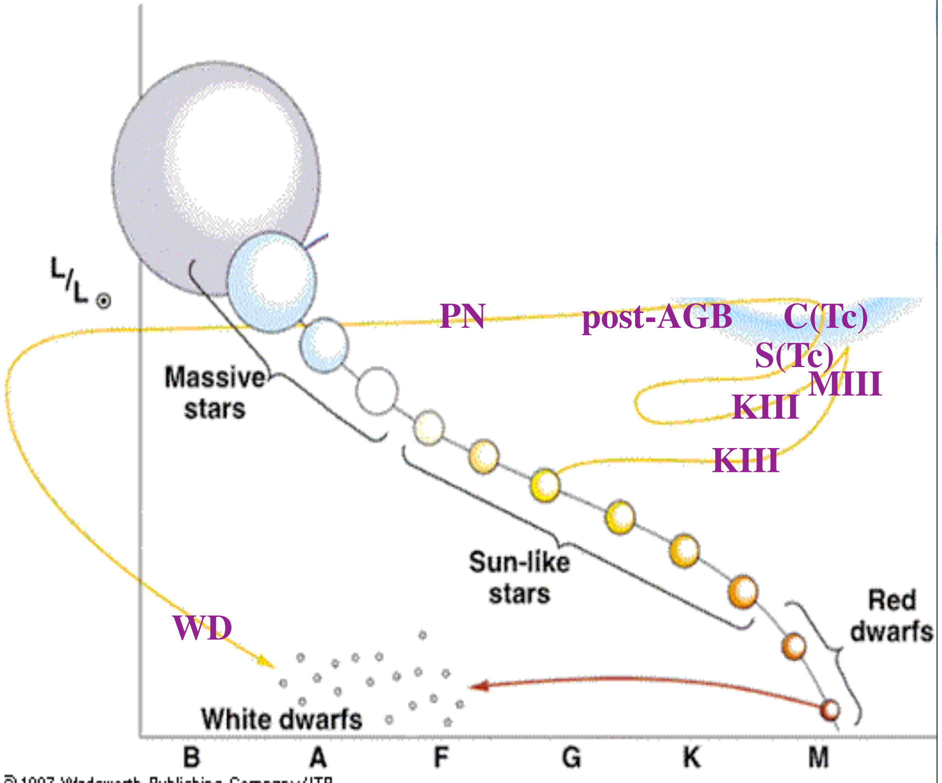
- P. Eggleton, Evolutionary Processes in Binary and Multiple Stars, Cambridge Univ. Press, 2001

Hence, from a_0, P_0, e_0, M_0, and these equations, it is possible to derive (e, P) for the current value of M.

Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

For example:





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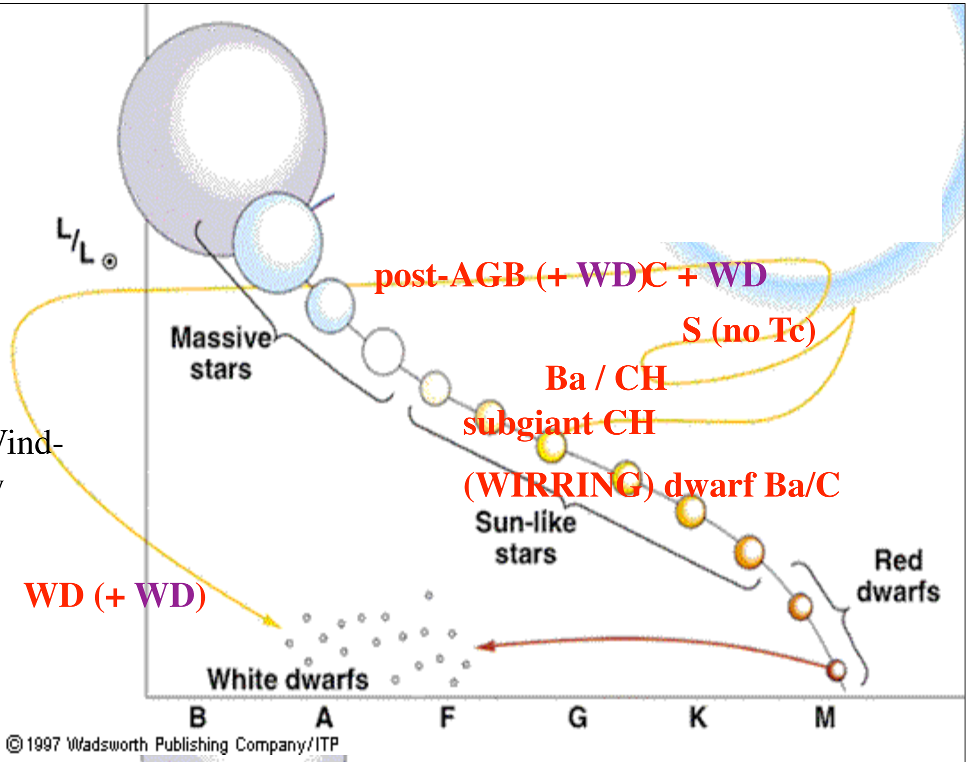
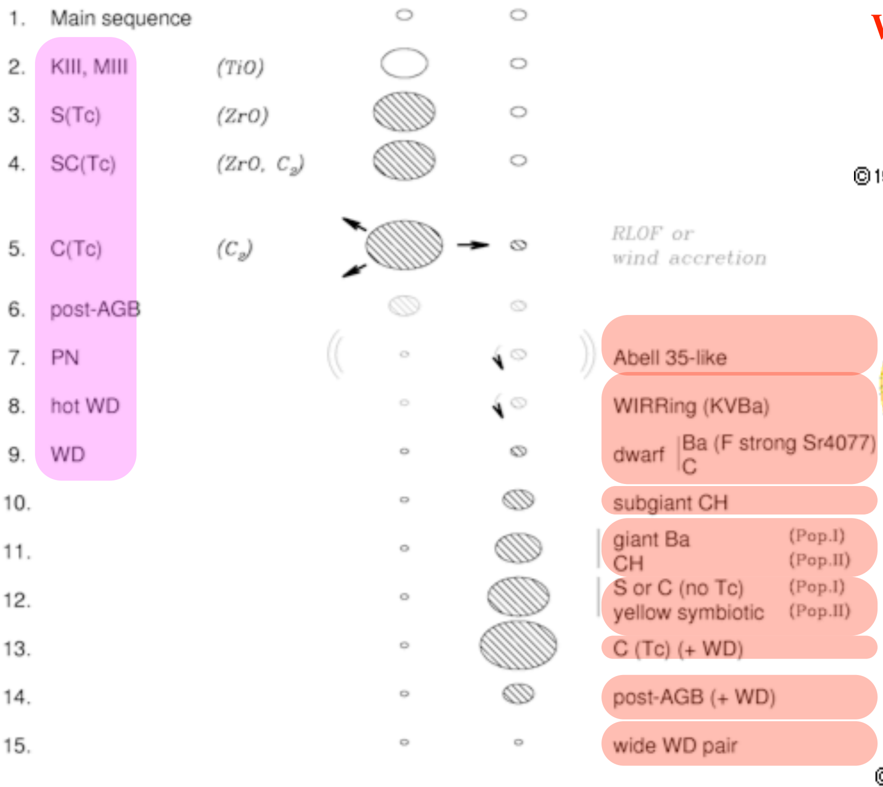
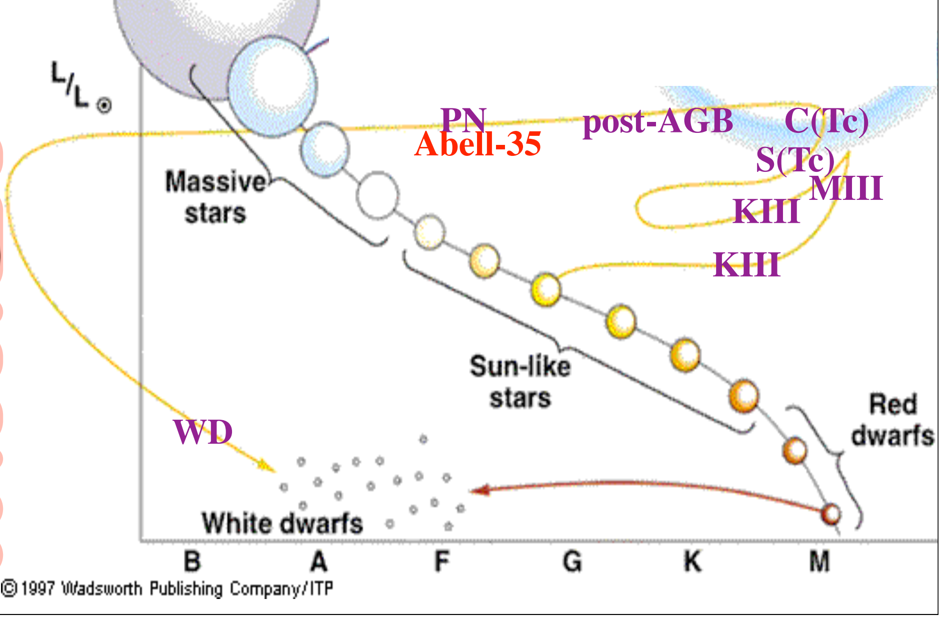
Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

For example:

WIRRING = ‘Wind-Induced Rapidly RotatING’





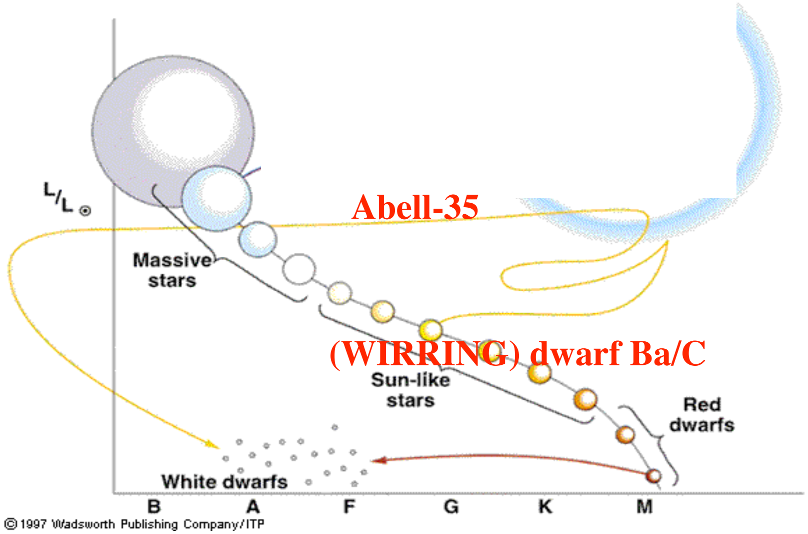


1. About the possibility to accrete spin angular momentum in detached binaries

A hot debate...

From observations of rapidly-rotating post-mass-transfer stars *(in detached binaries?):* *YES*

WIRRING (KVBa) stars
Abell-35-like nuclei of PNs

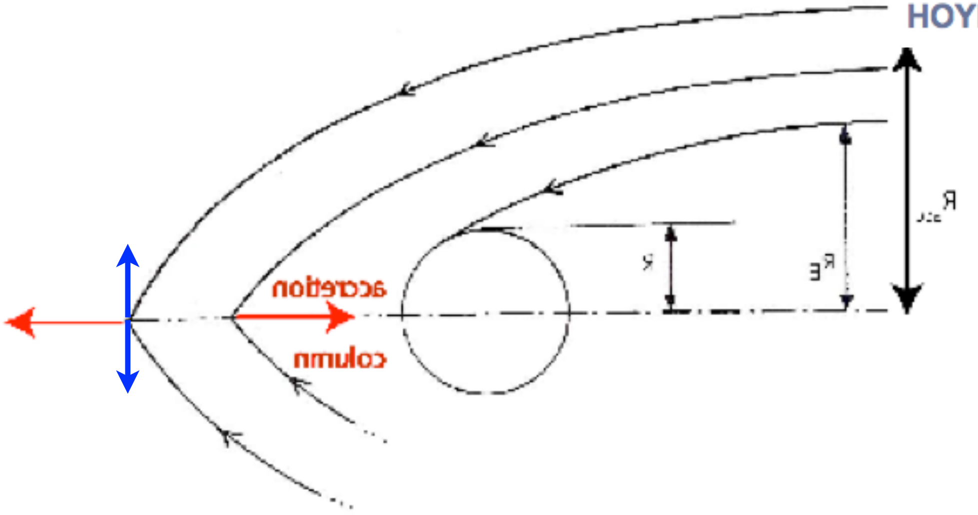


About the possibility to accrete spin angular momentum in detached binaries:

A hot debate...

From theory of Hoyle-Lyttleton flows: *NO*

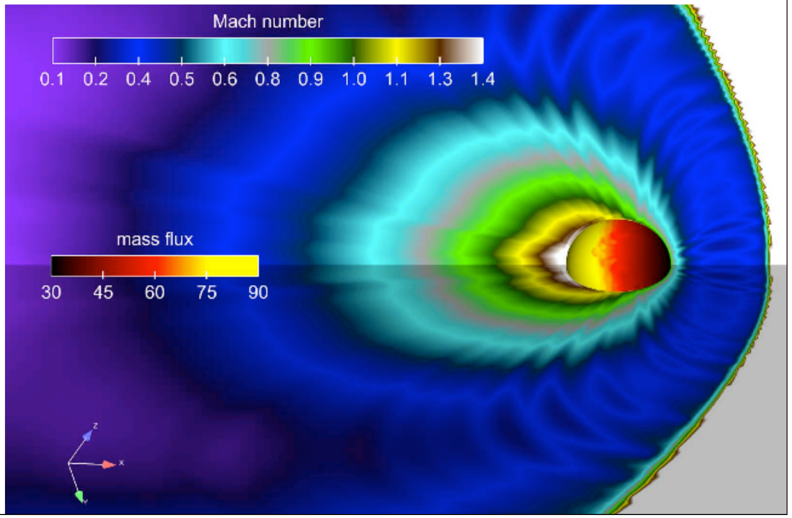
The flow is axisymmetric, which kills any transverse velocity component

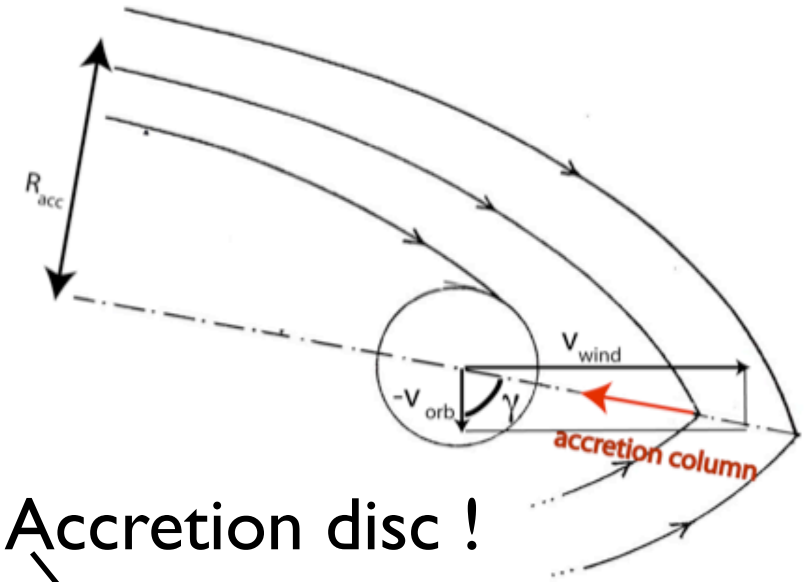


The Astrophysical Journal > Volume 752 > Number 1

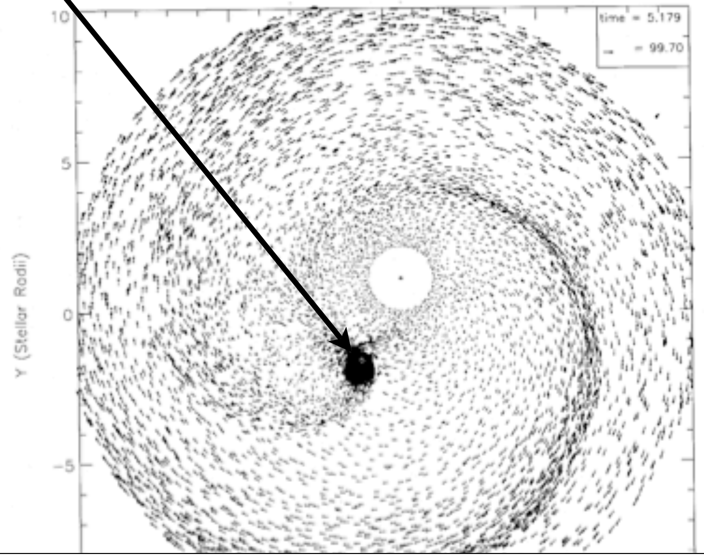
John M. Blondin and Eric Raymer 2012 *ApJ* **752** 30 doi:10.1088/0004-637X/752/1/30

HOYLE-LYTTLETON ACCRETION IN THREE DIMENSIONS





Accretion disc !



- Fast winds (binaries with OB stars):
  $k \equiv v_{\rm orb}/v_{\rm wind} << 1$

Accretion column, tilted by an angle $\gamma = \arctan v_{\rm wind}/v_{\rm orb}$ with respect to the orbital motion, with matter falling onto the compact star from its rear side (as viewed from the mass-losing star) with a rate $\dot{M}_{B-H}$

- Slow winds (detached binary systems involving an AGB star):
  $k \equiv v_{\rm orb}/v_\infty >> 1$

Accretion column distorted by Coriolis effect, must be investigated numerically.
Accretion rates $\lesssim 0.1\,\dot{M}_{\rm B-H}$

Theuns & Jorissen 1993, MNRAS 265, 946
Mastrodemos & Morris 1998, ApJ 497, 303
Folini & Walder 2000, Ap&SS 274, 189
Nagae et al. 2004, A&A 419, 335
Jahanara et al., 2005, A&A 441, 589

Wind may be increased by tidal forces

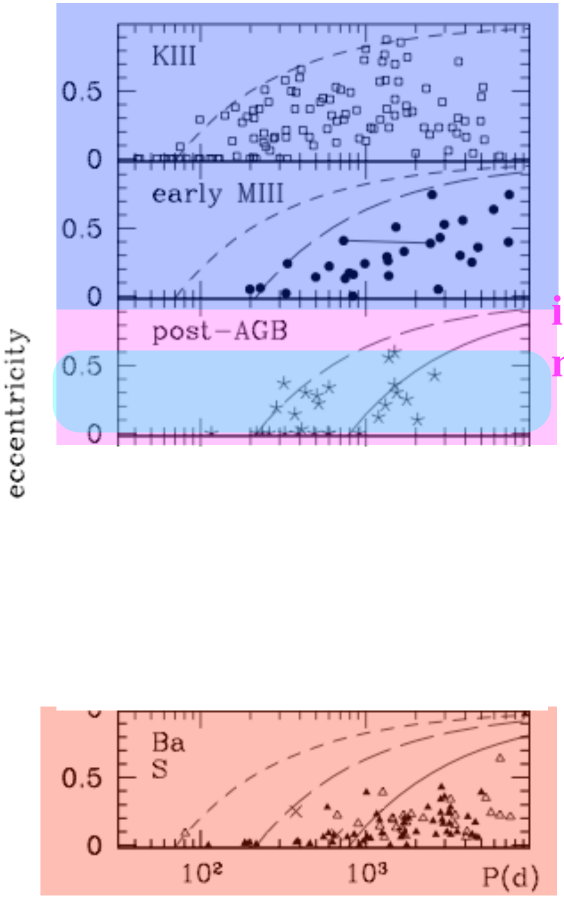
Tout & Eggleton 1988, MNRAS 231, 823
Frankowski & Tylenda 2001, A&A 367, 513

Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

For example:

A compilation of (e – log P) diagrams for several classes of pre- and post-mass-transfer binaries:

Jorissen et al., 2009, A&A 498, 489



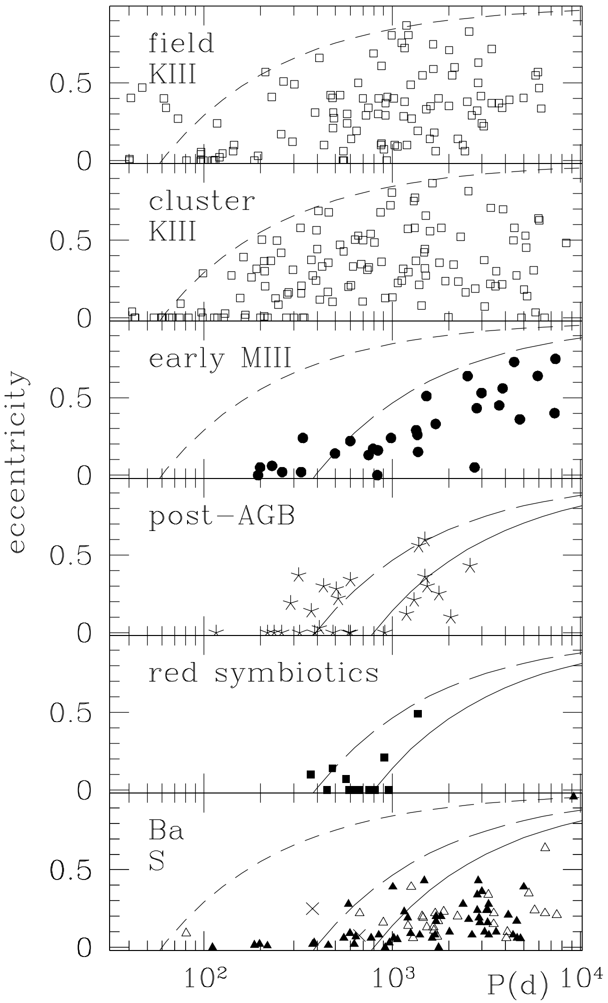
initial

inter-
mediate

+ final ?

final

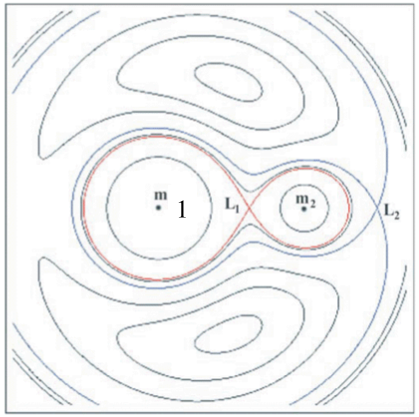
About the RLOF threshold in binaries



$$R_{R,2} = a\,(0.38 + 0.2 \log q) \qquad \text{for } 0.5 \le q = \frac{M_2}{M_1} \le 20$$

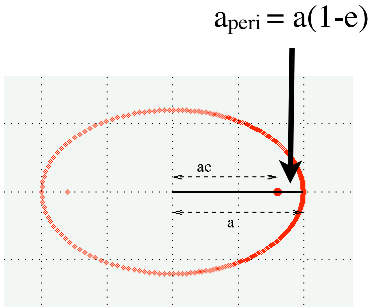
$$r(M_1 \text{to } L_1) = a\,(0.50 + 0.227 \log q)$$

$$r(M_2 \text{to } L_1) = a\,(0.50 - 0.227 \log q)$$



$$r(M_1 \text{to } L_1) = a_{\text{peri}} \qquad (0.50 + 0.227 \log q)$$

$$= a(1-e)\,(0.50 + 0.227 \log q)$$

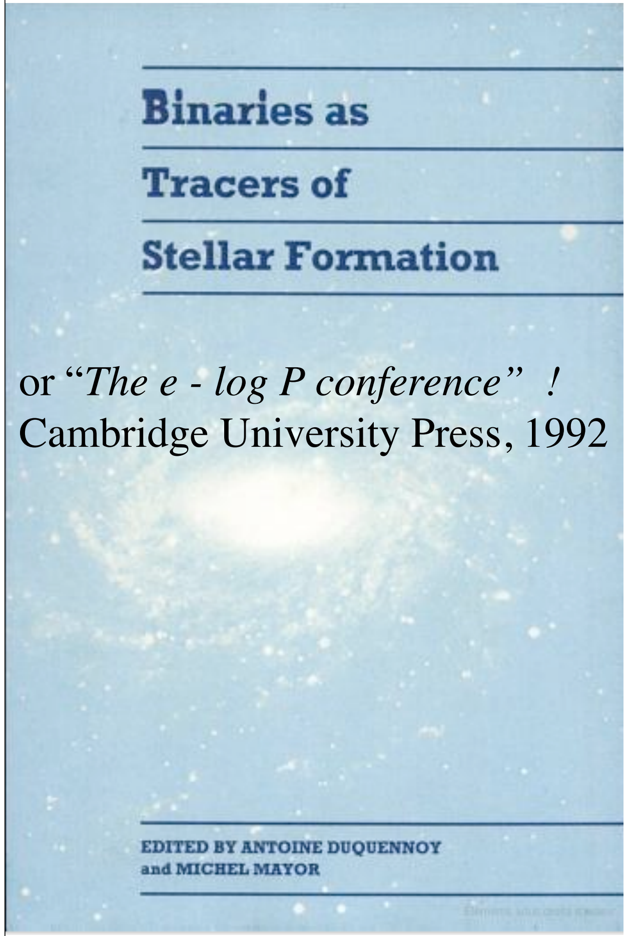


Fix the threshold by stating that *r(M₁ to L₁)* = R* :

$$R_* = a(1-e)\,(0.50 + 0.227 \log q) \quad \text{where } a^3 = P^2(M_1 + M_2)$$

$$\text{so } R_* = P^{2/3}(M_1 + M_2)^{1/3}(1-e)\,(0.50 + 0.227 \log q)$$

About the “avoidance zone” in pre-mass-transfer, non-circularized binaries



Binaries as
Tracers of
Stellar Formation

EDITED BY ANTOINE DUQUENNOY
and MICHEL MAYOR

or “*The e - log P conference*” !
Cambridge University Press, 1992

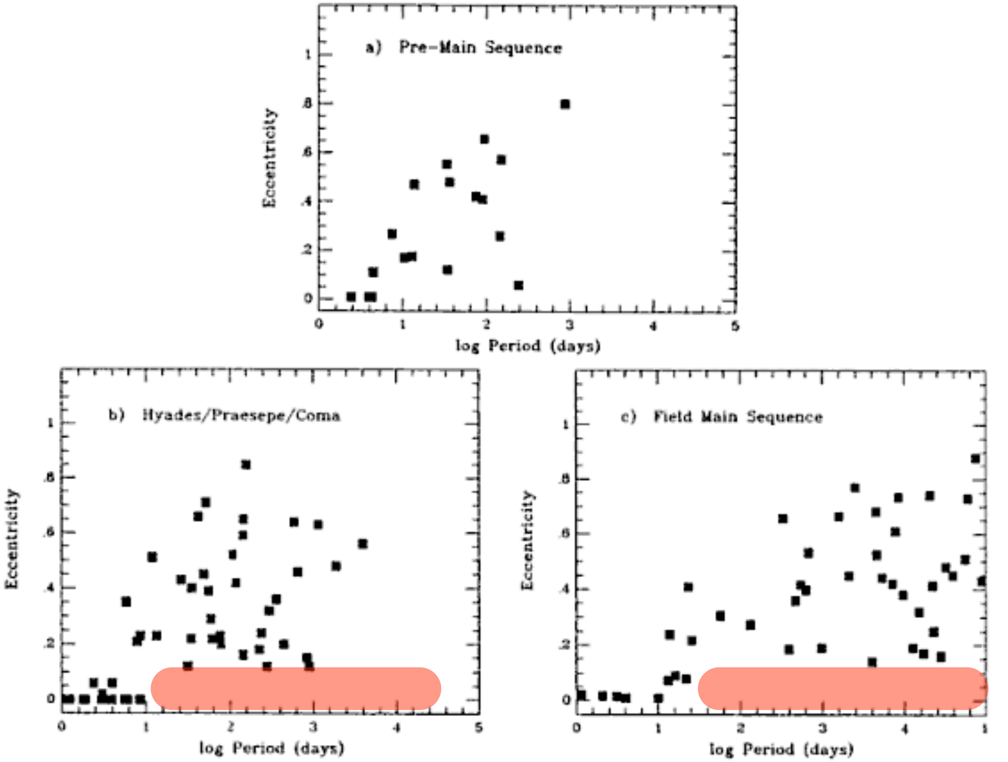
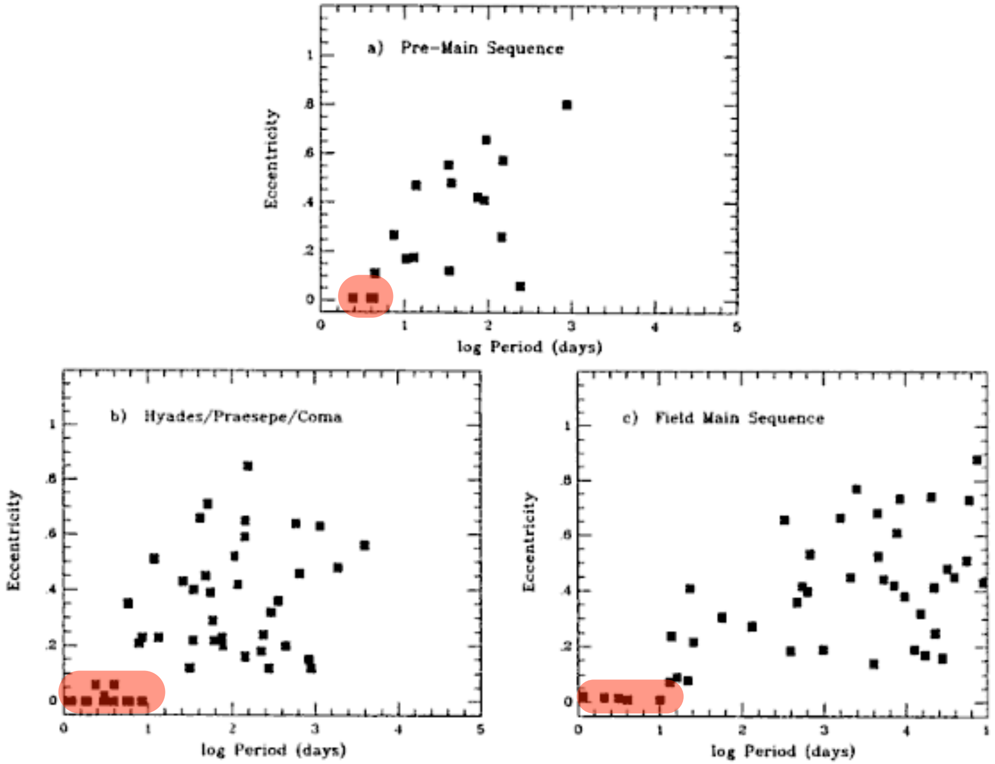


Figure 1. The period-eccentricity distribution for a) pre-main sequence binaries, b) main-sequence solar-mass binaries in the Hyades, Praesepe and Coma clusters [DMM92] and c) main-sequence solar-mass binaries in the field [DuM91].

About tidal circularization



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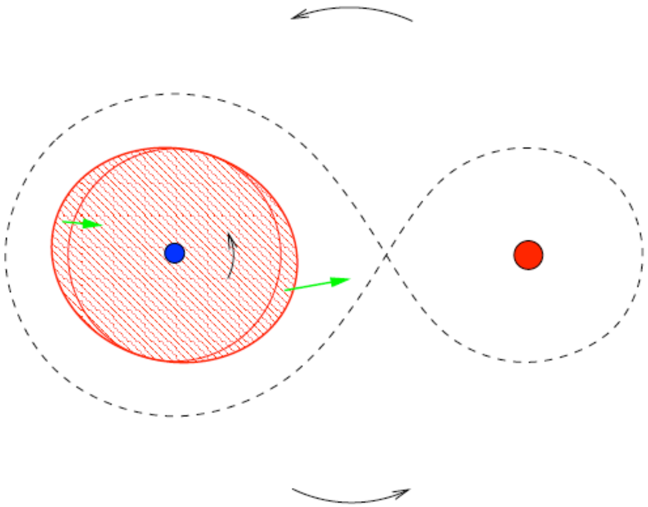
Tidal interaction



- minimum energy at constant J_{tot}: $\Omega_{\mathrm{spin}} = \Omega_{\mathrm{orb}}$ and $e = 0$
- if $\Omega_{\mathrm{spin}} \neq \Omega_{\mathrm{orb}}$ or $e \neq 0$:
  friction ⟶ dissipation ⟶ lag of tidal bulges ⟶ torque
- timescale depends on dissipation mechanism
  most efficient: turbulent viscosity in convective envelope

$$\frac{1}{\tau_{\mathrm{circ}}} \propto \frac{f}{\tau_{\mathrm{conv}}} \left(\frac{R}{a}\right)^8$$

$$\frac{1}{\tau_{\mathrm{sync}}} \propto \frac{f}{\tau_{\mathrm{conv}}} \left(\frac{R}{a}\right)^6$$

synchronization faster (since $R/a < 1$)

- as star expands: $\Omega_{\mathrm{spin}} < \Omega_{\mathrm{orb}}$
  tides transfer AM from orbit to star ⟶ separation reduced
  (and $e \to 0$)

Specific orbital energy $\varepsilon = \dfrac{E_{\text{tot}}}{\mu}$:

$$\varepsilon = \frac{v^2}{2} - \frac{\mu}{r} = -\frac{1}{2}\frac{\mu^2}{h^2}(1-e^2) = -\frac{\mu}{2a}$$

h = specific angular momentum

= total relative angular momentum / reduced mass

$$\overline{h} \quad = \overline{r} \times \overline{v} = \frac{\overline{J}_{\text{tot}}}{\mu} = \frac{\overline{J}_1 + \overline{J}_2}{\mu}$$

$$J = \left(\frac{G\, M_1^2 M_2^2 a}{M_1 + M_2}\right)^{1/2} \left(1-e^2\right)^{1/2}$$

$$= \mu\left[G\left(M_1 + M_2\right)a\left(1-e^2\right)\right]^{1/2}$$

$$= \mu h$$

$$h = \left[G\left(M_1 + M_2\right)a\left(1-e^2\right)\right]^{1/2}$$

Hence, from

$$\varepsilon = -\frac{1}{2}\frac{\mu^2}{h^2}(1-e^2),$$

minimum energy ε at constant angular momentum h

is reached when $e = 0$

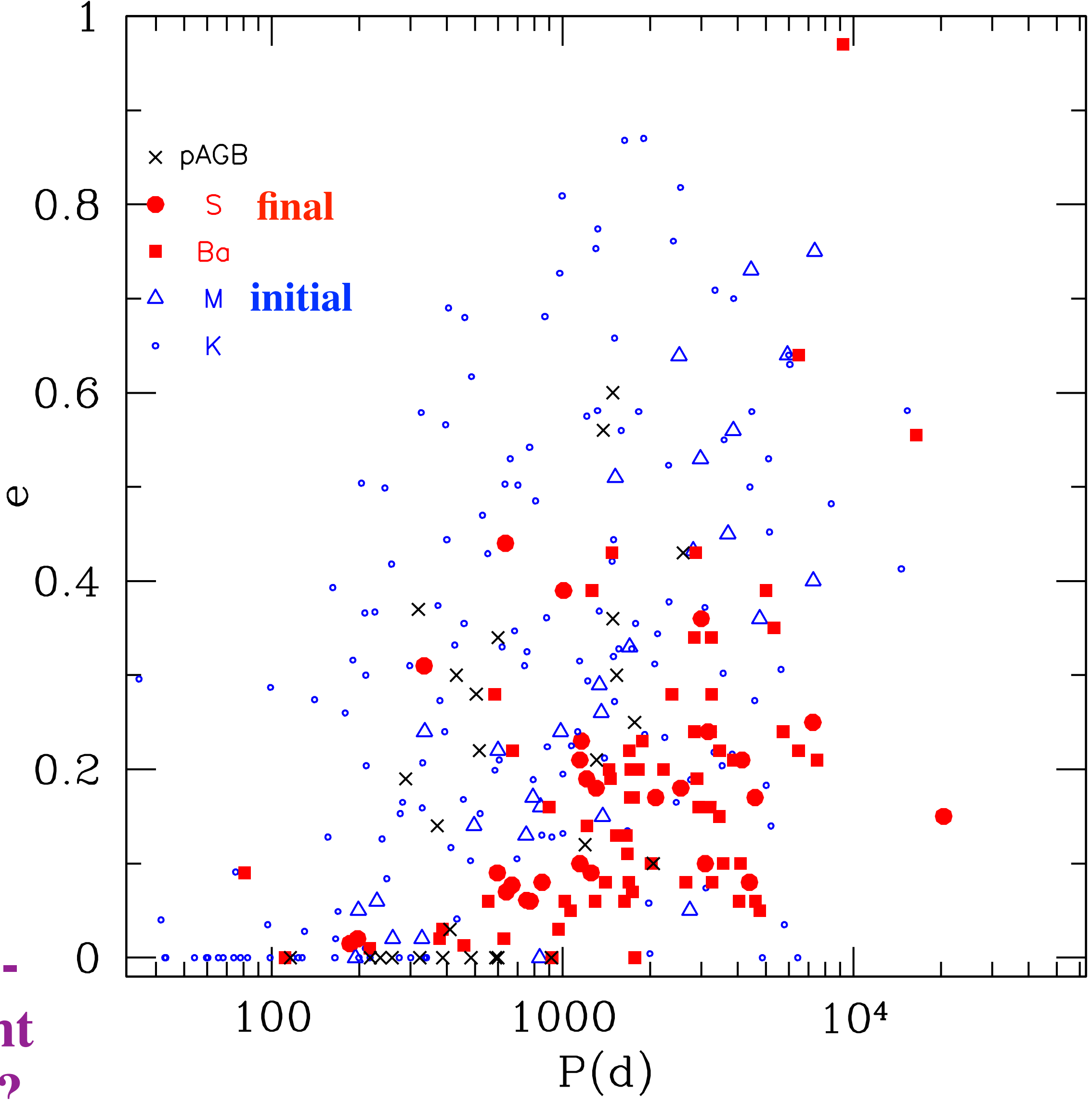
Eccentricity - period (e - P) diagrams may provide clues to identify mass-transfer / interaction processes

All in one :

From initial to final

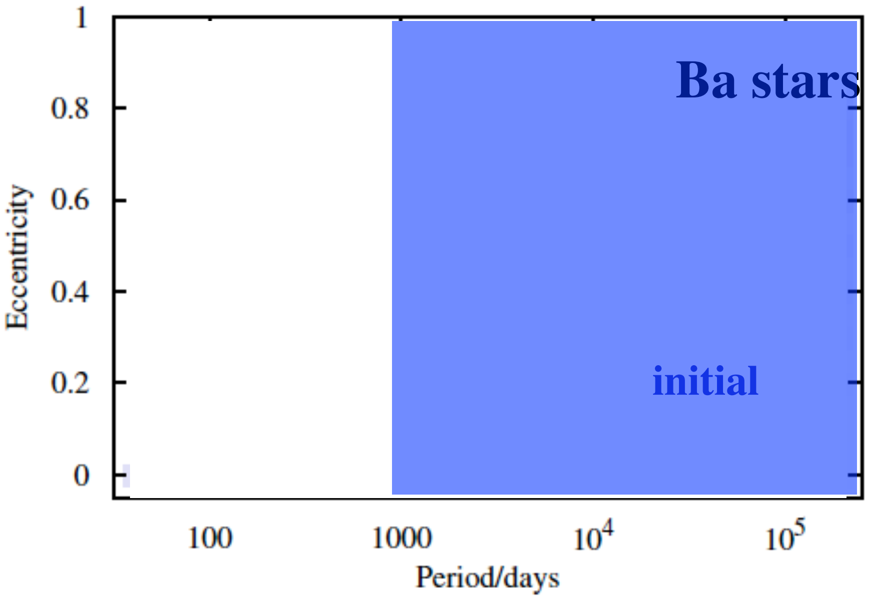
- reduction in the average eccentricity

- increase of the period



Which interaction / mass-transfer processes account for this kind of evolution?

Canonical binary evolution



Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897

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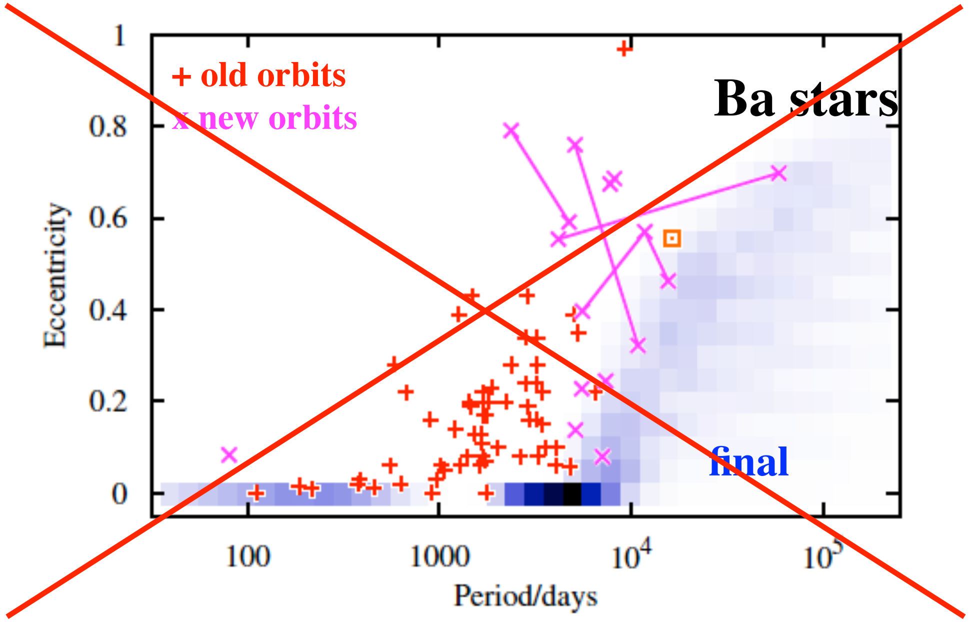
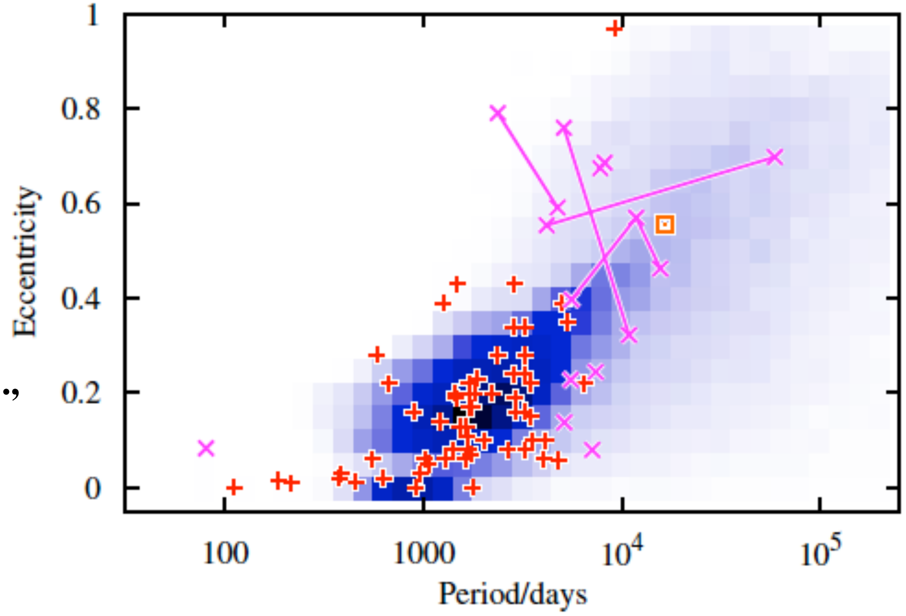


Hurley, J. R., Tout, C. A., & Pols, O. R. 2002,
MNRAS, 329, 897

+ WD kick,
disc-orbit interaction,
angular-momentum loss...



Izzard R., Dermine T., Church R.P..
2010, A&A 523, A10
Dermine T., Izzard R.. Jorissen A., Van Winckel H.,
2012, ArXiv:1203.6471

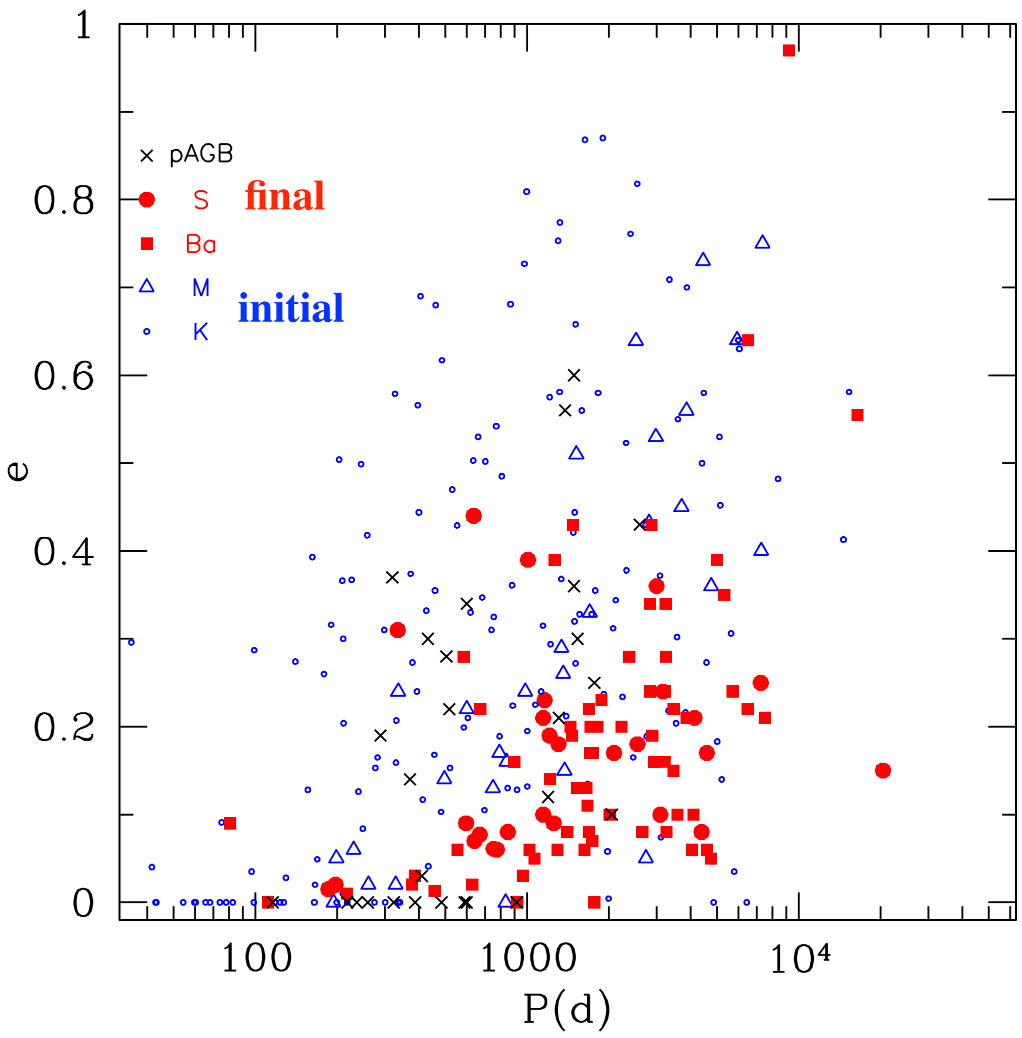
Which interaction / mass-transfer processes account for this kind of evolution?

A significant difference between initial and final samples : the (e, P) diagram

From initial to final

- reduction in the average eccentricity

- increase of the period



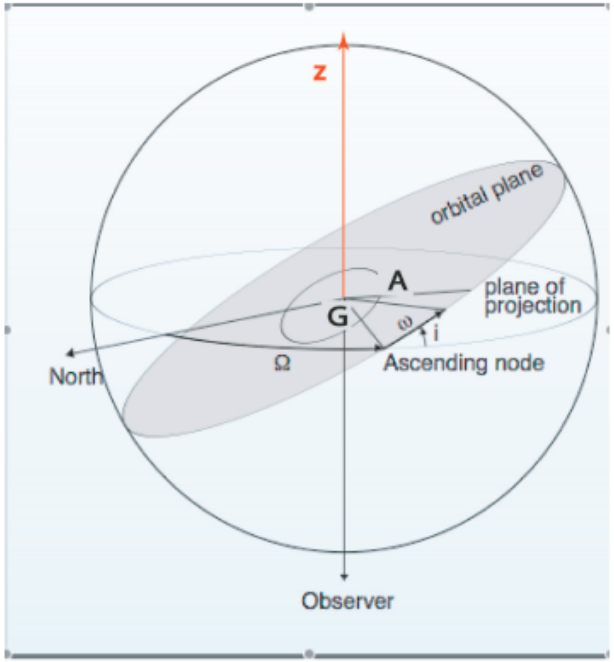
→ Eccentricity - period (e - P) diagrams provide clues to identify mass-transfer / interaction processes at work during binary evolution

Another significant difference between initial and final samples : the mass functions

Mass functions for SB1:

[→ Mazeh]

$$f(M)=\frac{\left(M_{\mathrm{comp}}\ \sin i\right)^{3}}{\left(M_{\mathrm{primary}}+M_{\mathrm{comp}}\right)^{2}}$$



Under the assumption that the orbits are oriented at random in space, the inclination angle *i* distributes as sin *i* :

Prob(*i*) d*i* = sin *i* d*i*

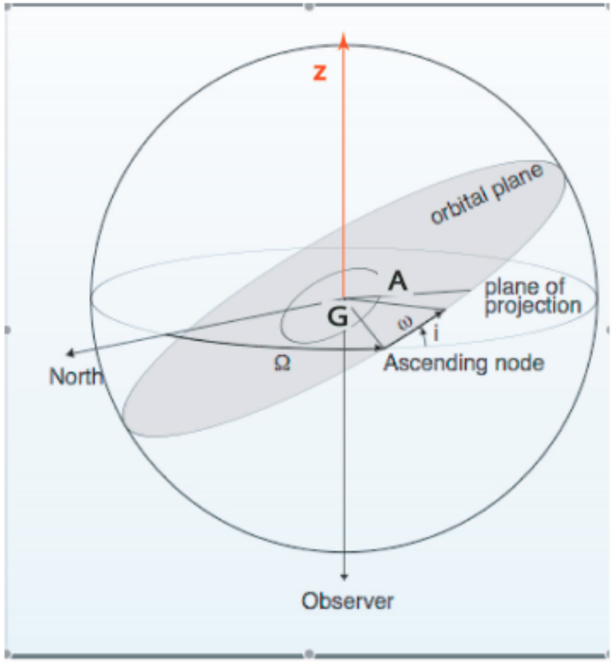
Hence, for a large sample of stars, the distribution of *f(M)* reflects the distributions of M_{primary} and $M_{\mathrm{companion}}$

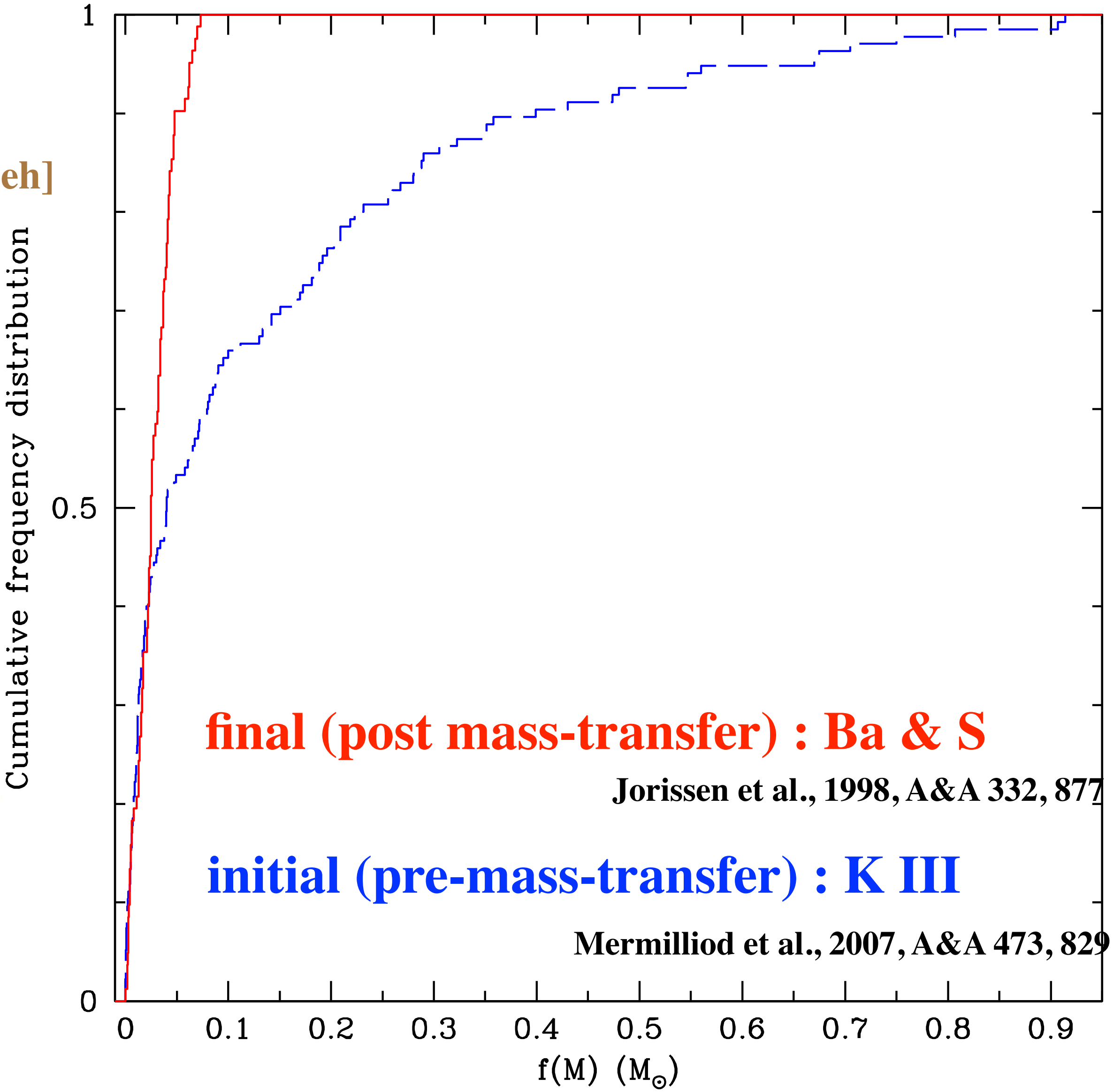
Another significant difference between initial and final samples : the mass functions

Mass functions for SB1:

[➙ Mazeh]

$$f(M) = \frac{\left(M_{\text{comp}} \sin i\right)^3}{\left(M_{\text{primary}} + M_{\text{comp}}\right)^2}$$





final (post mass-transfer) : Ba & S

Jorissen et al., 1998, A&A 332, 877

initial (pre-mass-transfer) : K III

Mermilliod et al., 2007, A&A 473, 829

Another significant difference between initial and final samples : the mass functions

Mass functions for SB1:

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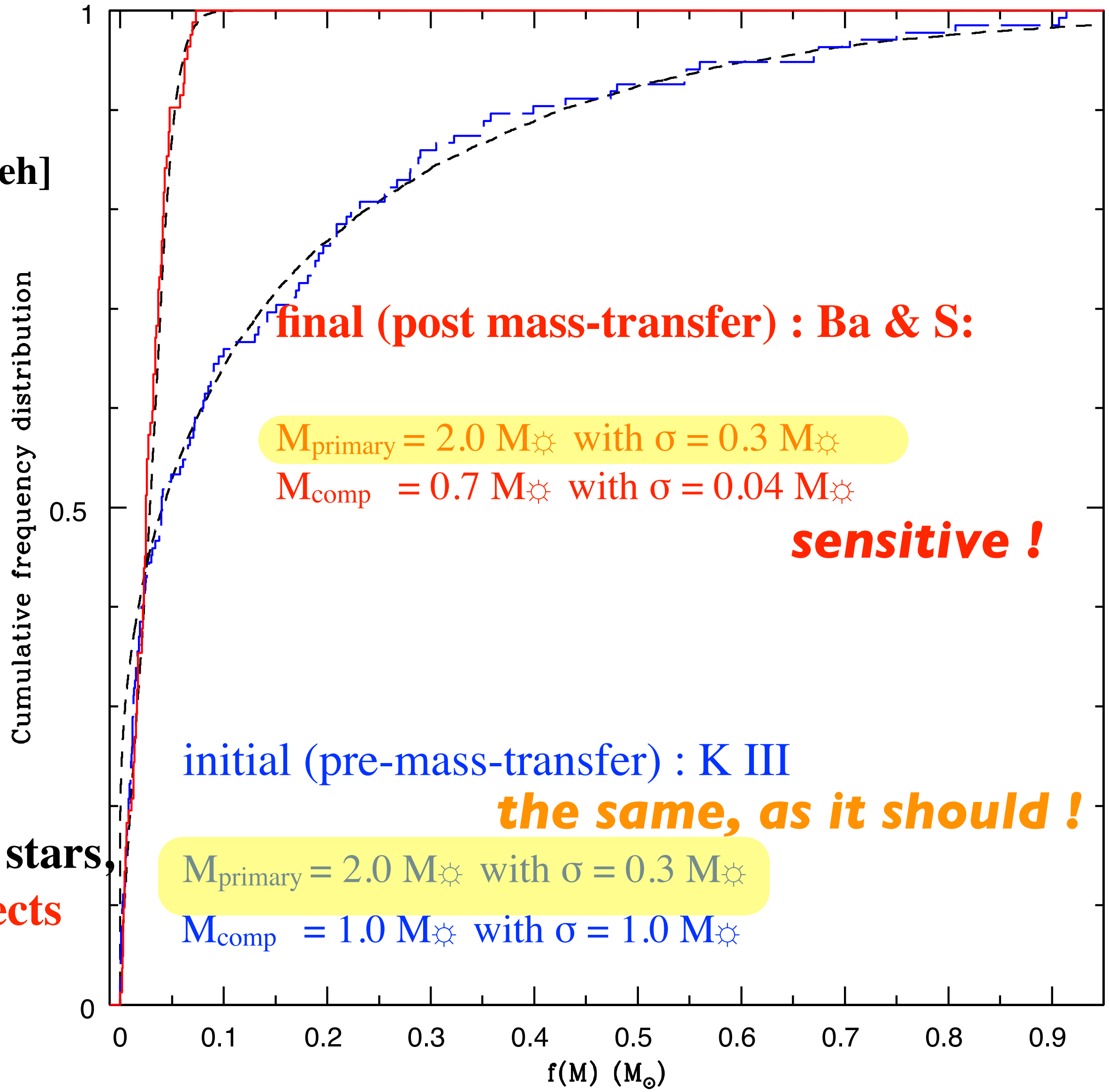


final (post mass-transfer) : Ba & S:

$M_{\text{primary}} = 2.0$ M☼ with $\sigma = 0.3$ M☼
$M_{\text{comp}} = 0.7$ M☼ with $\sigma = 0.04$ M☼

sensitive !

initial (pre-mass-transfer) : K III

the same, as it should !

$M_{\text{primary}} = 2.0$ M☼ with $\sigma = 0.3$ M☼
$M_{\text{comp}} = 1.0$ M☼ with $\sigma = 1.0$ M☼

Hence, for a large sample of stars, the distribution of *f(M)* reflects the distributions of M_{primary} and $M_{\text{companion}}$

Another significant difference between initial and final samples : the mass functions

Mass functions for SB1:

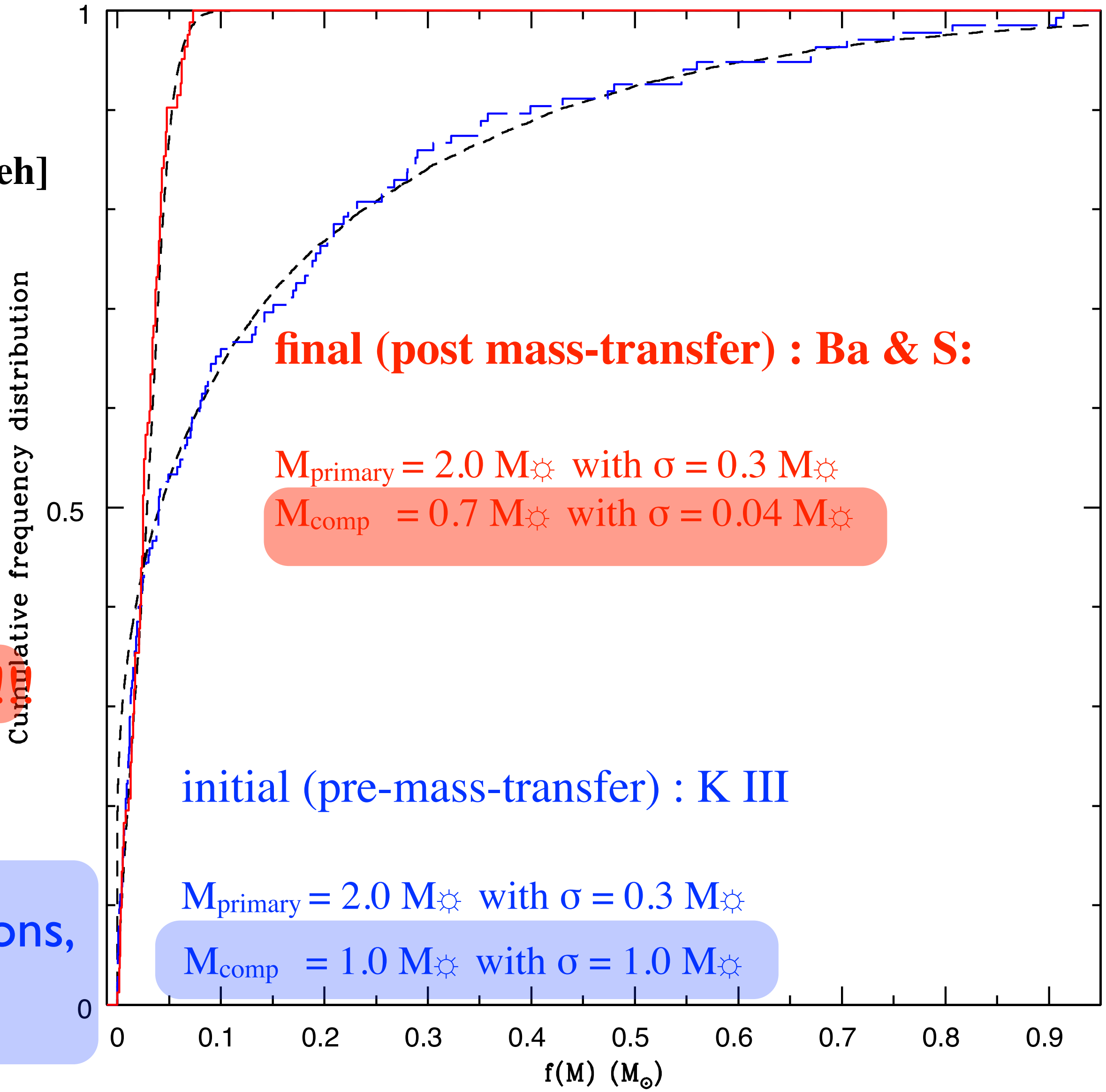
[→ Mazeh]

$$f(M) = \frac{\left(M_{\mathrm{comp}} \sin i\right)^3}{\left(M_{\mathrm{primary}} + M_{\mathrm{comp}}\right)^2}$$

Prob(*i*) d*i* = sin *i* d*i*

white dwarf companions !!!

no constraint on companions, except $M_{\mathrm{comp}} \leq M_{\mathrm{primary}}$!!!



final (post mass-transfer) : Ba & S:

M_{primary} = 2.0 M☼ with σ = 0.3 M☼

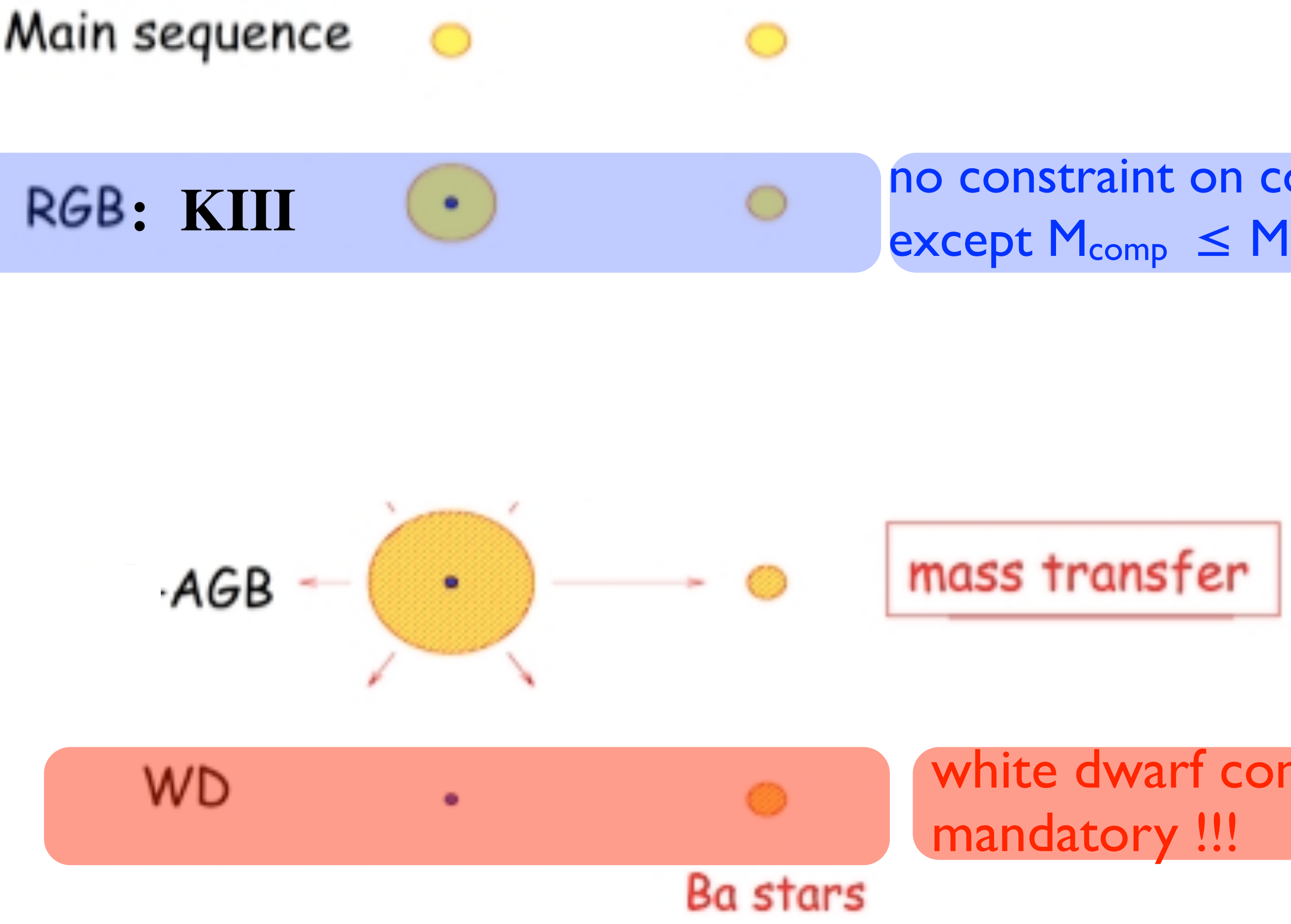
M_{comp} = 0.7 M☼ with σ = 0.04 M☼

initial (pre-mass-transfer) : K III

M_{primary} = 2.0 M☼ with σ = 0.3 M☼

M_{comp} = 1.0 M☼ with σ = 1.0 M☼

Evolutionary sequence involving KIII and Ba, S no-Tc binaries



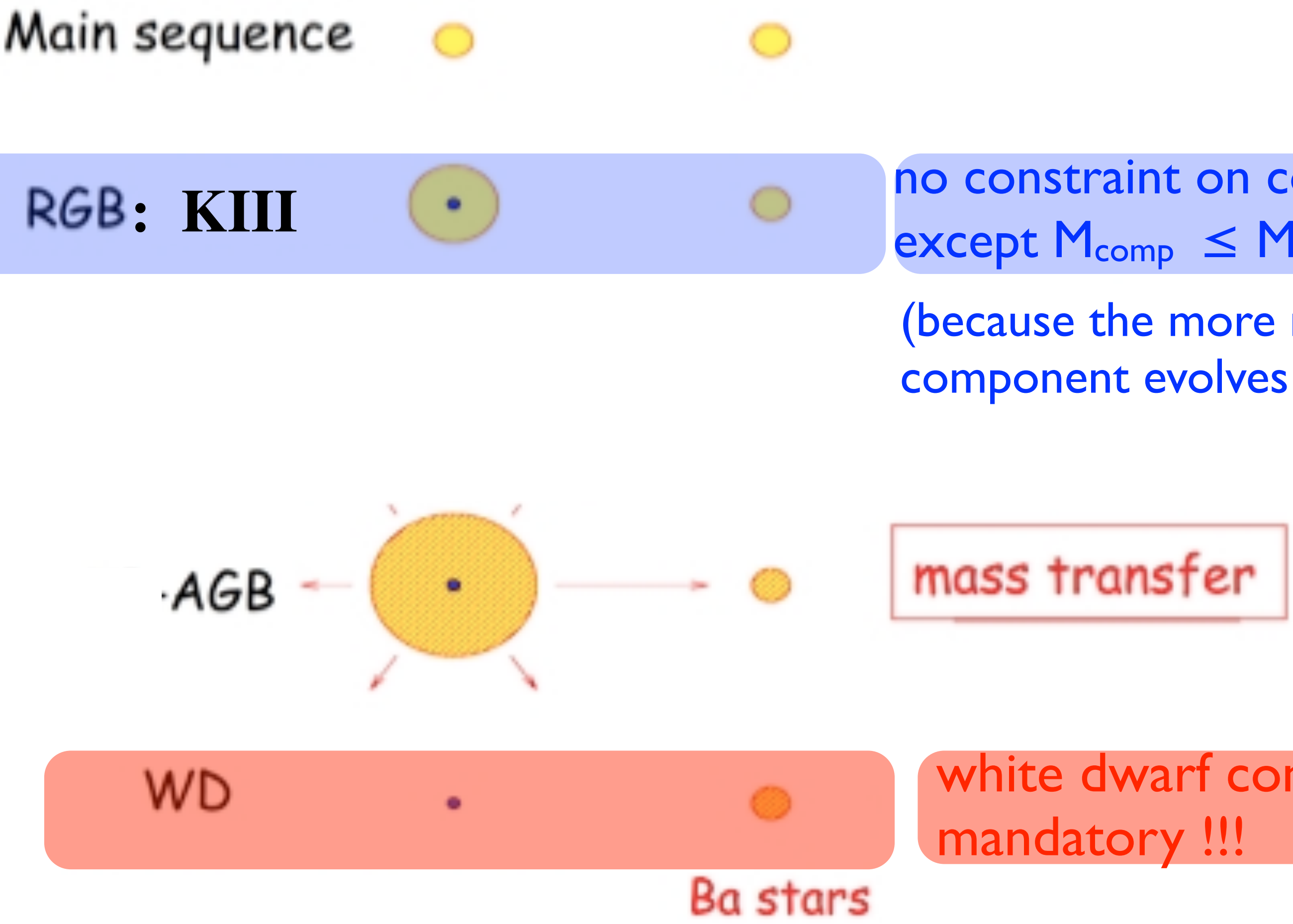
KIII

no constraint on companions, except $M_{comp} \leq M_{primary}$!!!

white dwarf companions mandatory !!!

Tc-no S stars

Evolutionary sequence involving KIII and Ba, S no-Tc binaries



KIII

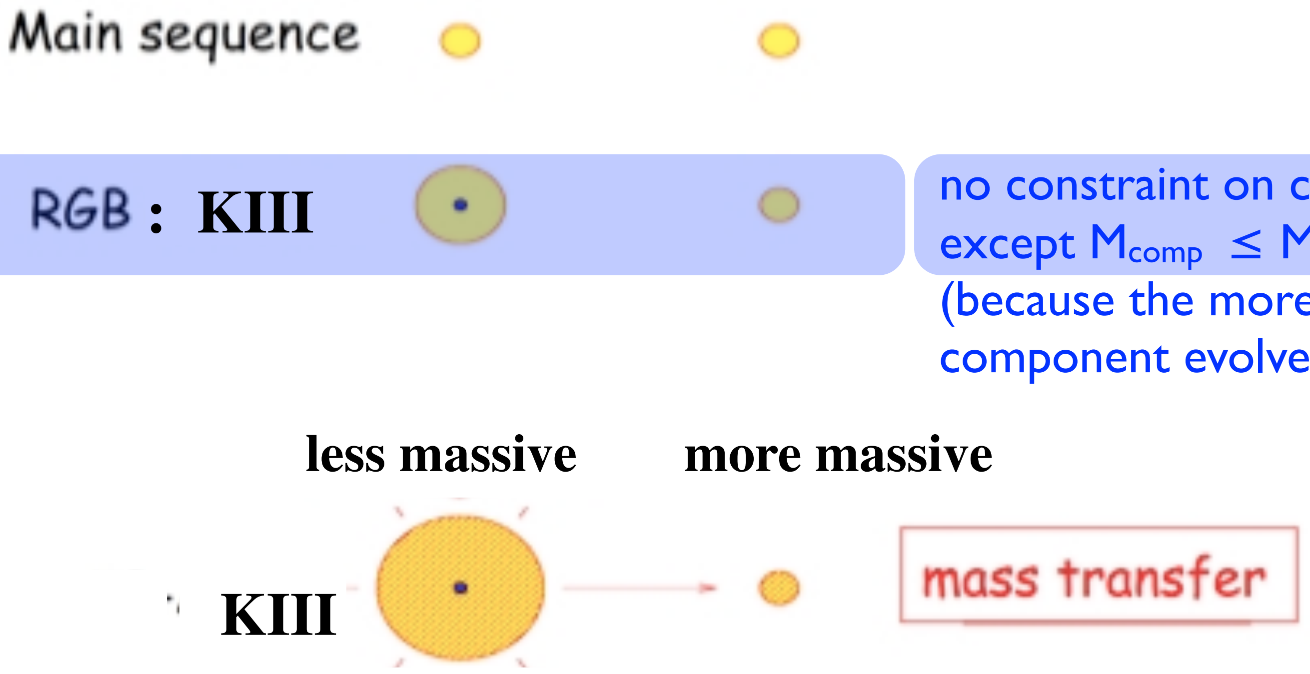
no constraint on companions, except $M_{comp} \leq M_{primary}$!!!

(because the more massive component evolves faster)

white dwarf companions mandatory !!!

Tc-no S stars

Evolutionary sequence involving KIII and Ba, S no-Tc binaries

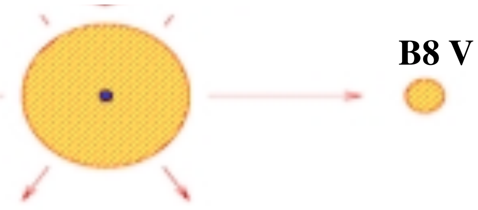


no constraint on companions, except $M_{comp} \leq M_{primary}$!!! (because the more massive component evolves faster)

One exception:

the Algol paradox : on-going mass transfer...

The **Algol paradox** : on-going mass transfer...



G8 III

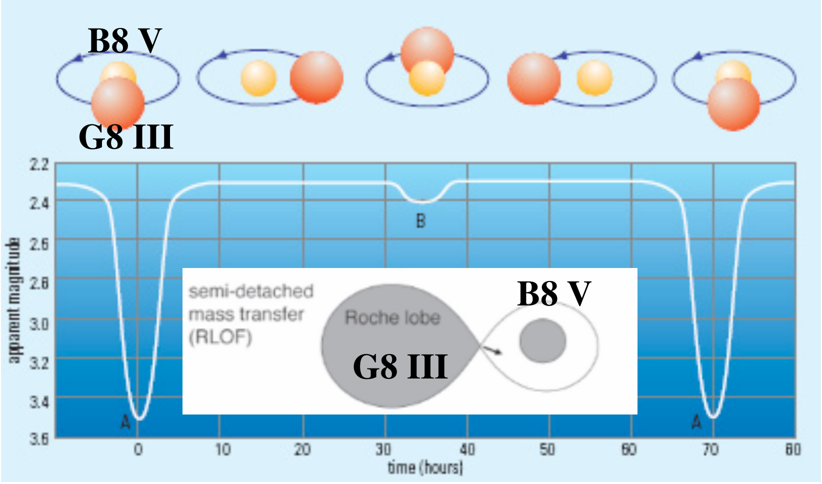
B8 V

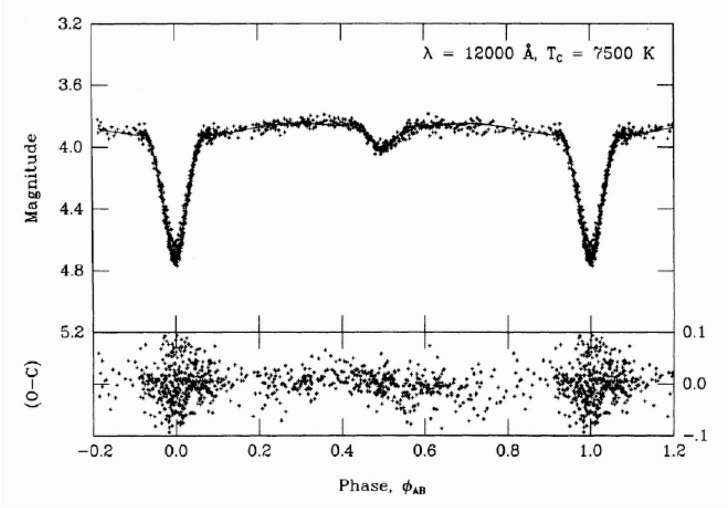
mass transfer

less massive **more massive**

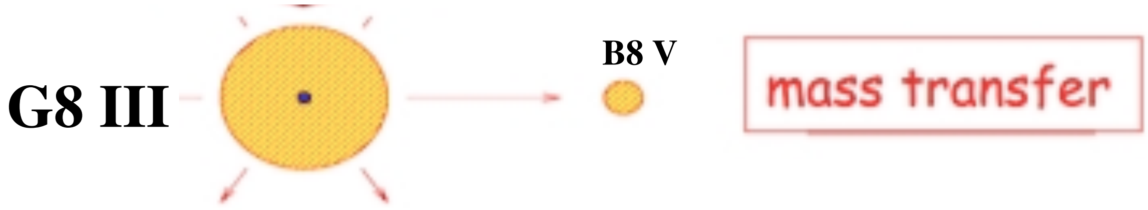
The defining properties of Algols are

- initially empirical: eclipsing lightcurve

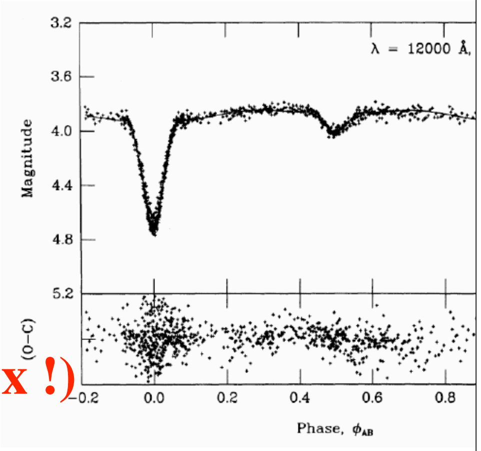




The Algol paradox : on-going mass transfer...



less massive **more massive**

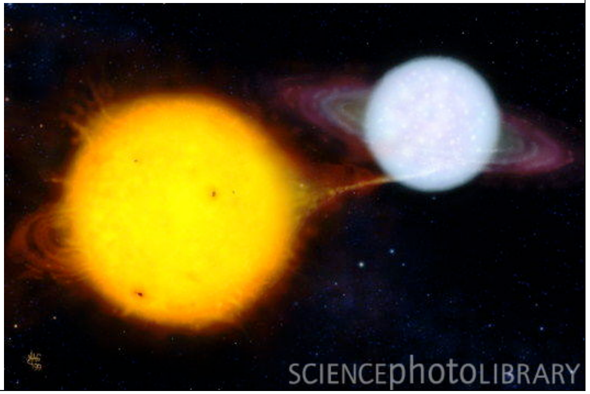


The defining properties of Algols are

- **initially empirical: eclipsing lightcurve**
- **then theory/evolution : giant is the less massive (paradox !)**

name	spectra	P (d)	M_1	M_2	R_1	R_2	log L_1	log L_2
β Per (Algol)	G8III + B8V	2.87	0.8	3.7	3.5	2.9	0.65	2.27

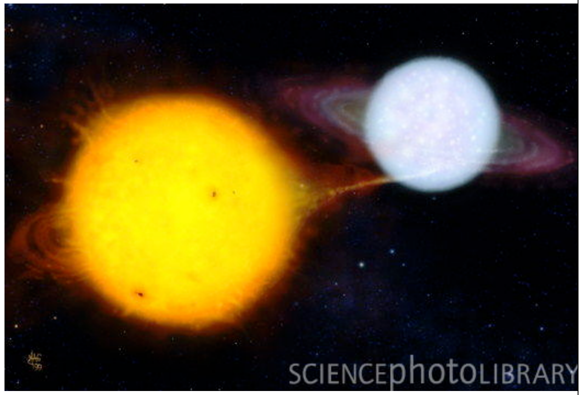
- **finally theory/binary : on-going, slow mass transfer (case A, slow - nuclear - time scale)**



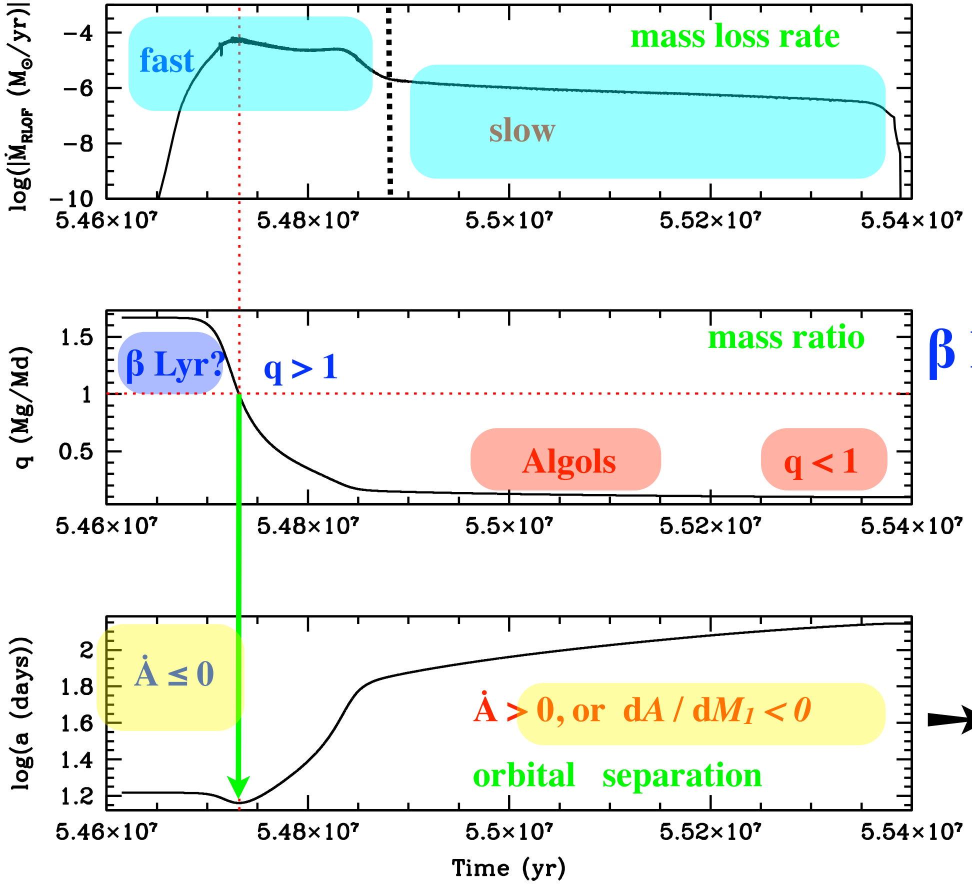
The **Algol paradox** : on-going mass transfer...

The defining properties of Algols are

- finally theory/binary : on-going, slow mass transfer
  (case A, nuclear time scale)



[➞ Lionel Siess, BINSTAR]



**β Lyr : on-going, fast mass transfer
precursors of Algols ?**

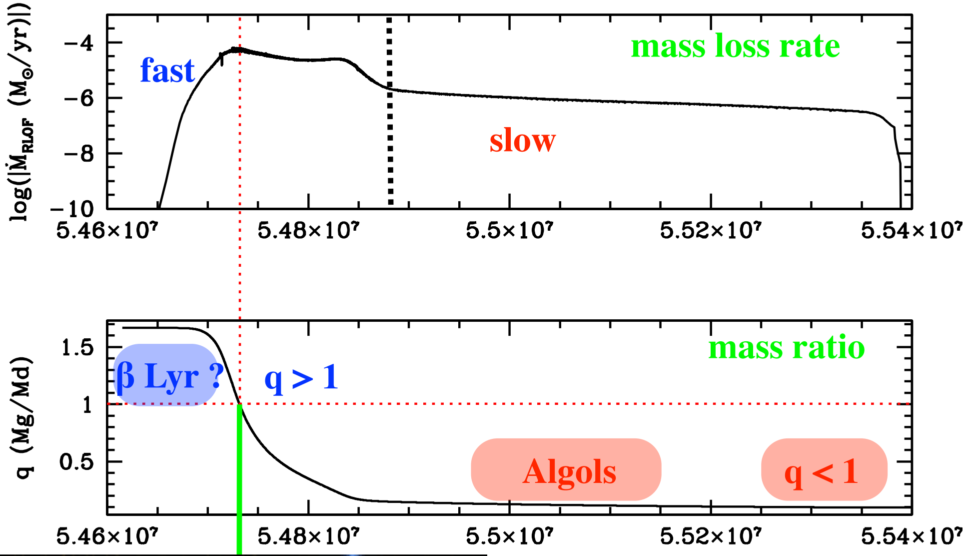
➞ $$\zeta_R = \frac{\partial \ln R_R}{\partial \ln M_2} = \frac{\mathrm{d}\ln A}{\mathrm{d}\ln M_2} + \frac{\mathrm{d}\ln f_2(q)}{\mathrm{d}\ln q}\,\frac{\mathrm{d}\ln q}{\mathrm{d}\ln M_2}$$

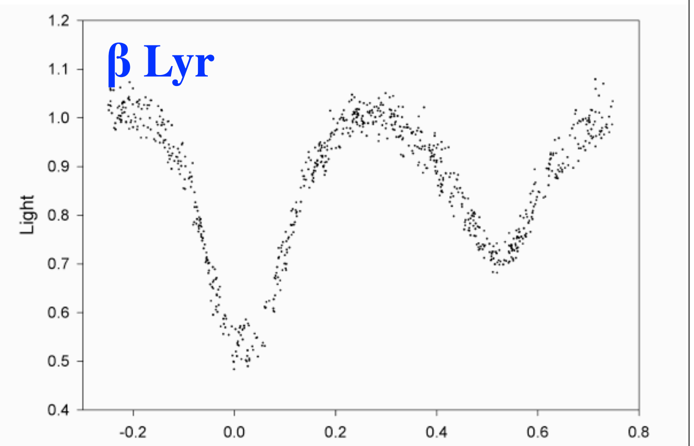
➞ governs the stability of the mass transfer

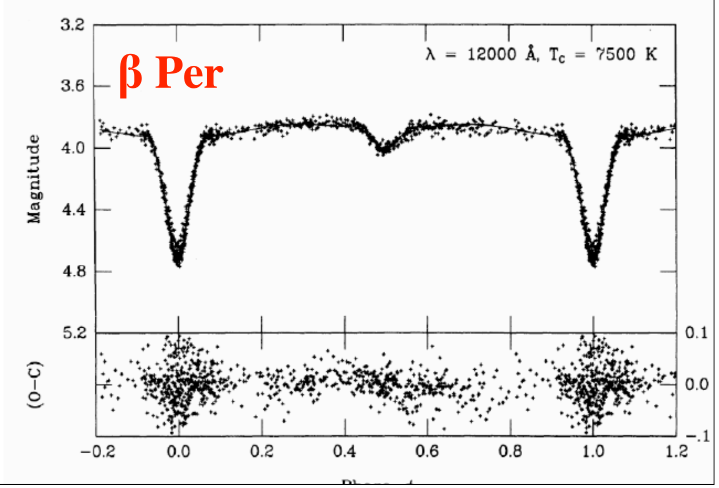
The Algol paradox : Algols vs β Lyr...

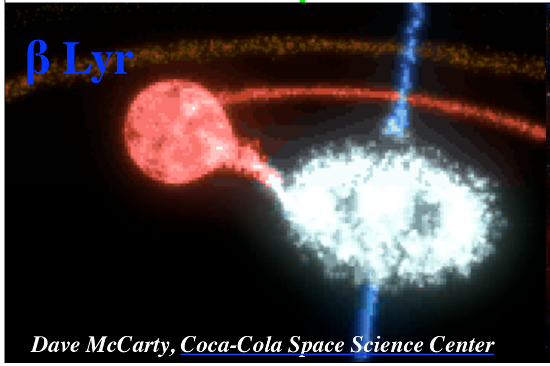
- Algols : on-going, slow mass transfer

- β Lyr : on-going, fast mass transfer
  precursors of Algols ?

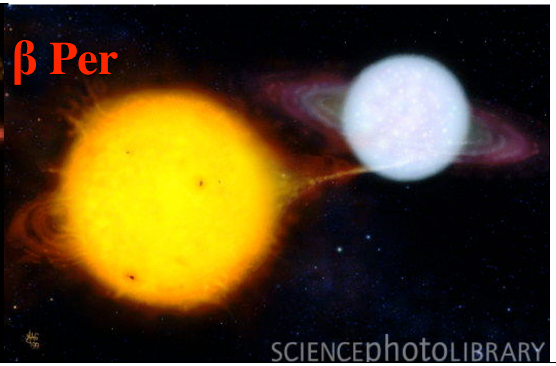








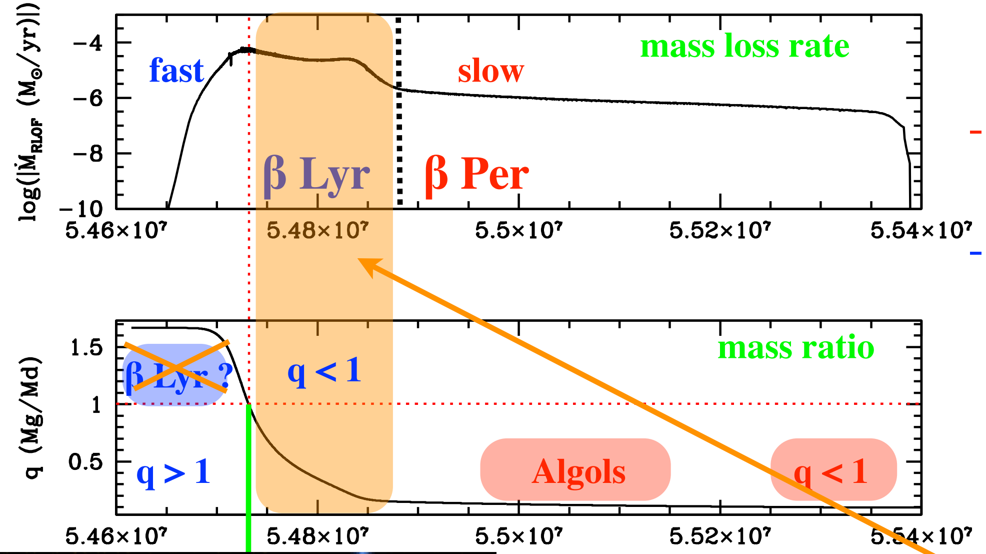
Dave McCarty, Coca-Cola Space Science Center



The Algol paradox : Algols vs β Lyr...

name	spectra	P (d)	M_1	M_2	R_1	R_2	$\log L_1$	$\log L_2$
β Per (Algol)	G8III + B8V	2.87	0.8	3.7	3.5	2.9	0.65	2.27
β Lyr	**B8 II + BV?+ disk**	**12.9**	**4 ?**	**14 ?**				

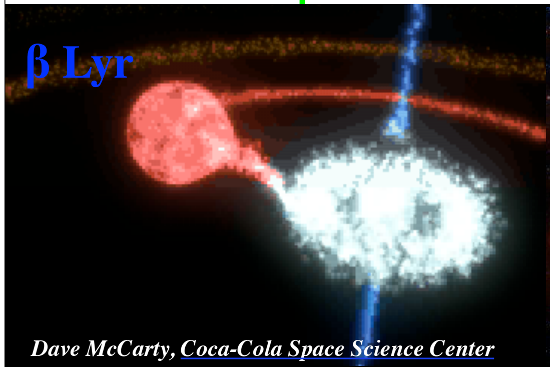
Van Rensbergen et al., A&A 528, A16, 2011



- Algols : on-going, slow mass transfer

- β Lyr : on-going, fast mass transfer

precursors of Algols ?



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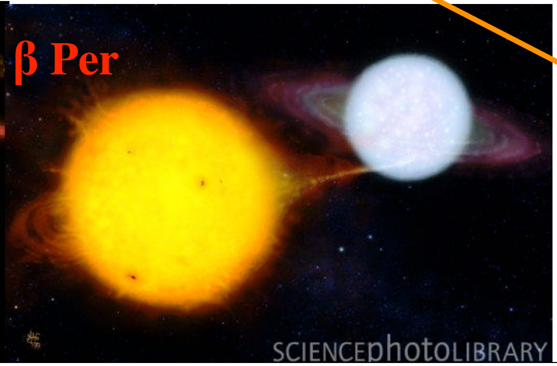


β Lyr itself:

fast mass transfer, $\dot{P}$, disc, jet : OK !

$T_{\text{prim.eclipse}}(\text{d}) =$
$\text{JD}2408247.966 + 12.913780\,E + 3.87196\ 10^{-6}\,E^2$

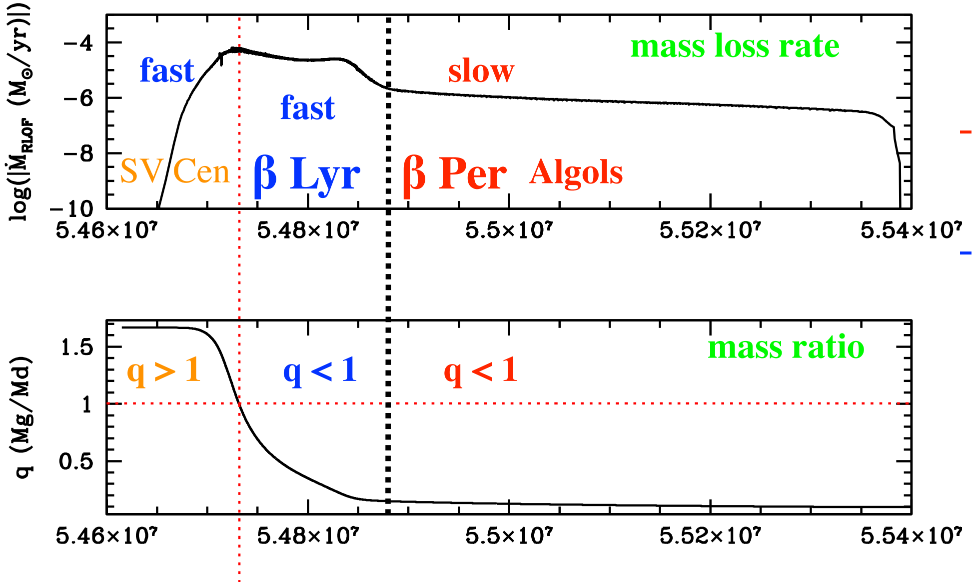
BUT: q < 1 ! with fast mass transfer

The **Algol paradox** : Algols vs β Lyr...

name	spectra	P (d)	M_1	M_2	R_1	R_2	$\log L_1$	$\log L_2$
β Per (Algol)	G8III + B8V	2.87	0.8	3.7	3.5	2.9	0.65	2.27
β Lyr	**B8 II + BV?+ disk**	**12.9**	**4 ?**	**14 ?**				
SV Cen	**B3 II + B1V**	**1.66**	**11**	**9**	**$\dot{M} = 1.6\ 10^{-4}$**			

Van Rensbergen et al., A&A 528, A16, 2011

Van Rensbergen et al., 2011



- Algols : on-going, slow mass transfer

- β Lyr : on-going, fast mass transfer

precursors of Algols ?

SV Cen better candidate ?

Evolutionary sequence ?

SV Cen → β Lyr → Algols
W Ser

A technical parenthesis is needed about how to derive stellar masses...
(later on !)

The binary zoo

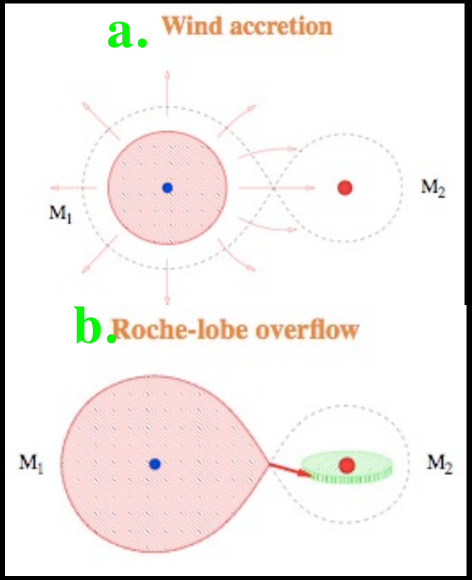
Classification of binary stars:

There are three possible ways to classify binary stars, based on:

i) Mass transfer:

- a. Detached system
- b. Semi-detached system
- c. Contact system

- a. wind accretion
- b. Roche-lobe overflow



ii) Observational properties

- a. photometric binary
- b. [peculiar] ‘abundance’ binary
- c. ....

iii) Evolutionary stage

Knowing the location of the binary in all 3 schemes often is the goal of binary-star research !

The binary zoo

Classification of binary stars:

There are three possible ways to classify binary stars, based on:

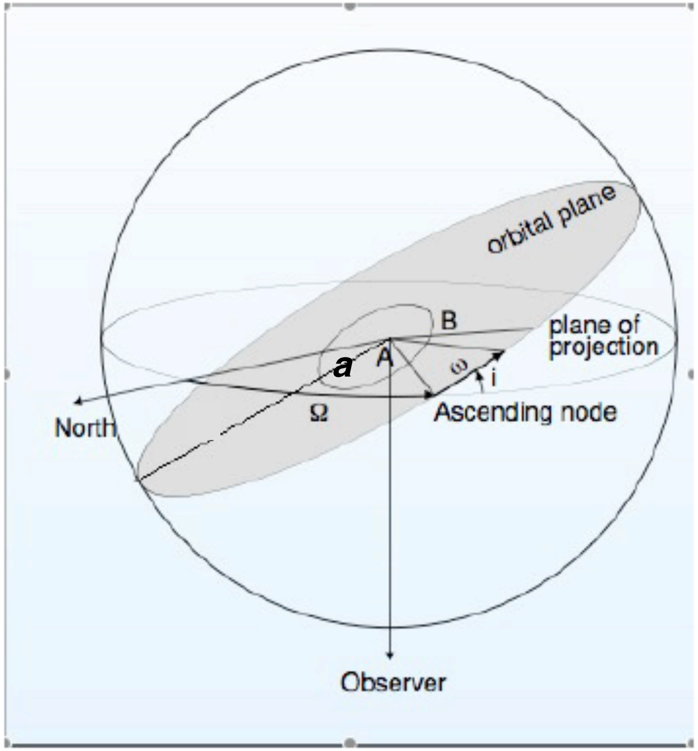
i) Mass transfer
ii) Evolutionary stage
iii) Observational properties

We now go through every class of 'observational properties'

But first, some definitions about orbital elements... [→ Mazeh, Marsh]

Orbital elements

Relative orbit (B with respect to A)



Kepler third law (in relative orbit):

$$a^3/P^2 = G\,(M_A + M_B)/4\pi^2$$

Orbital elements

Size of orbit:

a	semi-major axis (B wrt A)
e	eccentricity $= \sqrt{a^2 - b^2}/a$ ($b =$ semi-minor axis)

Orientation in plane:

ω	argument of periastron

Orientation of plane wrt sky:

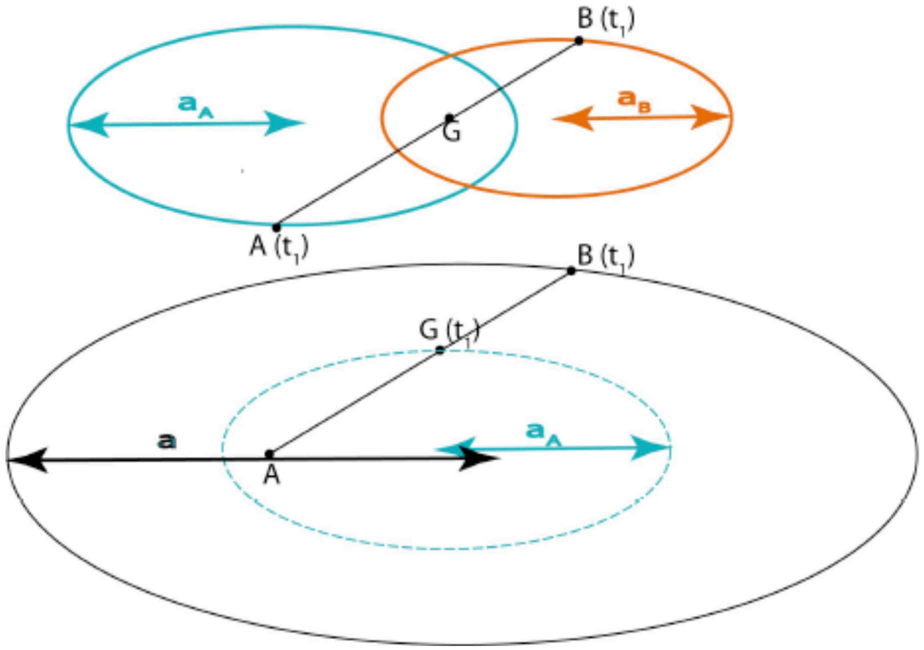
Ω	Position angle of ascending node
i	inclination on the plane of the sky

Time:

P	orbital period
T	Epoch of passage (usually at periastron)

Absolute and relative orbits

G: center-of-mass; A, B components



Absolute orbits
(A, B wrt G): a_A, a_B

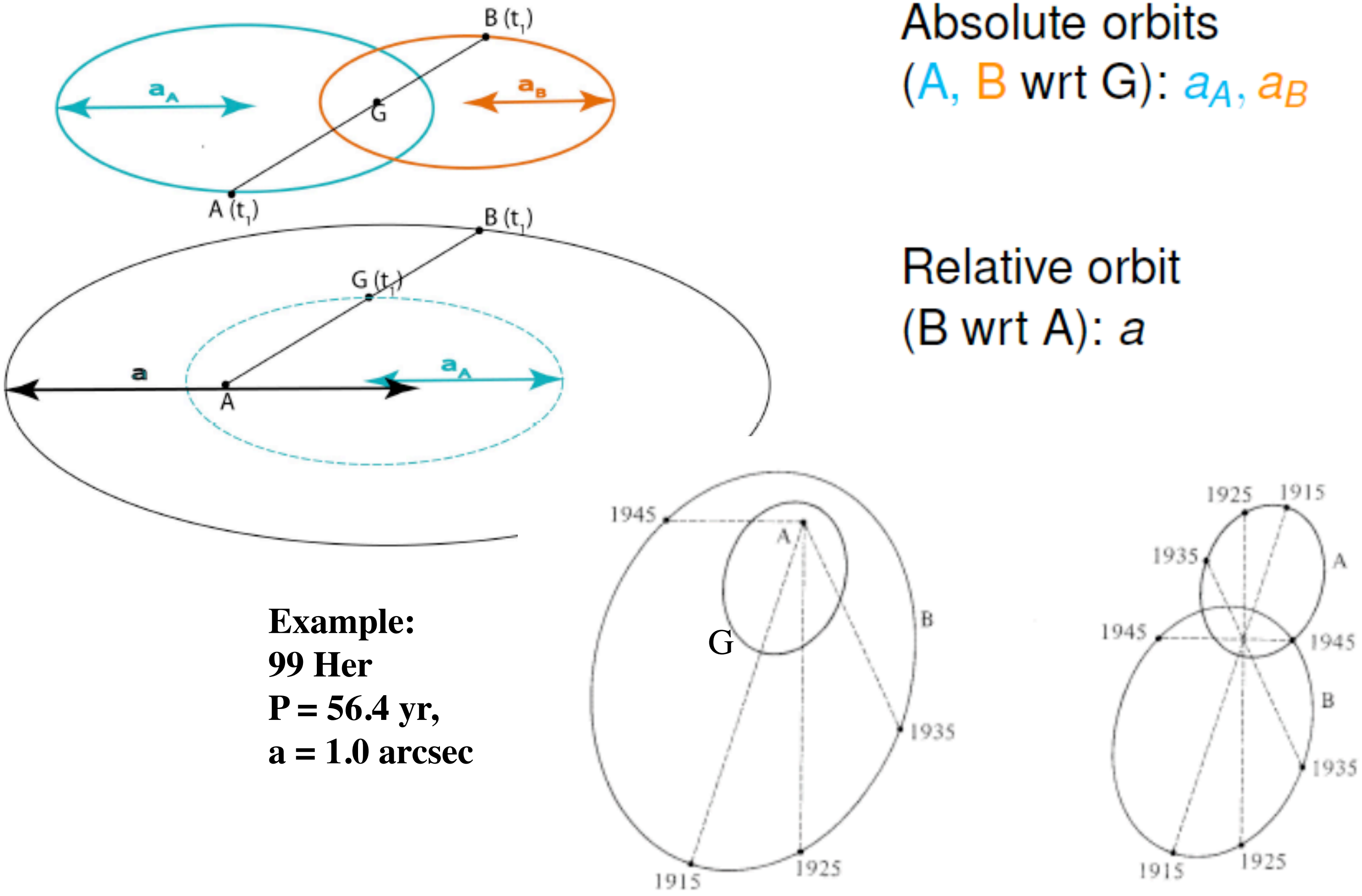
Relative orbit
(B wrt A): a

A moves on an ellipse around G ➙ G moves on an ellipse around A   (a_A)
B is always further out, on the same AG ($\equiv r_A$) segment
At all times: $r_A M_A = r_B M_B$ (definition of G) ➙ $r_B = r_A M_A / M_B$ ➙ $r_{AB} = r_A + r_B = r_A (M_A + M_B) / M_B$.

Since motion of G around A is an ellipse, then motion of B around A will be an ellipse as well, with a semi-major axis scaled by the same factor $(M_A + M_B) / M_B$: $a_{AB} = a_A + a_B = a_A (M_A + M_B) / M_B$

Absolute and relative orbits

G: center-of-mass; A, B components



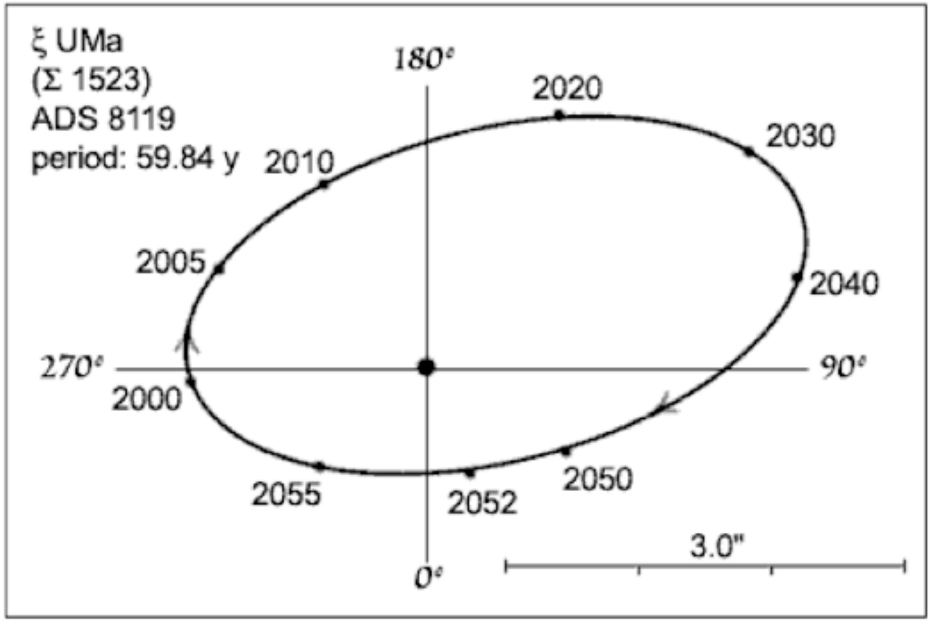
Absolute orbits
(A, B wrt G): a_A, a_B

Relative orbit
(B wrt A): a

Example:
99 Her
P = 56.4 yr,
a = 1.0 arcsec

The various kinds of binaries

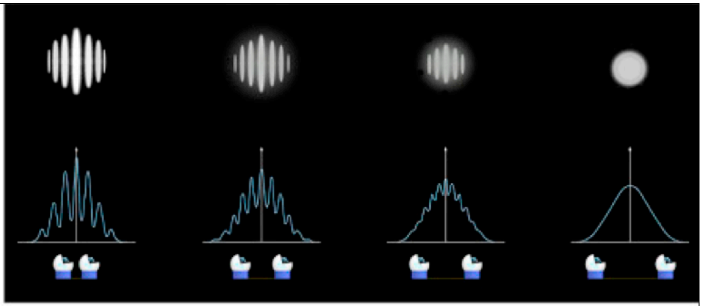
Type	Notation	Two stars visible?	orbit	dimension
visual and interferometric	VB	yes	relative	angular



The two stars are resolved and we can see them orbit each other

Orbit of ξ UMa, the first visual orbit ever computed in 1827

The various kinds of binaries

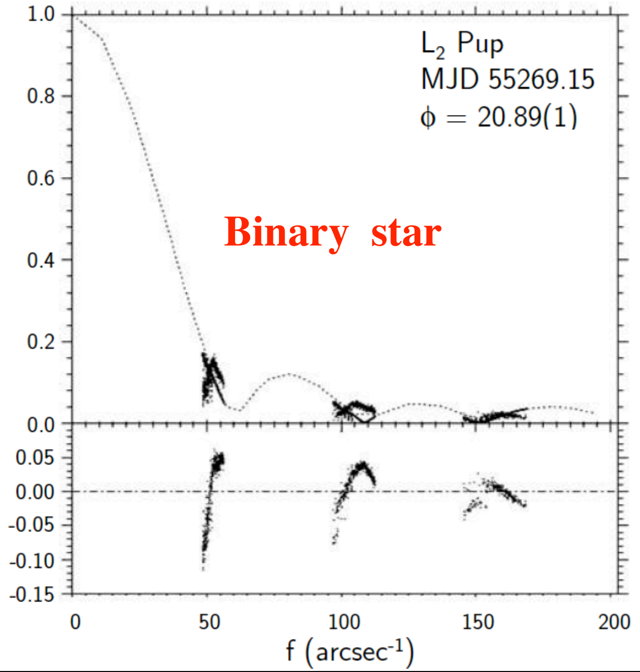


Interferometric Fringes at Different Telescope Baselines (Simulation)

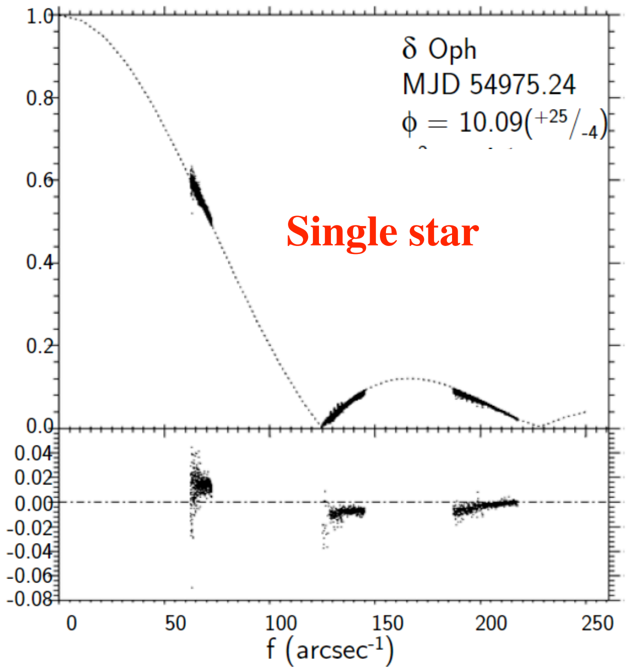
ESO PR Photo 10e/01 (18 March 2001)

© European Southern Observatory

Type	Notation	Two stars visible?	orbit	dimension
visual and interferometric	VB	yes	relative	angular



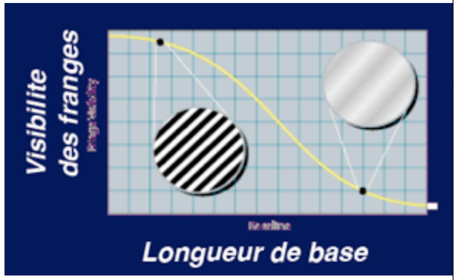
Binary star



Single star

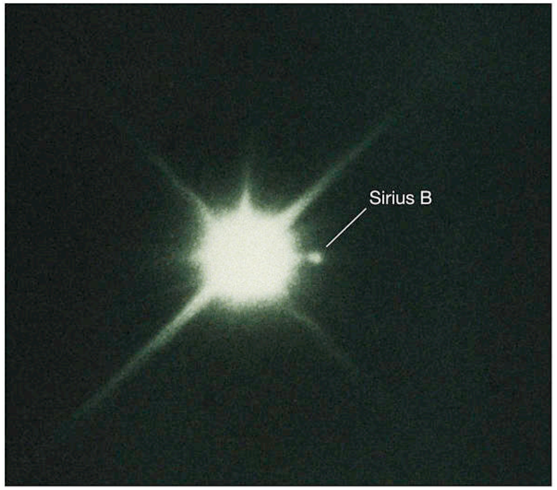
Use the fringe visibility as a function of telescope baseline

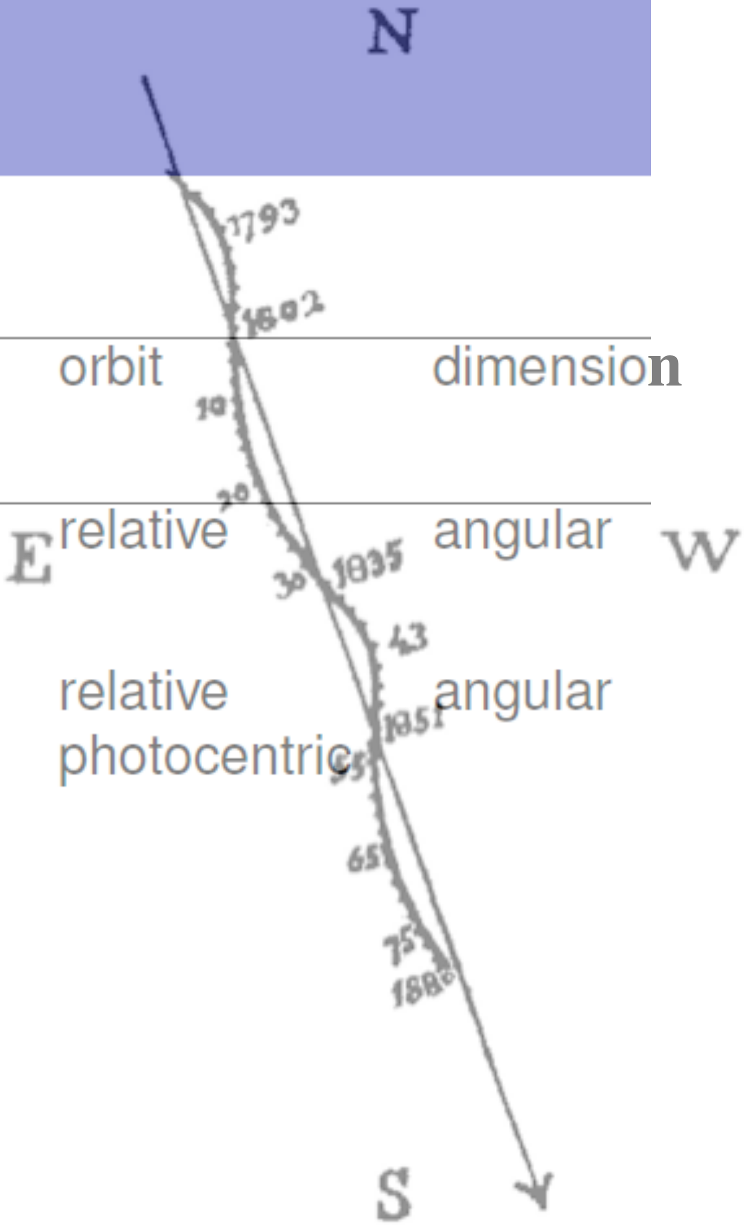
Fringe visibility



The various kinds of binaries

Type	Notation	Two stars visible?	orbit	dimension
visual and interferometric	VB	yes	relative	angular
astrometric	AB	yes no	relative photocentric	angular

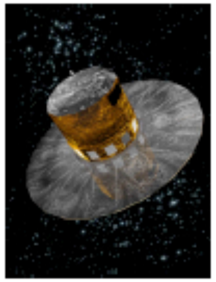


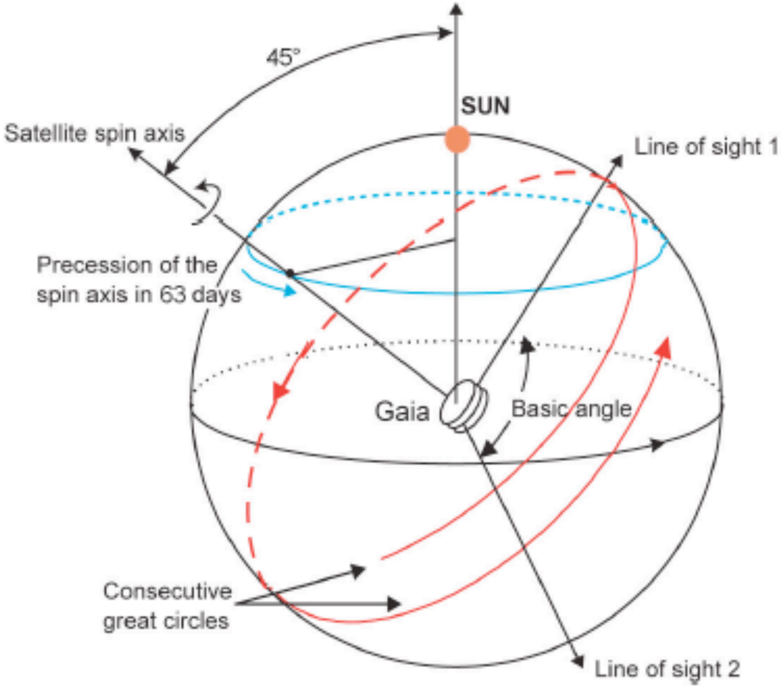


Non-linear motion on the sky

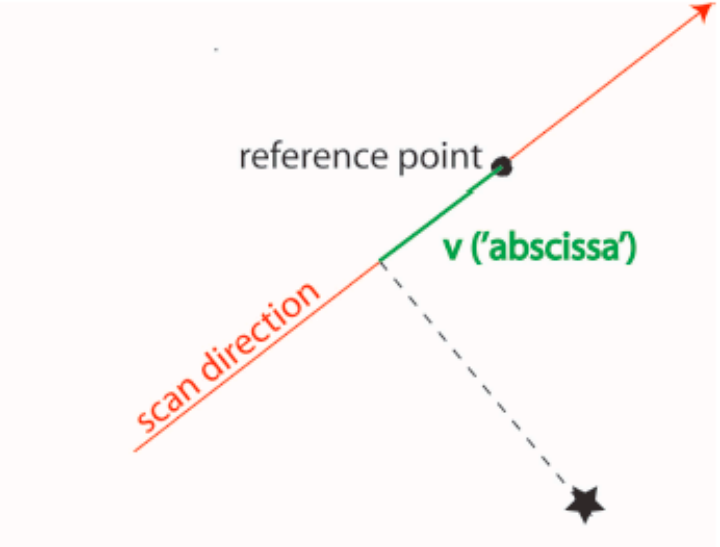
Astrometric binaries (I)

Basic principles



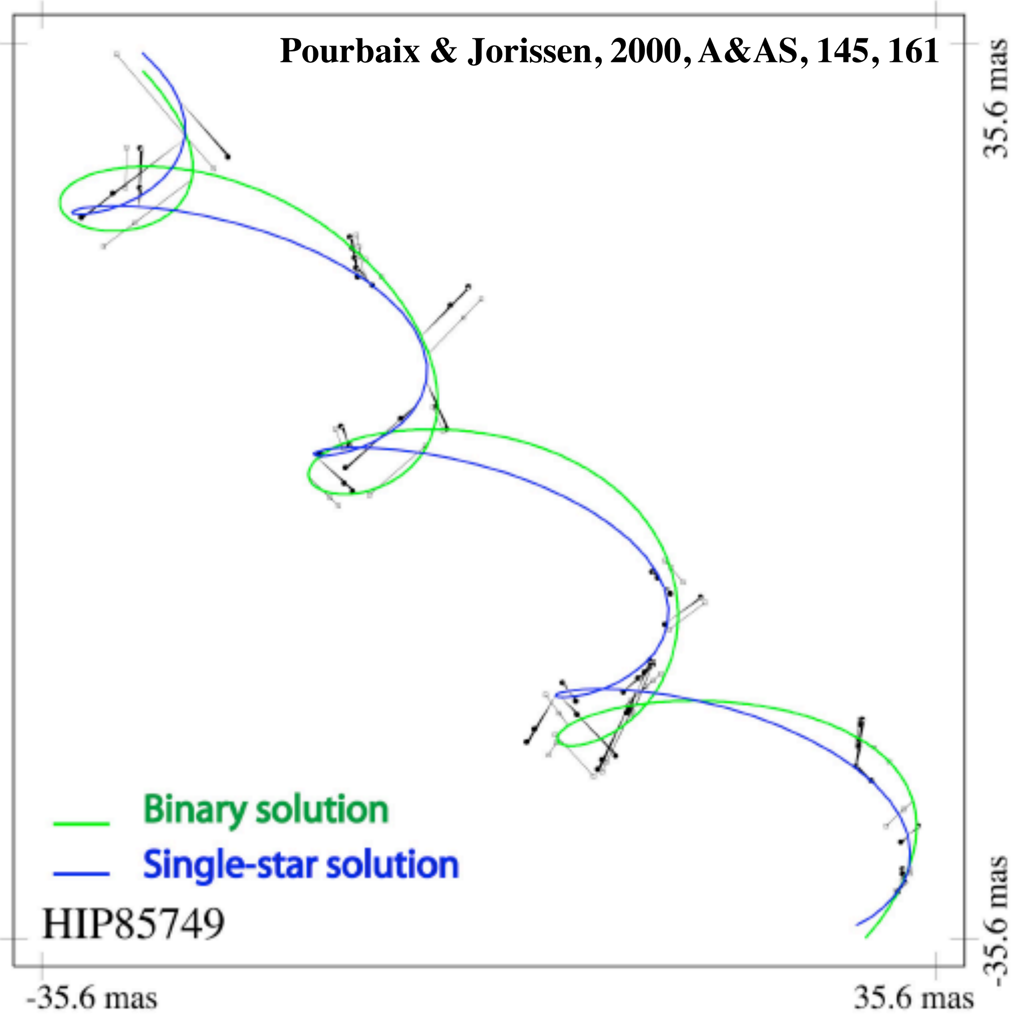


The Hipparcos and Gaia satellites scan the sky and perform 1D positional measurements



Astrometric binaries(II)

Basic principles



Comparison of the parallactic motion of the center of mass

(more precisely photocenter)

with the true motion of the star, after addition of the orbital motion

$$a_{\text{photocentre}} = (a_A + a_B) \times \left(\frac{M_B}{M_A + M_B} - \frac{1}{1 + 10^{0.4 \Delta m}} \right)$$

In case of perfect twins (SB2 with $\Delta m = 0$, $M_A = M_B$):

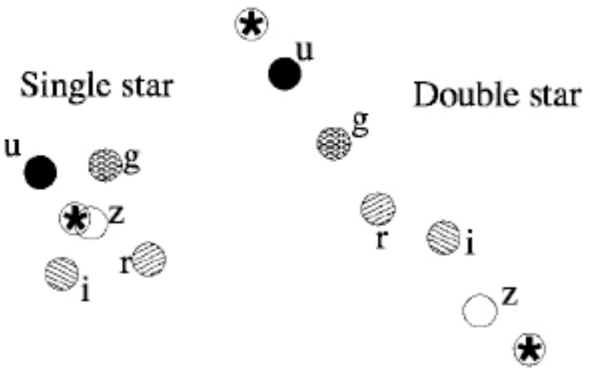
$$a_{\text{photocentre}} = 0$$

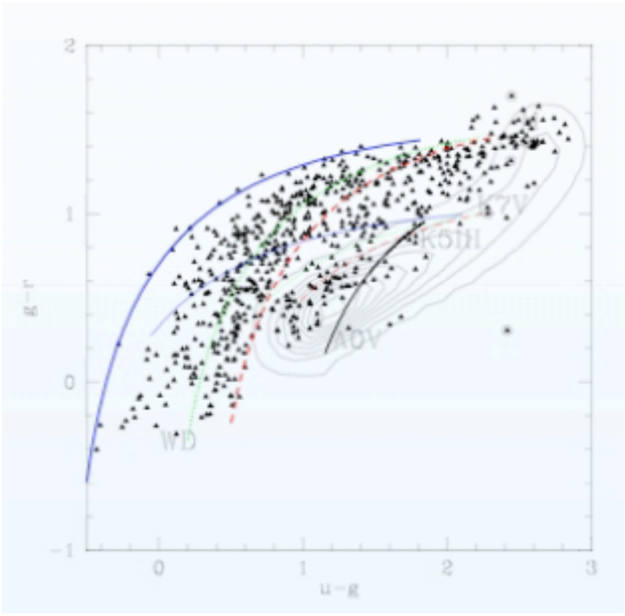
For SB1 ($\Delta m = \infty$):

$$a_{\text{photocentre}} \sim a_A$$

Astrometry (V)

Color-induced displacement - Application to SDSS





The position of the photocentre of two stars with different colours is a function of wavelength (e.g., Gunn *u,g,r,i,z*) but is always located on the segment joining the two stars.

Look for stars with $d(u,z) > 0.2''$
[and exclude asteroids !]

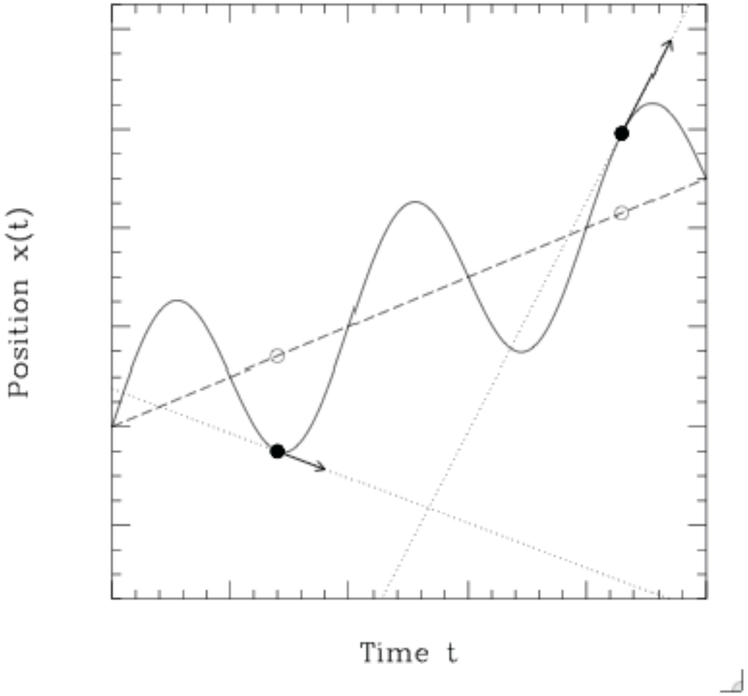
These stars are binaries
(mostly WD + MV pairs)
because they also exhibit composite colors

Pourbaix et al. 2004, A&A 423, 755

Astrometry (VI)

$\Delta\mu$ binaries (I)

Proper motion measured on short time scale (e.g. Hipparcos: 3 y) with respect to orbital period will contain a strong orbital component and will differ from true proper motion measured on long time scale (e.g. Tycho-2: 100 y)



Wielen, 1997, A&A 325, 367

Astrometry (VI)

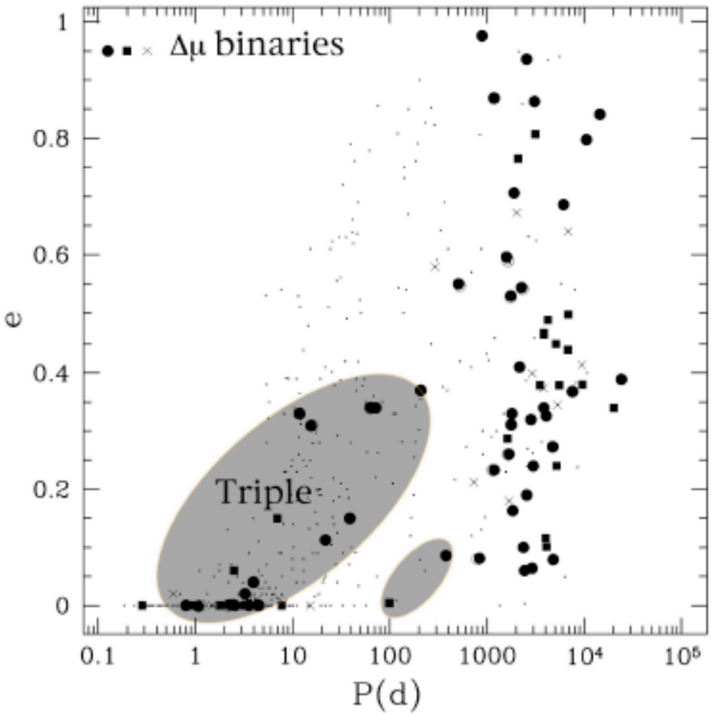
$\Delta\mu$ binaries (II)

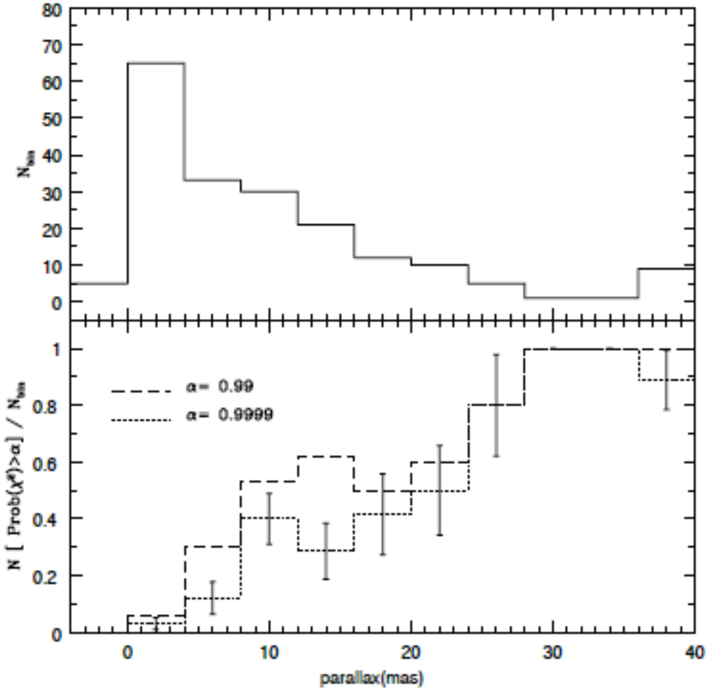
$\Delta\mu$ binaries found among spectroscopic binaries with known P:

- expected at $P >\sim 1500$ d
- triple systems at $P <\sim 400$ d

Frankowski et al. 2007, A&A 464, 377

Detection efficiency of $\Delta\mu$ binaries rises to 100% at parallaxes > 30 mas





The various kinds of binaries

Type	Notation	Two stars visible?	orbit	dimension
visual and interferometric	VB	yes	relative	angular
astrometric	AB	yes no	relative photocentric	angular
spectroscopic	SB2 SB1	yes no	absolute absolute	linear

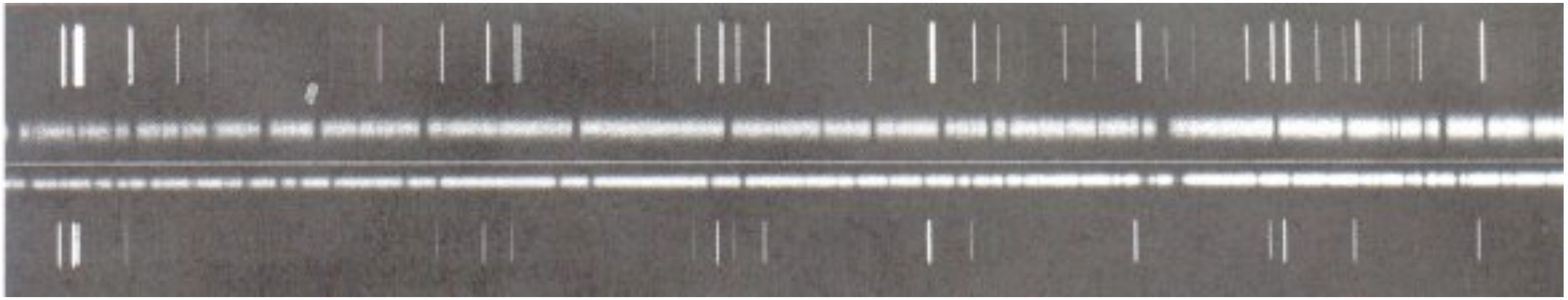
Spectroscopic binaries (I)

Spectral lines of one (SB1) or both (SB2) stars show Doppler shifts

Example: α Gem (SB1)

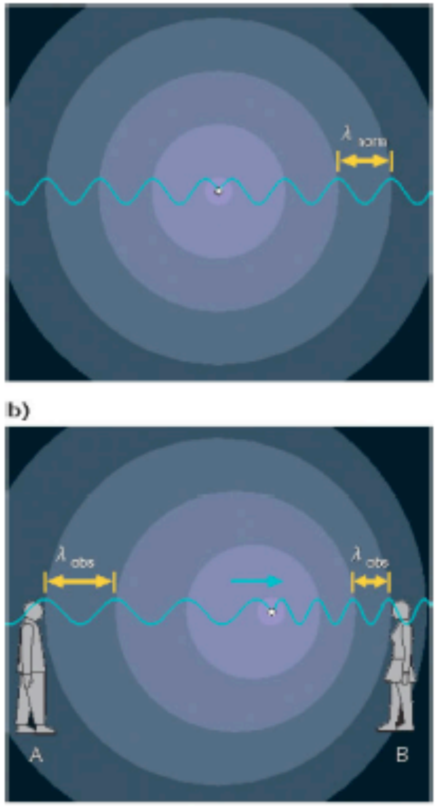

Lab ref
t_1
t_2
Lab ref

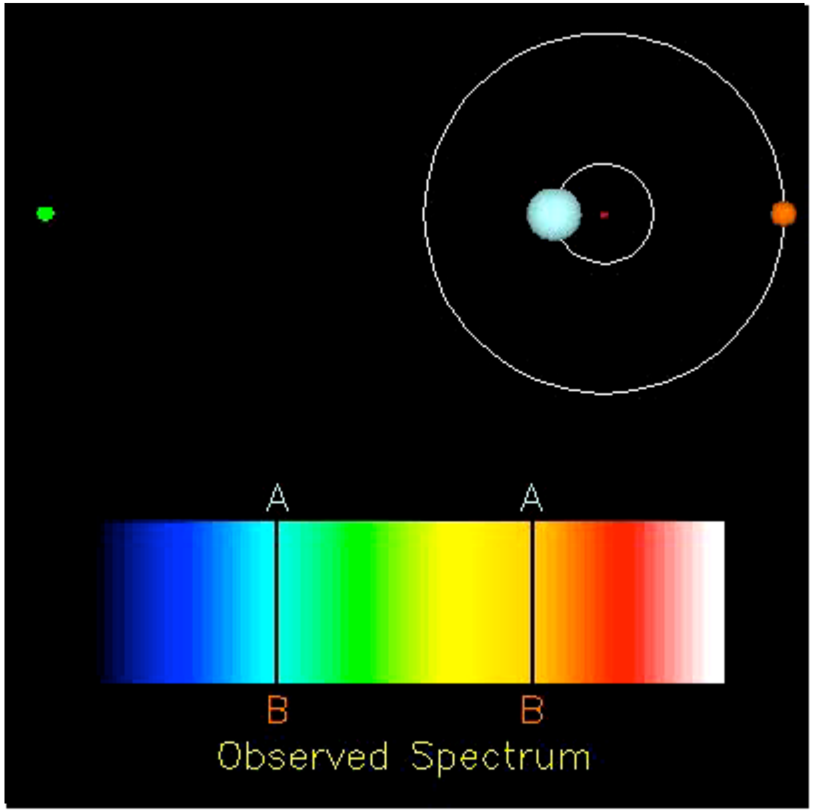
Example: ϰ Ari (SB2)


Lab ref
t_1
t_2
Lab ref

Spectroscopic binaries (I)

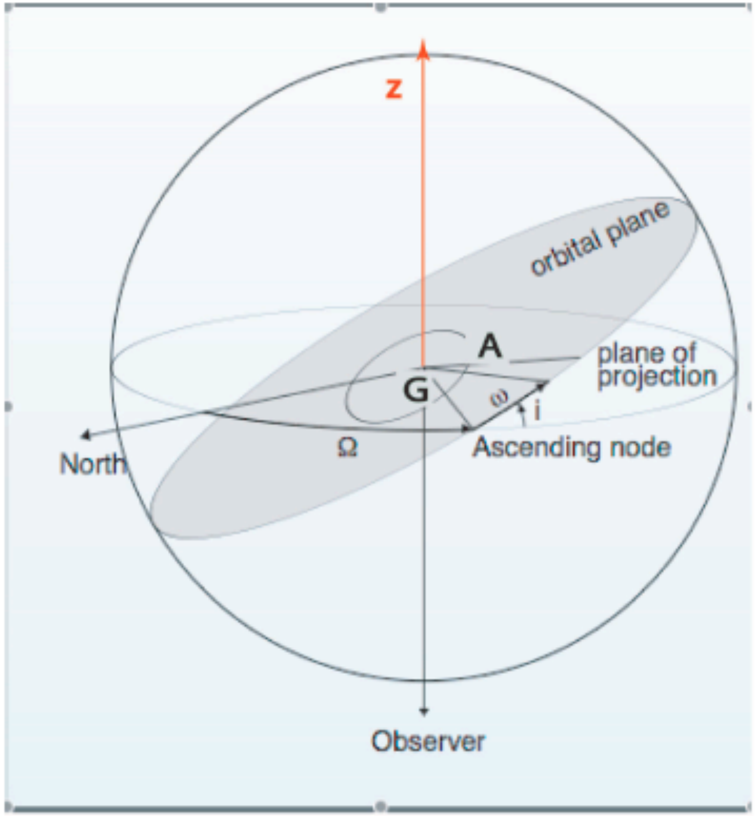
Detection (of absolute orbit) based on the Doppler effect:





Spectroscopic binaries (II)

The radial-velocity curve



G : center of gravity of the A+B components
A : visible component
B : invisible component

$$V_r(\mathrm{A})$$

$$= V_r(\mathrm{G}) \ + \ \mathrm{d}z(\mathrm{A})/\mathrm{dt}$$

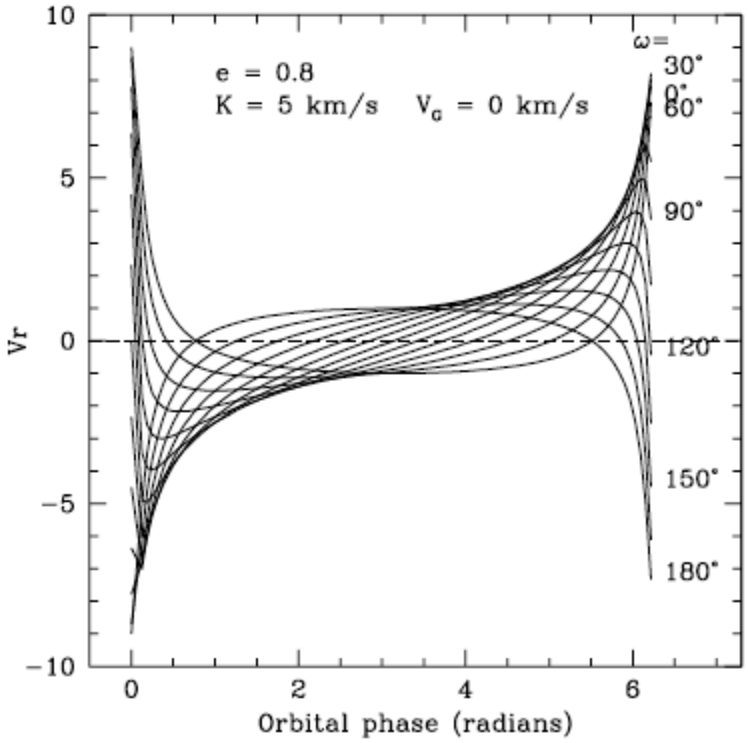
$$= V_r\,(\mathrm{G}) \ + \ K_A\,(e\cos\omega + \cos(\omega + \nu(t)))$$

where

$$K_A = \frac{2\pi}{P} \times \frac{a_A \sin i}{(1 - e^2)^{1/2}}$$

Spectroscopic binaries (III)

The radial-velocity curve



$$V_r(\mathrm{A})$$

$$= K_A\left(e\cos\omega + \cos\left(\omega + \nu(t)\right)\right)$$

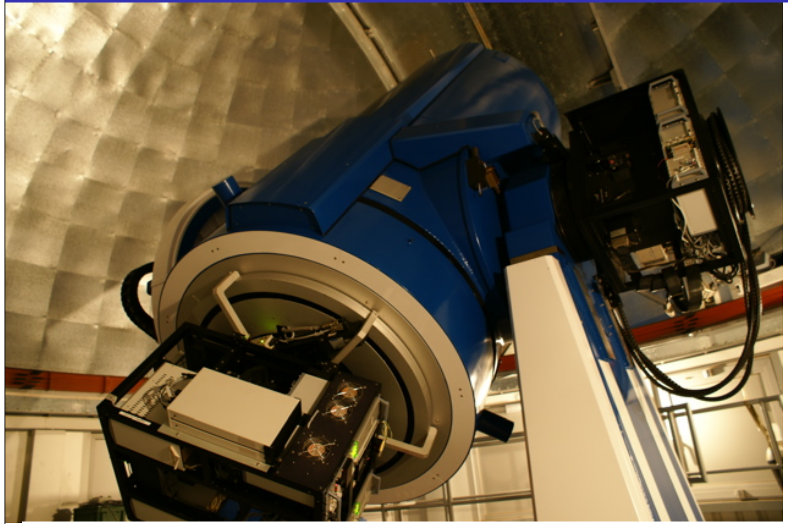
where

$$K_A = \frac{2\pi}{P} \times \frac{a_A \sin i}{(1-e^2)^{1/2}}$$

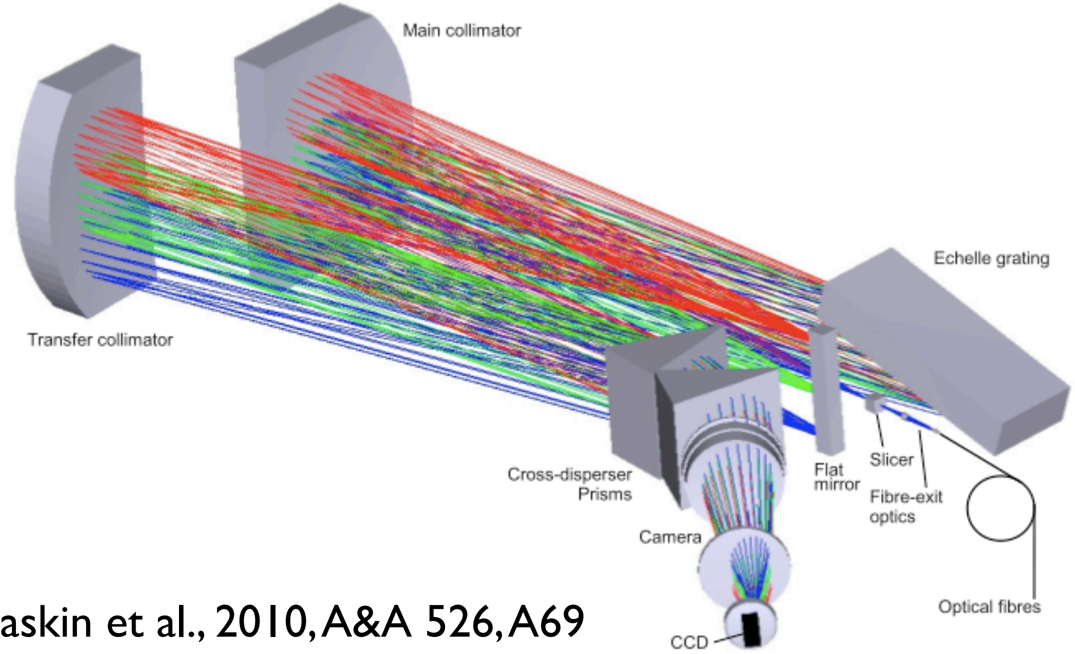
(see also the radial-velocity curve generator at

`http://www.astro.cornell.edu/academics/courses/astro1101/java/binary/binary.htm`

Spectroscopic binaries: HERMES/Mercator spectrograph



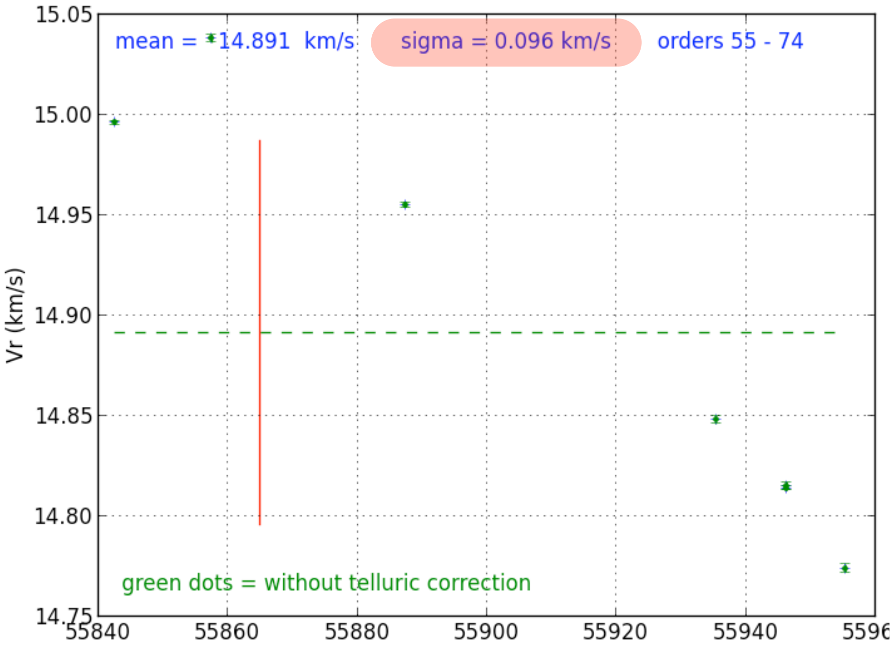
Mercator 1.2m telescope
operated by KULeuven
at Roque de los
Muchachos Observatory
(La Palma, Canary Islands)

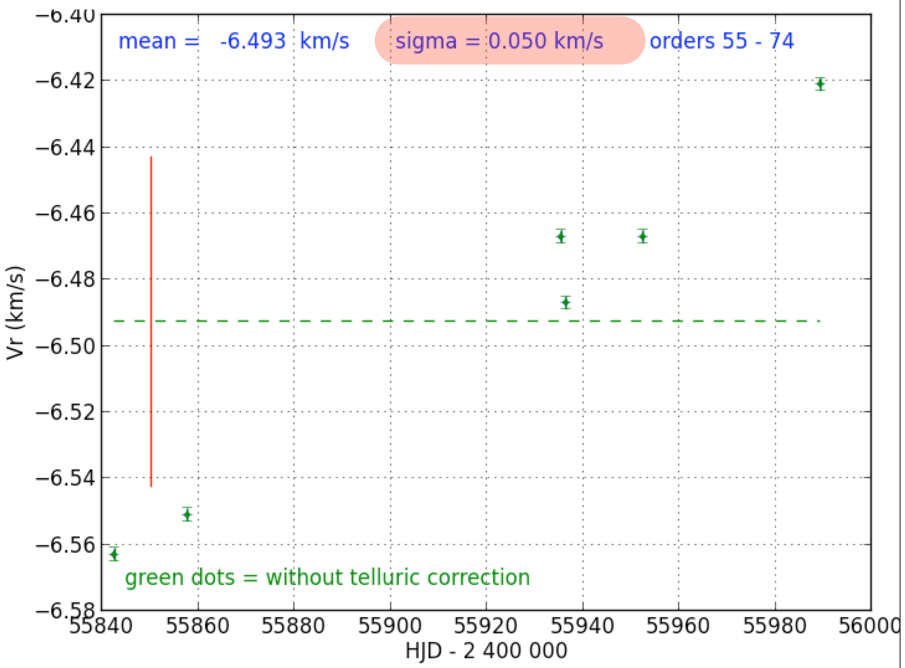


Raskin et al., 2010, A&A 526, A69

Spectroscopic binaries (III)

The radial-velocity curve





Spectroscopy: Difficulties (I)

- A one-dimensional measurement:
  only partial access to orbital elements
- Pulsation of atmosphere (Miras, Cepheids, RV Tau...)
  causes intrinsic velocity variations
  and make binary detection difficult/impossible

Spectroscopy: Difficulties (III)

Only partial access to orbital elements

$$V_r(\mathrm{A}) = K_A\,(e\cos\omega + \cos(\omega + \nu(t)))$$

where

$$K_A = \frac{2\pi}{P} \times \frac{a_A \sin i}{(1-e^2)^{1/2}}$$

- If only one observable spectrum (A) (because companion too faint: on the low MS or WD) :
  - degeneracy between i and a_A: $K_A \propto a_A \sin i$ (relative a cannot be derived)

Spectroscopy: Difficulties (III)

Only partial access to orbital elements

$V_r(\mathrm{A})$
$=$
$K_A\,(e\cos\omega + \cos\,(\omega + \nu(t)))$

where

$$K_A = \frac{2\pi}{P} \times \frac{a_A \sin i}{(1-e^2)^{1/2}}$$

- If only one observable spectrum (A) (because companion too faint: on the low MS or WD) :
  - degeneracy between i and a_A: $K_A \propto a_A \sin i$ (relative a cannot be derived)
  - only mass function $f(M)$ can be derived:
    $$f(M) = \frac{(M_B \sin i)^3}{(M_A + M_B)^2}$$
    $$= K_A^3\; P\; (1-e^2)^{3/2} /\; (2\pi G)$$

Spectroscopy: Difficulties (III)

Only partial access to orbital elements

$V_r(\mathrm{A})$

$=$

$K_A\,(e\cos\omega + \cos(\omega + \nu(t)))$

where

$$K_A = \frac{2\pi}{P} \times \frac{a_A \sin i}{(1 - e^2)^{1/2}}$$

Same for $V_r(B)$ and K_B

- If only one observable spectrum (A) (because companion too faint: on the low MS or WD) :
  - degeneracy between i and a_A: $K_A \propto a_A \sin i$ (relative a cannot be derived)
  - only mass function $f(M)$ can be derived: $$f(M) = \frac{(M_B \sin i)^3}{(M_A + M_B)^2}$$ $$= K_A^3\,P\,(1 - e^2)^{3/2} / \,(2\pi G)$$
- if two observable spectra (components of approx. equal L, aka 'composite spectra'): only $M_A \sin i, M_B \sin i, M_A/M_B$

The various kinds of binaries

and deriving masses

Binaries	Vis. and interf.	Astrometric AB1	 AB2	Spectroscopic SB1	 SB2	Eclipsing
Max $P \sim$ Min $P \sim$	200 y 1 y	100 y 1 y		30 y 1 d		$\sim$ 1 y 1 h
i ?	yes	yes	yes	no	no	yes
a ? (units)	$a_A + a_B$ ('')	$a_{\mathrm{photocentre}}$ ('')	$a_{A,B}$ ('')	$a_A \sin i$ (km)	$a_{A,B} \sin i$ (km)	a (R_*)
Masses	$(M_A + M_B)d^3$		$M_{A,B}$	$\frac{(M_B \sin i)^3}{(M_A + M_B)^2}$	$M_{A,B} \sin^3 i$	

AB2 systems are rare (Sirius, α Cen: Demarque et al. 1986)

Ecl + SB2 (Ex: HD 35155): individual masses may be derived **or Vis + SB2 or Astrom. + SB2**

Spectroscopy: Difficulties (I)

Despite the fact that the spectral Doppler shift is unavoidable in a binary, there are binary families however where it is hard, even impossible, to detect:

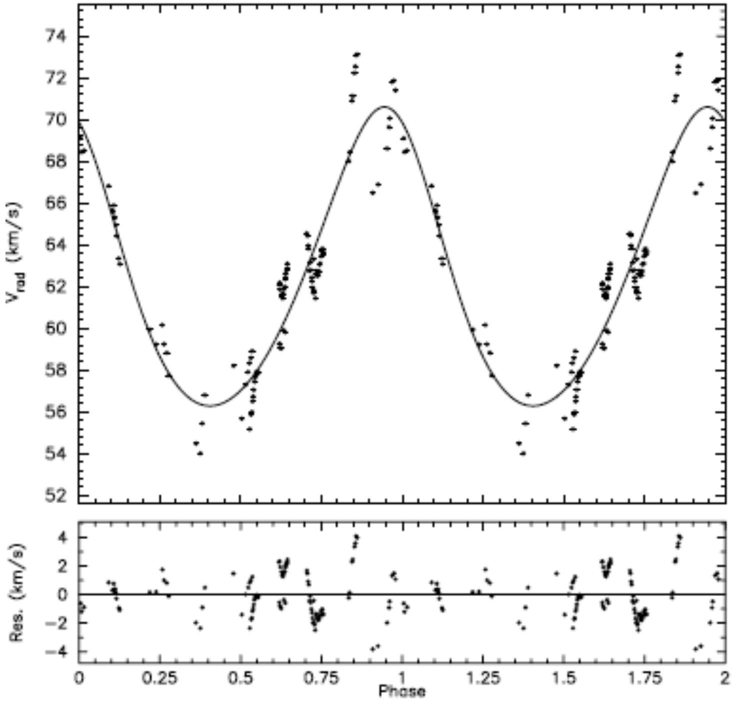
- Pulsation of atmosphere (Miras, Cepheids, RV Tau...) causes intrinsic velocity variations and make binary detection difficult/impossible

Spectroscopy: Difficulties (IV)

Intrinsic radial velocity variations: RV Tau

Binary post-AGB star IRAS 08544-4431

Orbital solution:



Orbital residuals due to pulsation

RV Tau variable:

$P_{\mathrm{orb}} = 499$ d, $K_{\mathrm{orb}} = 8$ km/s

Note that $K_{\mathrm{puls}} < K_{\mathrm{orb}}$

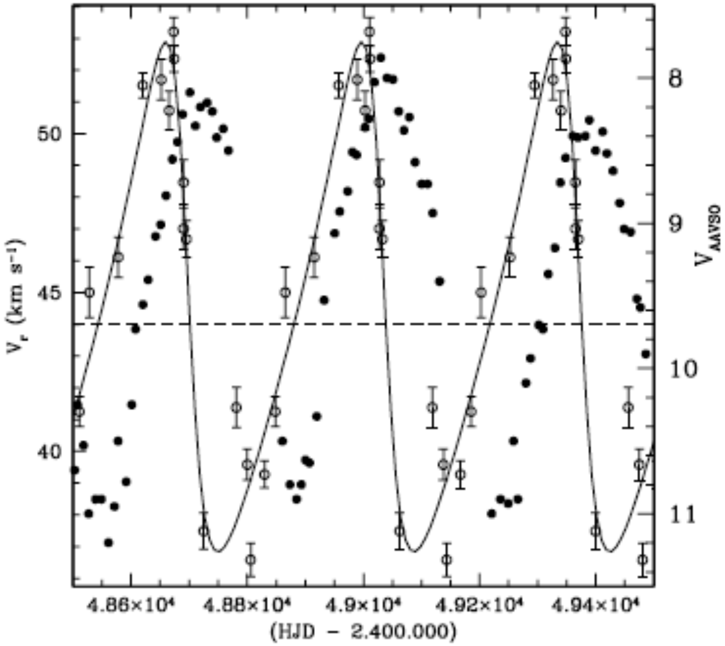
$\rightarrow$ Orbit could be derived !

$P_{\mathrm{puls}} \sim 90$ d, $K_{\mathrm{puls}} = 4$ km/s

(Maas et al., 2003, A&A 405, 271)

Spectroscopy: Difficulties (V)

Intrinsic radial-velocity variations: Miras



(Jorissen, 2003, AGB Stars, eds. Habing & Olofsson, Springer)

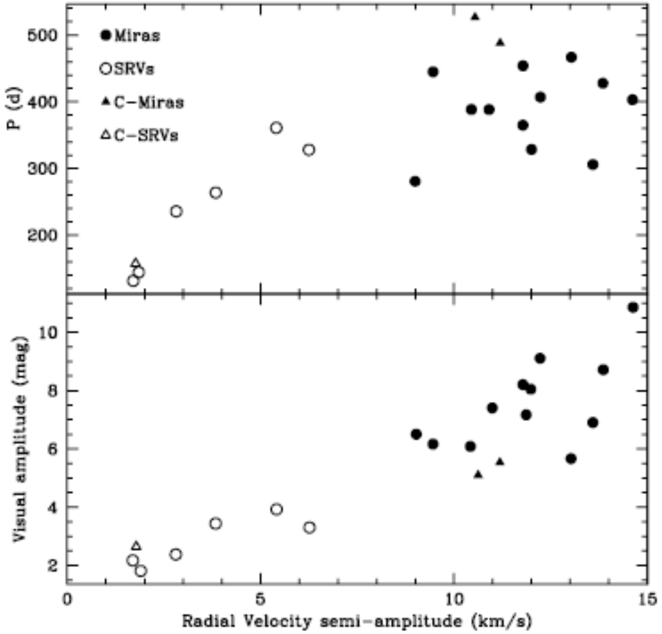
The radial-velocity curve (0) of the Mira star R CMi is strongly correlated with its light curve (●)

$P_{\rm puls} = 337.8$ d;
$K_{\rm puls} = 8$ km/s

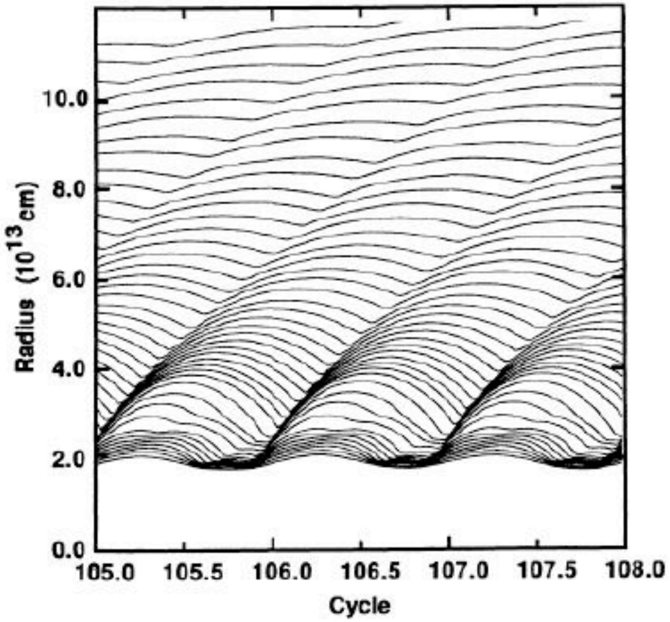
→ intrinsic Vr variations due to pulsation

Spectroscopy: Difficulties (VII)

Intrinsic radial-velocity variations: Miras



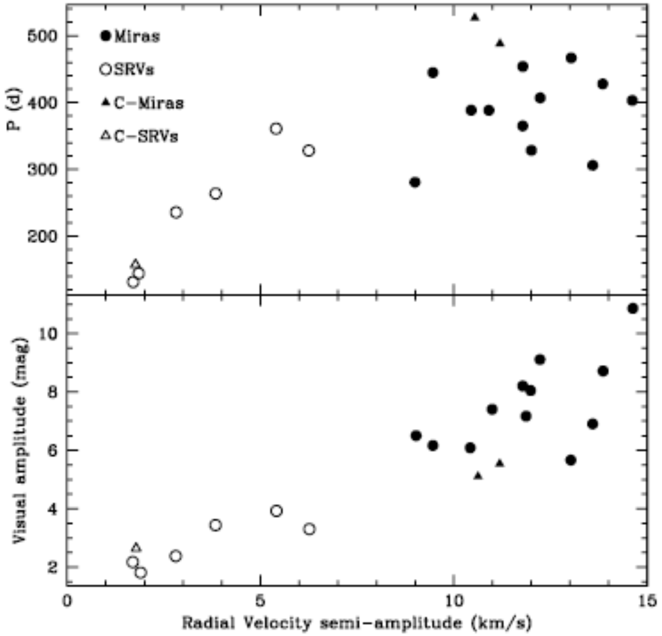
Vr semi-amplitude $K_{\mathrm{puls}} \geq 10$ km/s due to pulsation for Mira variables



(Jorissen, 2003, AGB Stars, eds. Habing & Olofsson, Springer)

Spectroscopy: Difficulties (VIII)

Intrinsic radial-velocity variations: Miras



(Jorissen, 2003, AGB Stars, eds. Habing & Olofsson, Springer)

Vr semi-amplitude $K_{\rm puls} \geq 10$ km/s due to pulsation for Mira variables

$K_{\rm orb}$ (km/s) =
213 $f(M_A, M_B)^{1/3}\ P^{-1/3}({\rm d})\ (1 - e^2)^{-1/2}$

Adopting

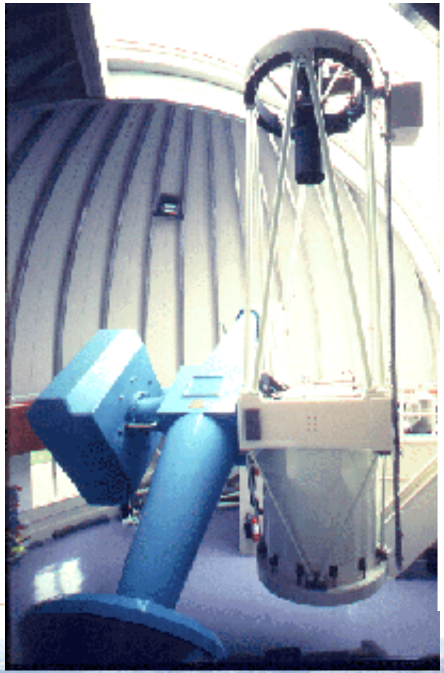
$P = 1000$ d, $e = 0$, $M_A = 1.5$ M$_o$, $M_B = 0.5$ M$_o$

yields $K_{\rm orb} = 6.7$ km/s $< K_{\rm puls}$

Not many spectroscopic binaries are known among Mira variables because $K_{\rm orb} \leq K_{\rm puls}$

Other detection methods must be used!

Photometry: MACHO (I)

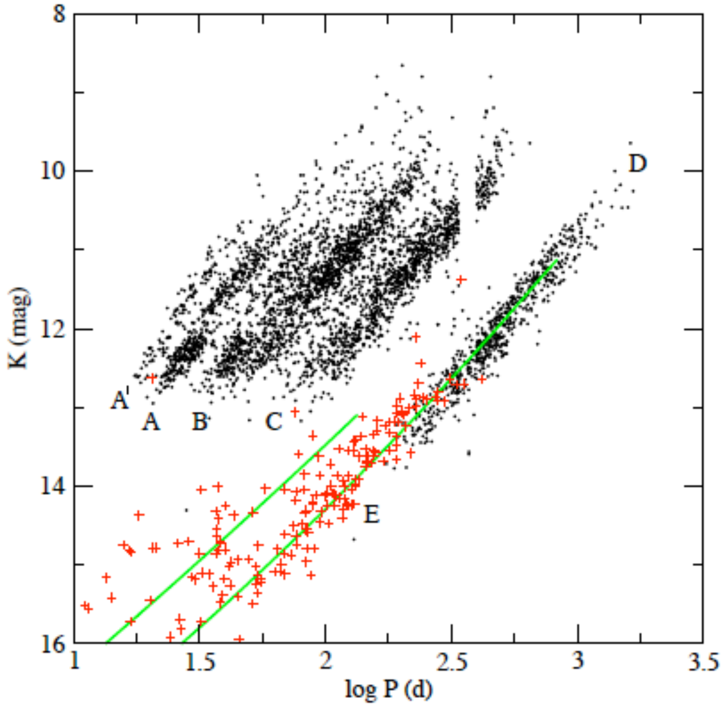


Originally, a survey for micro lensing events in the LMC with Mount Stromlo 50” telescope

Photometry: MACHO (II)

A survey of long-period variables in the LMC

P-L relationship for LPVs in LMC



Wood 2000, PASA 17,18; Derekas et al., 2006, ApJ 650, L55

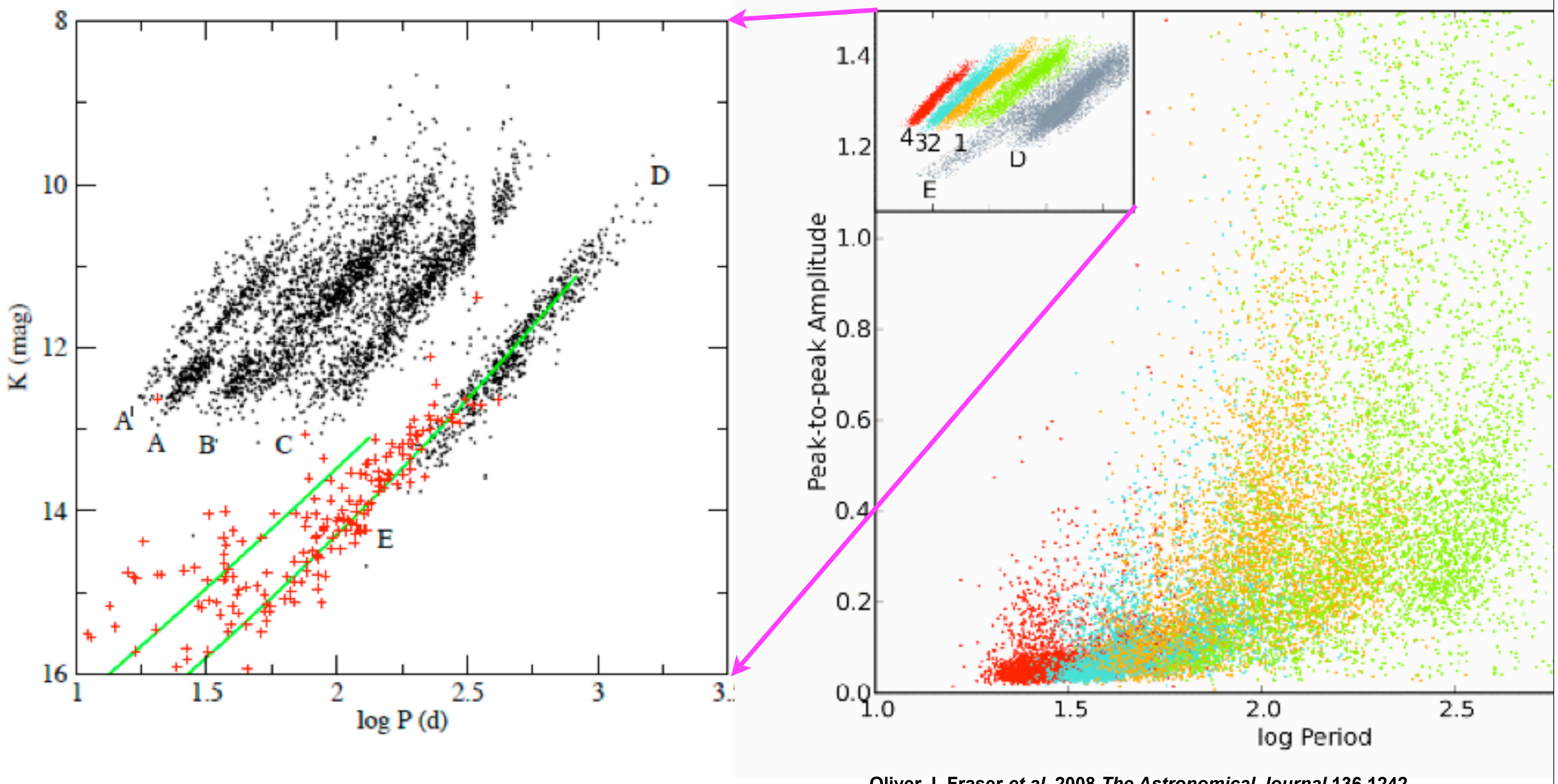
C	Mira fundamental mode
A, B	higher overtones

The enigmatic D and E sequences

Photometry: MACHO (III)

A survey of long-period variables in the LMC

1 = C = fundamental Mira pulsators
2, 3, 4 = A’, A, B = overtone pulsators



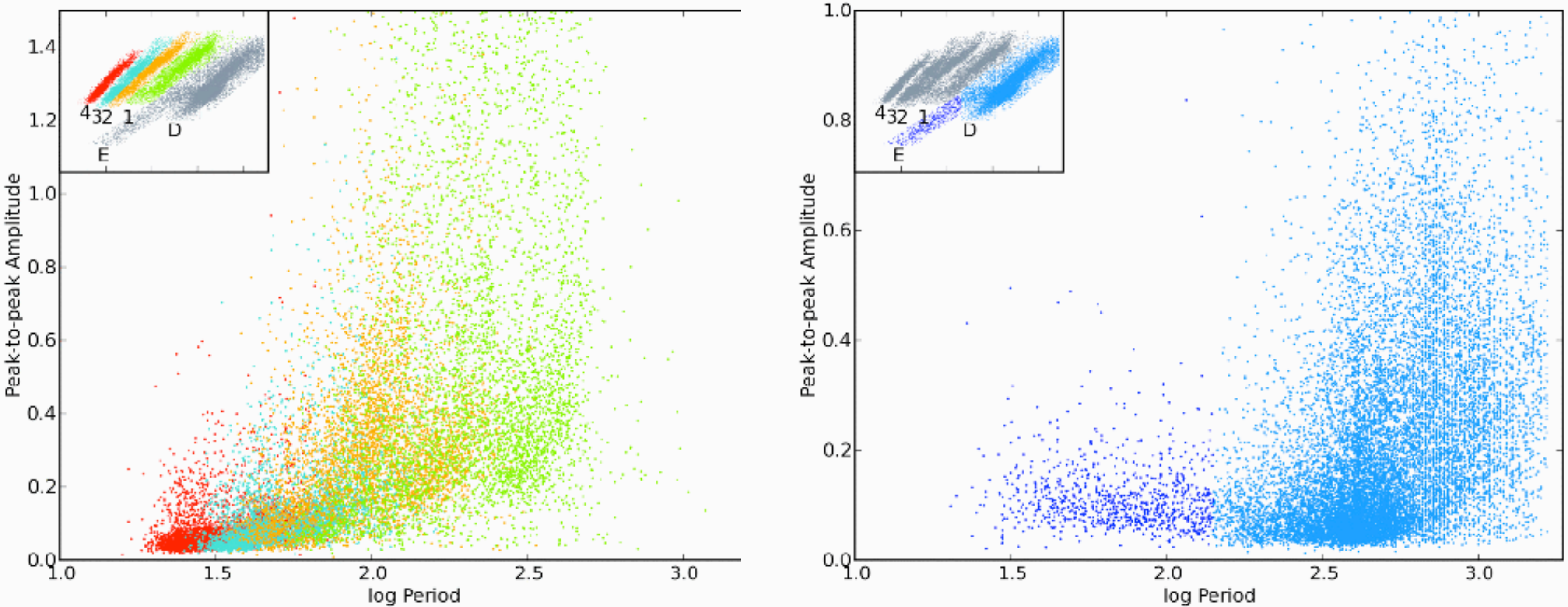
Oliver J. Fraser *et al.* 2008 *The Astronomical Journal* 136 1242

Photometry: MACHO (IV)

A survey of long-period variables in the LMC

1 = C = fundamental Mira pulsators
2, 3, 4 = A’, A, B = overtone pulsators

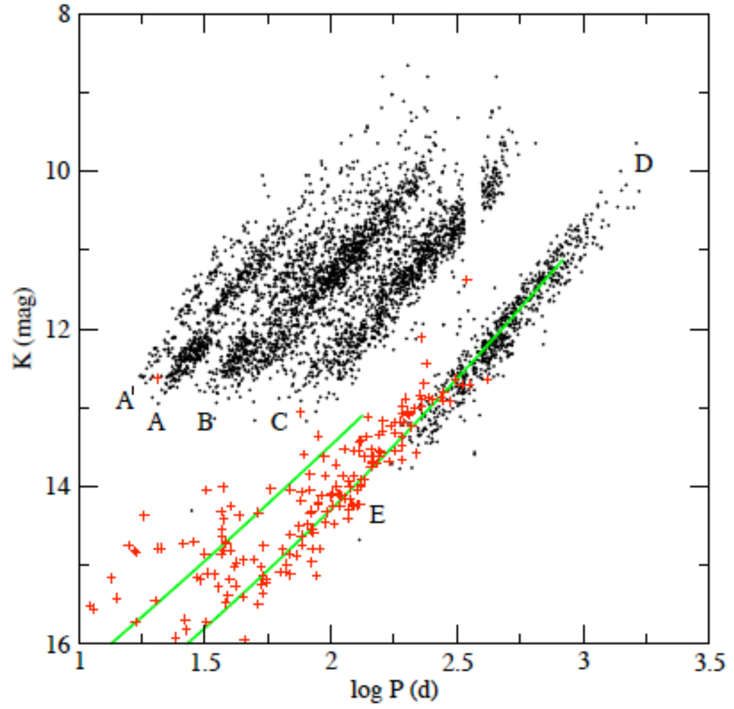
The enigmatic D and E sequences



Oliver J. Fraser *et al.* 2008 *The Astronomical Journal* 136 1242

Photometry: MACHO (V)

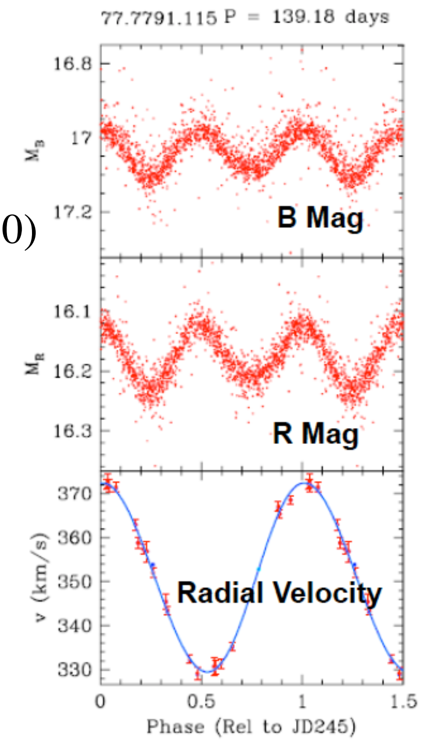
P-L relationship for LPVs in LMC



Wood 2000, PASA 17,18; Derekas et al., 2006, ApJ 650, L55

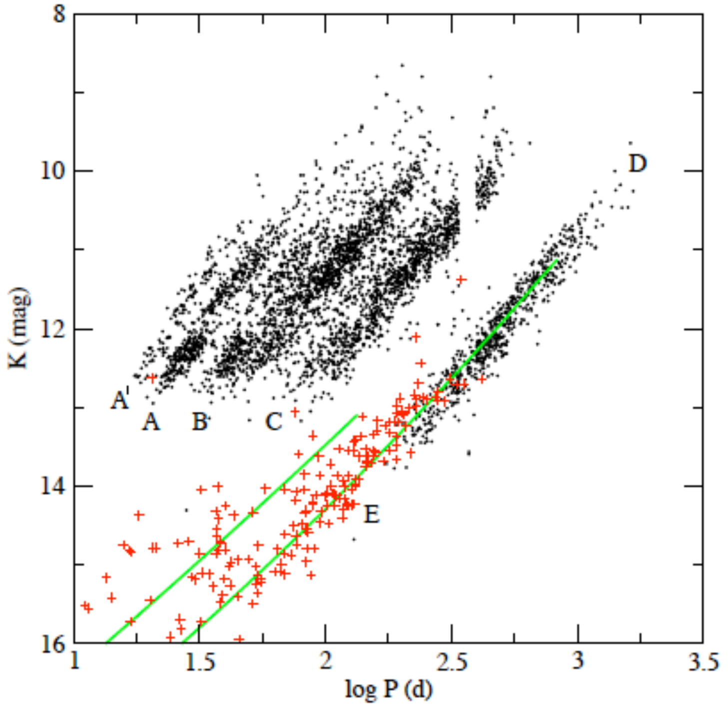
C	Mira fundamental mode
A, B	higher overtones
E	eclipsing & ellipsoidal (+)

Nicholls et al.
(2010 MNRAS 405, 1770)
from radial velocities
confirm that sequence E
stars are binaries



Photometry: MACHO (V)

P-L relationship for LPVs in LMC



Wood 2000, PASA 17,18; Derekas et al., 2006, ApJ 650, L55

C	Mira fundamental mode
A, B	higher overtones
E	eclipsing & ellipsoidal (+)
D	??

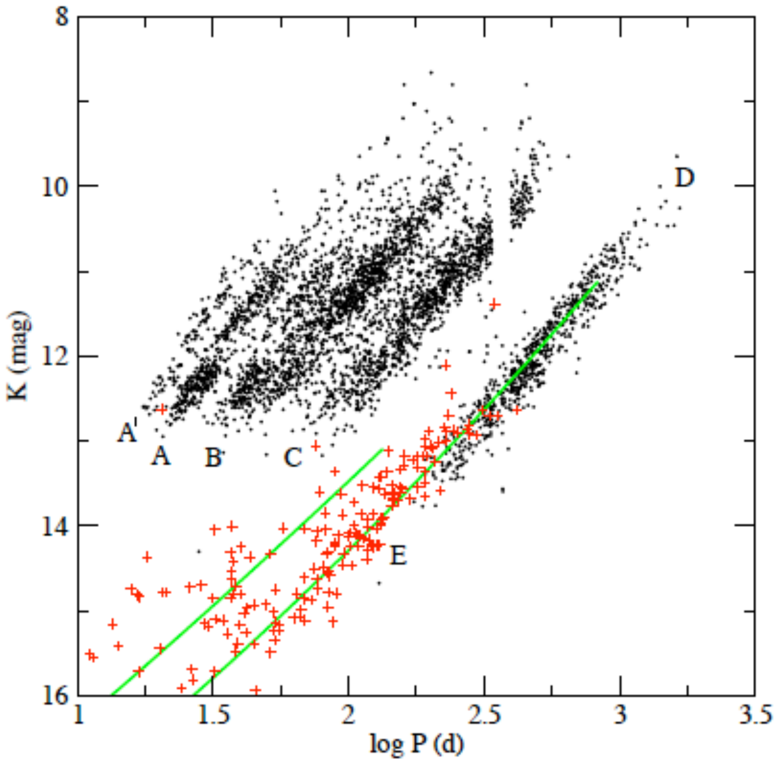
(also called 'LSP': 'long secondary periods')

25% of LMC LPV are on sequence D (!),

Can they all be binaries ?

For comparison, among M giants, the frequency of spectroscopic binaries with periods in the range 200 - 10000 d is between 16 and 21%

Photometry: MACHO (VII)

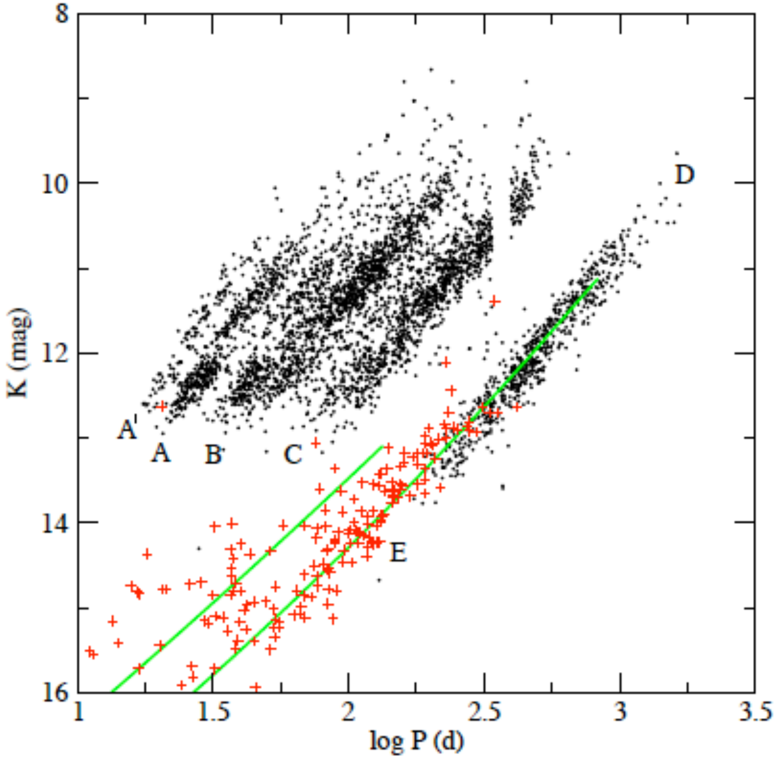


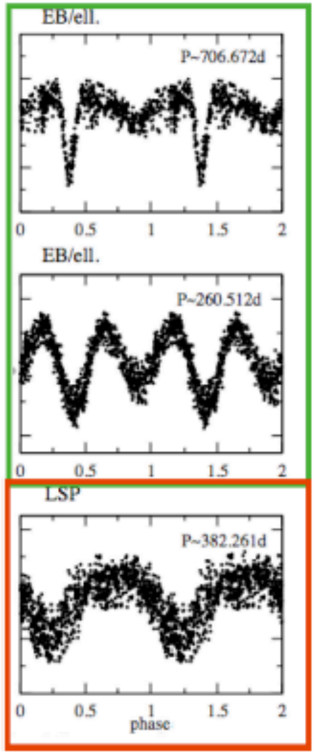
Green lines = *P* for RLOF

Derekas et al., 2006, ApJ 650, L55

→25% of LMC LPVs fill their Roche lobe if all sequence D stars are binaries !?

Photometry: MACHO (VII)





Only 5%
among D sequence
show clear eclipsing
or ellipsoidal behaviour

What is the nature of the other D stars ?

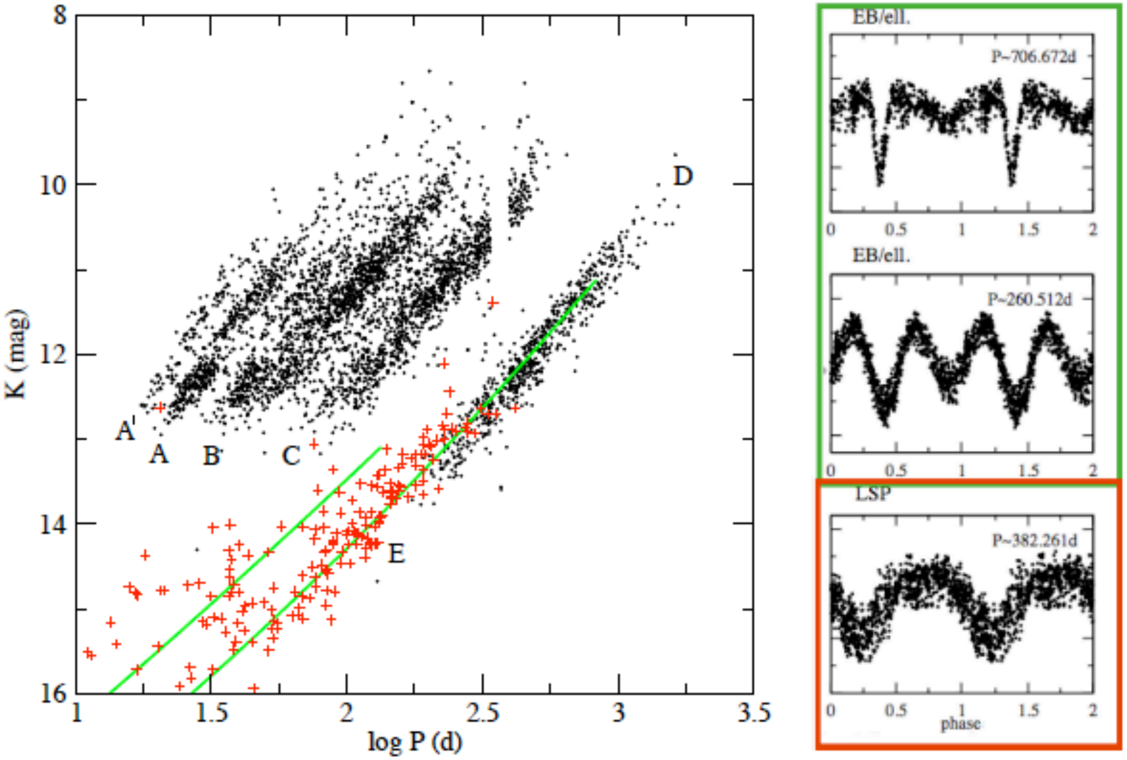
Green lines = *P* for RLOF

Derekas et al., 2006, ApJ 650, L55

Photometry: MACHO (VII)

Binaries among LPVs: none from spectroscopy, too many from MACHO!

25% of LMC LPVs fill their Roche lobe if all sequence D stars are binaries !?



Green lines = *P* for RLOF

Derekas et al., 2006, ApJ 650, L55

Only 5%
among D sequence
show clear eclipsing
or ellipsoidal behaviour

What is the nature
of the other D stars?

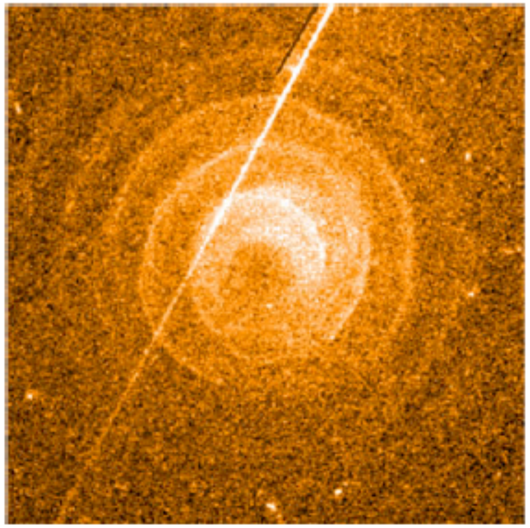
D sequence caused by
dust obscuration
in Roche-lobe-filling
AGB stars?
(Soszynski 2007, ApJ, 660, 1486)
Dust in spiral wave
forming around binary
LPVs,

as predicted by SPH

simulations

Direct imaging of circumstellar shell:

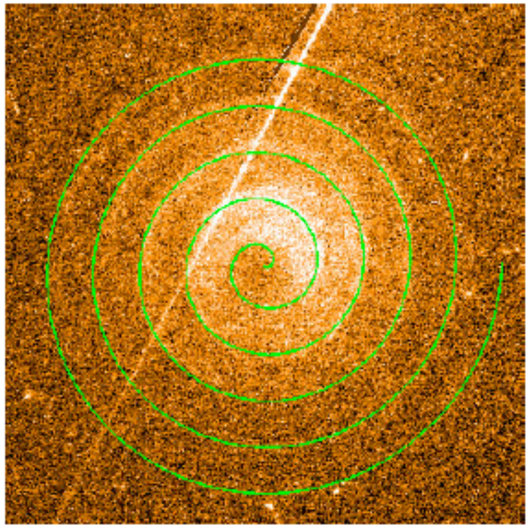
The proto PN AFGL 3068

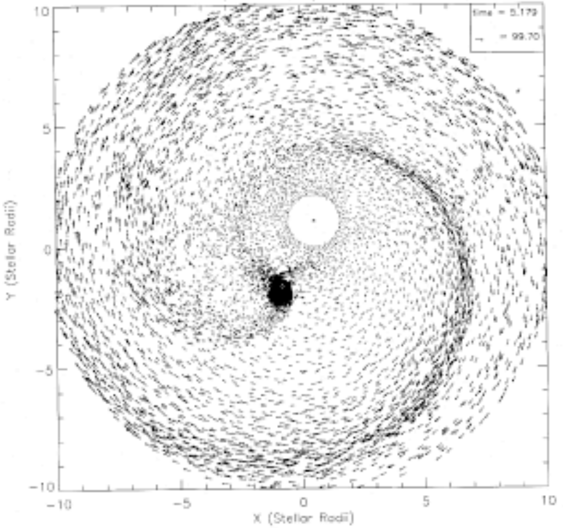


Mauron & Huggins, 2006, A&A 452, 257

Periodic dust obscuration from this spiral wave is probably what causes variability along D sequence

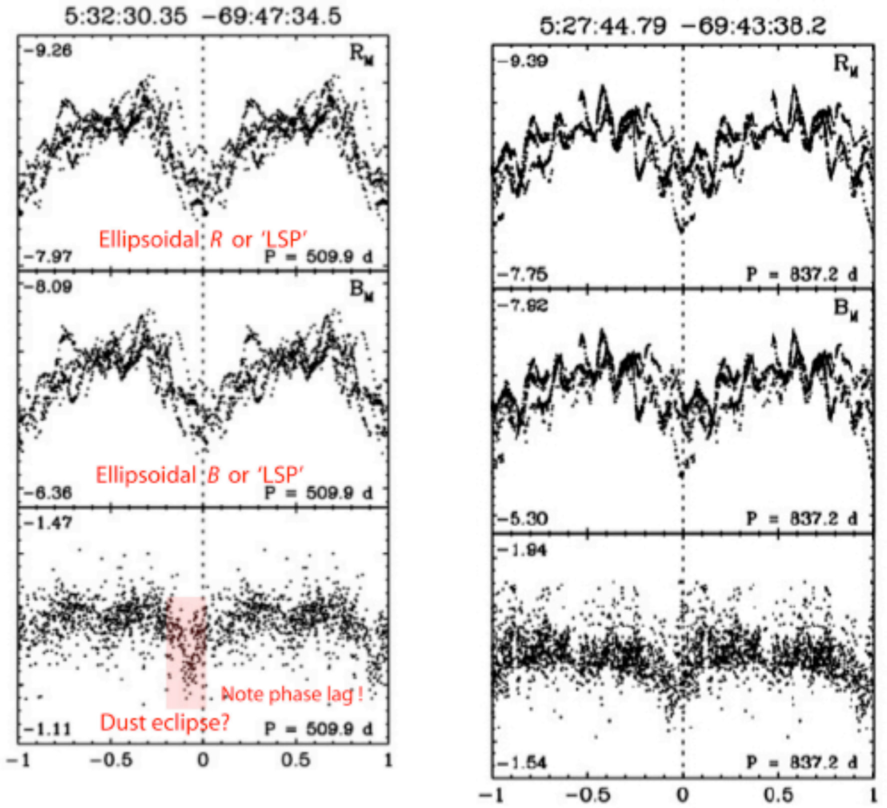
Theuns & Jorissen 1993, MNRAS 265, 946
Mastrodemos & Morris 1998, ApJ 497, 303
Nagae et al. 2004, A&A 419, 335





More on photometry

Eclipses by dust: stars on sequence D



Soszynski 2007 ApJ 660, 1486

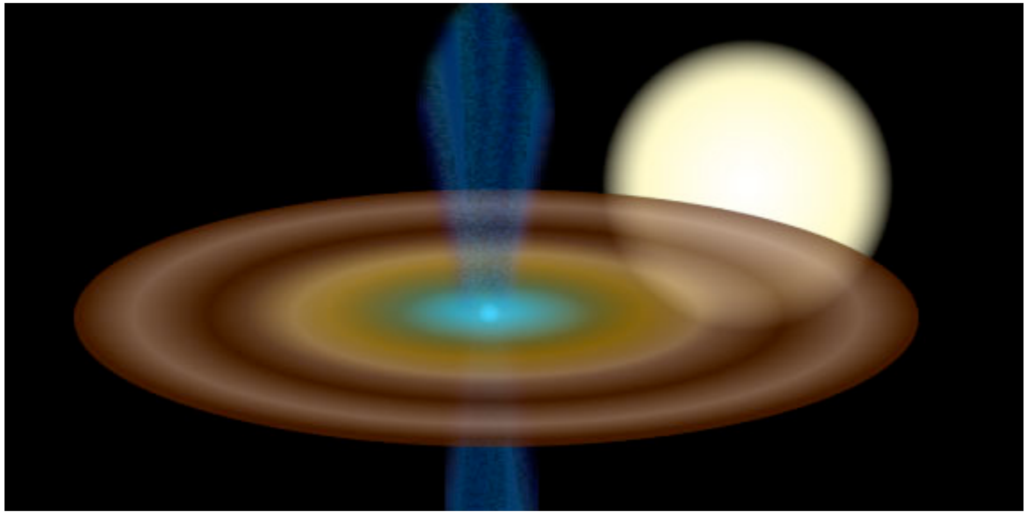
R band

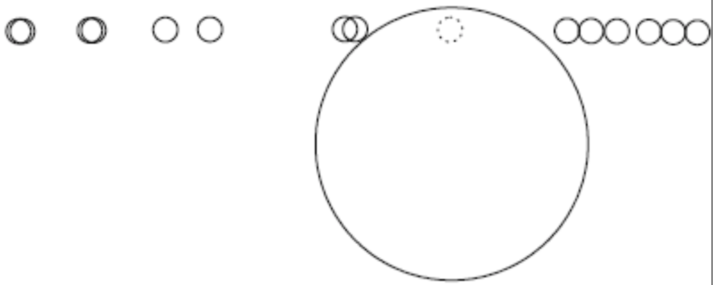
B band

R-B : low-amplitude eclipses show up

Note the phase lag

Photometric binaries:
Eclipsing





Other classes of eclipsing binaries :

- **ε Aur : eclipses by an inclined disk, with a 27-yr period**

- **ζ Aur and VV Cep : eclipses of a hot main-sequence star by the atmosphere of a giant or supergiant : eclipses probe the wind from the hot star**

Carpenter, 1992, IAU Symp 151, 51

The various kinds of binaries

Type	Notation	Two stars visible?	orbit	dimension
visual and interferometric	VB	yes	relative	angular
astrometric	AB	yes no	relative photocentric	angular
spectroscopic	SB2 SB1	yes no	absolute absolute	linear
photometric (eclipsing, ellipsoidal)	EB	'yes' (composite)	relative	relative (radius *)

A given system may belong to more than one category!

Photometric binaries:
Eclipsing, ellipsoidal

a. Detached system

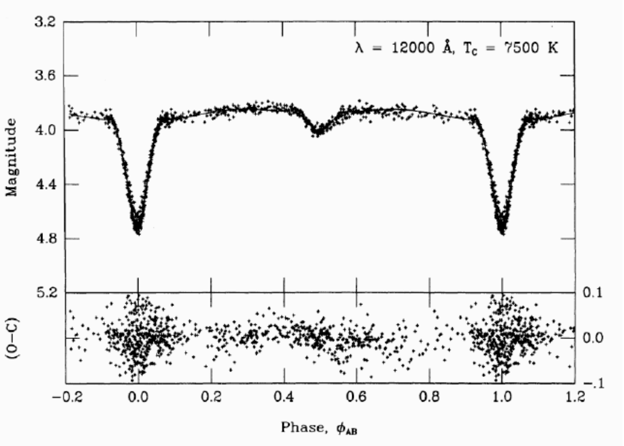
b. Semi-detached system

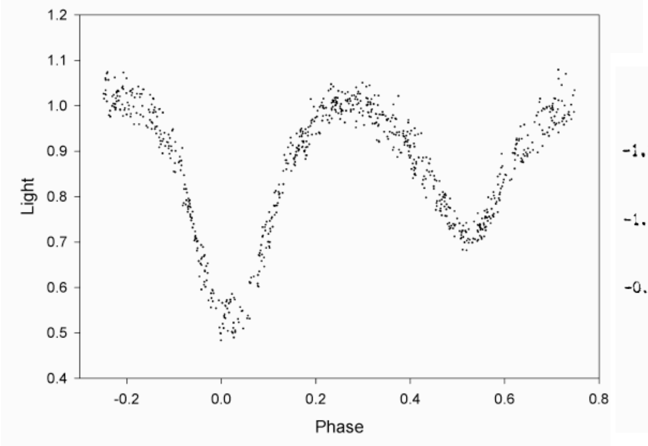
aka ellipsoidal

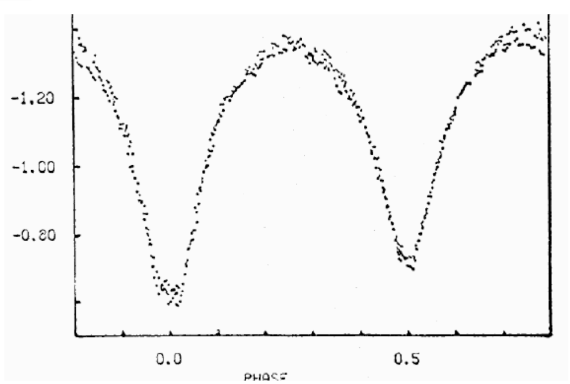
c. Contact system

β Per / β Lyr / W Ser / SV Cen

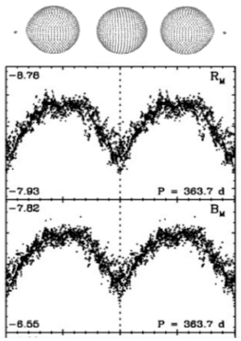
W UMa







For semi-detached and contact systems, the photometric variations must be (close to) achromatic

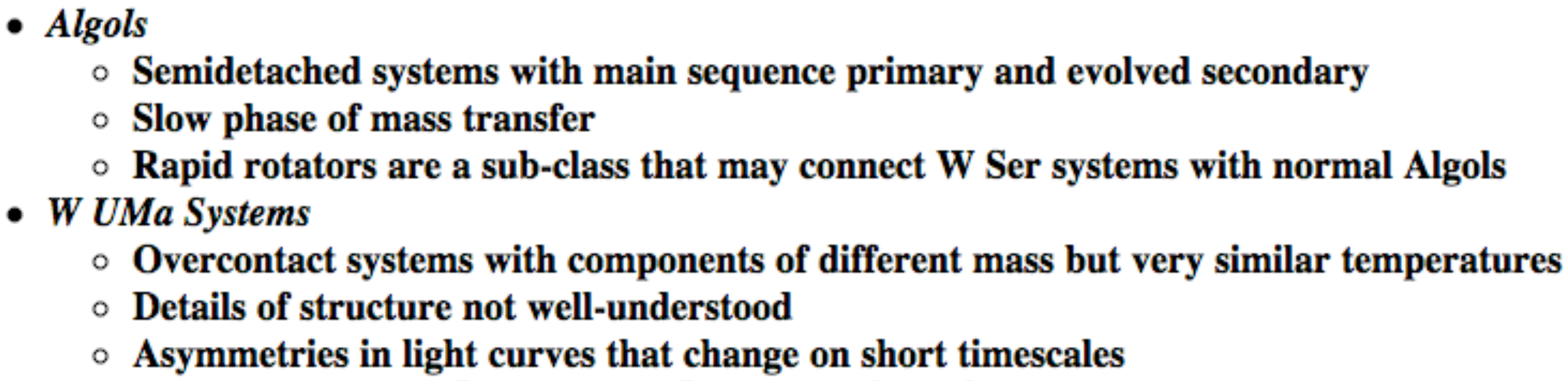


R band

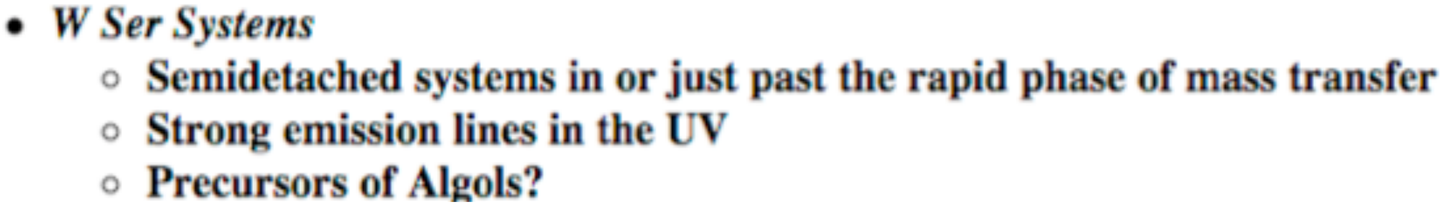
B band

Photometric binaries

These are the binaries we just discussed :



- *Algols*
  - **Semidetached systems with main sequence primary and evolved secondary**
  - **Slow phase of mass transfer**
  - **Rapid rotators are a sub-class that may connect W Ser systems with normal Algols**
- *W UMa Systems*
  - **Overcontact systems with components of different mass but very similar temperatures**
  - **Details of structure not well-understood**
  - **Asymmetries in light curves that change on short timescales**



- *W Ser Systems*
  - **Semidetached systems in or just past the rapid phase of mass transfer**
  - **Strong emission lines in the UV**
  - **Precursors of Algols?**

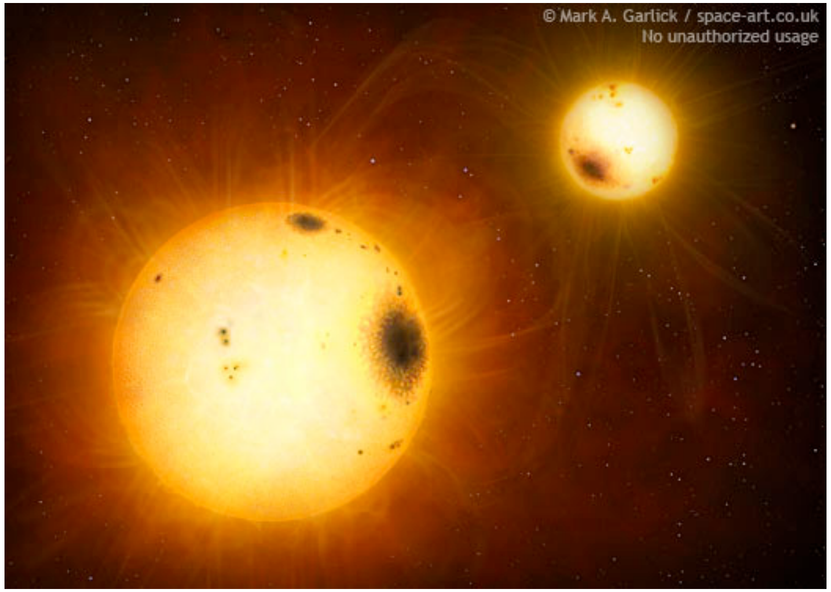
Other classes of eclipsing binaries :

- ε Aur : eclipses by an inclined disk

- ζ Aur and VV Cep : eclipses of a hot main-sequence star by the atmosphere of a giant or supergiant

Photometric binaries:
Spotted

- ***RS CVn Systems***
  - **Detached systems with F or G-type primary and K subgiant secondary**
  - **Enormous cool spots that migrate on a yearly timescale**
  - **The binary system is close enough (P < 100 d) for the stars to be spun up by tidal locking, which then causes a dynamo effect, magnetic field, and spots**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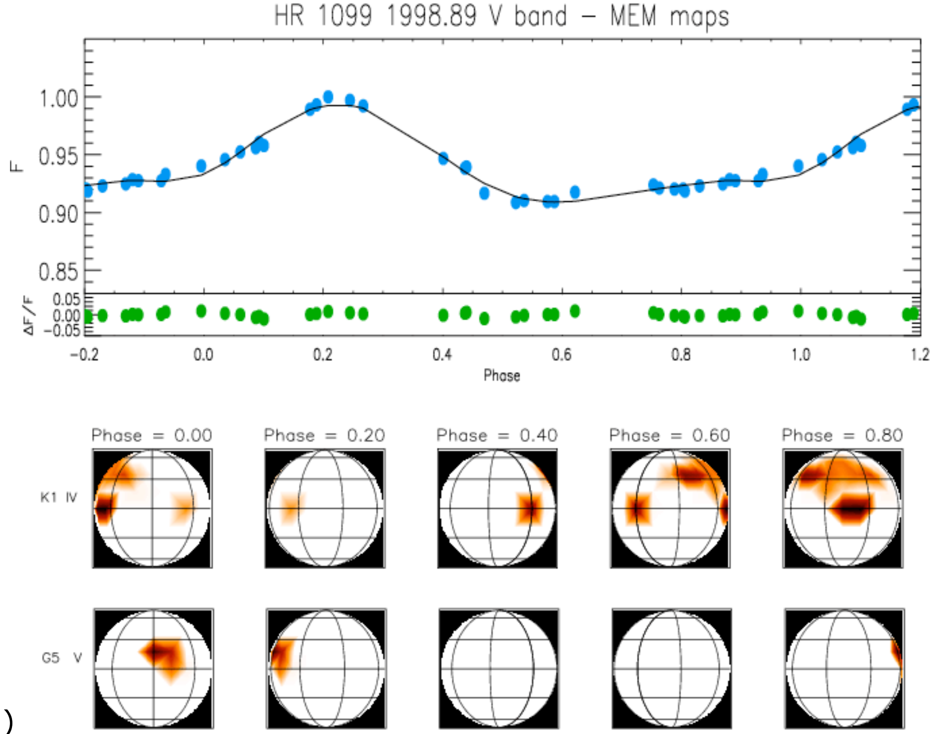
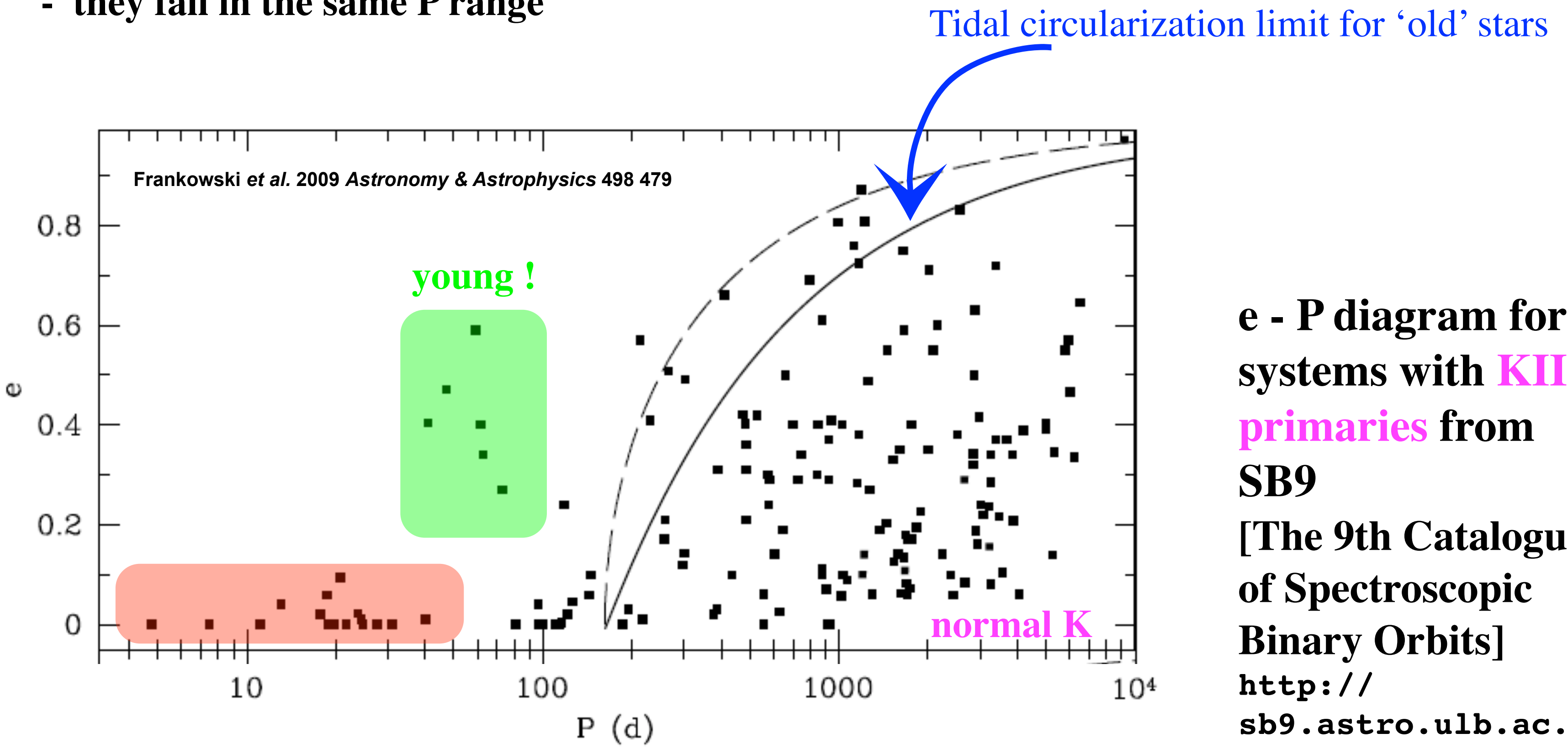


Garcia-Alvarez et al., A&A 397, 285-303 (2003)

Eccentricity - period diagrams

RS CVn often confused with pre-MS binaries, because

- both have spectral type K
- they fall in the same P range

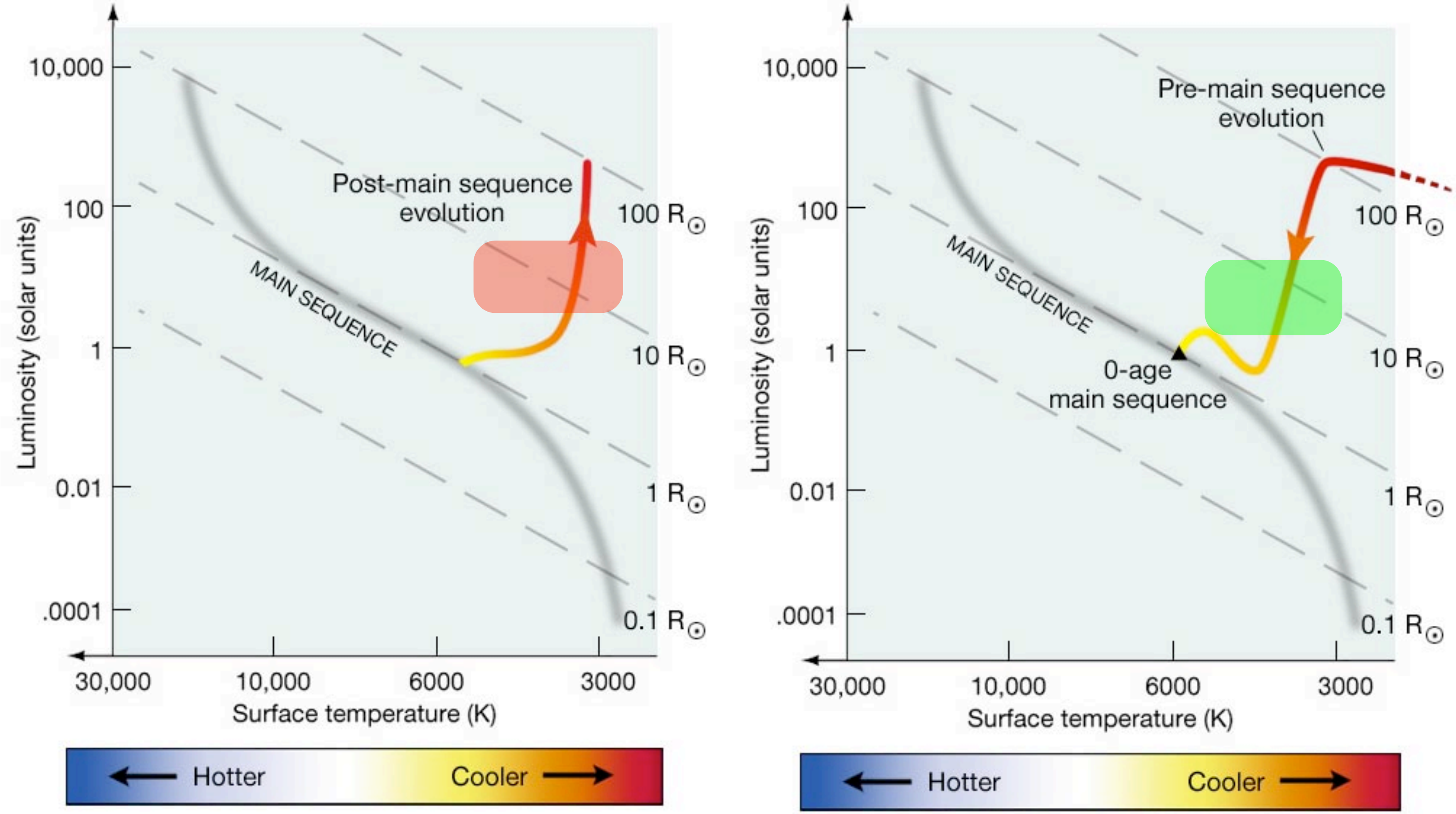


e - P diagram for systems with KIII primaries from SB9

[The 9th Catalogue of Spectroscopic Binary Orbits]

`http://sb9.astro.ulb.ac.be`

RS CVn versus pre-main-sequence

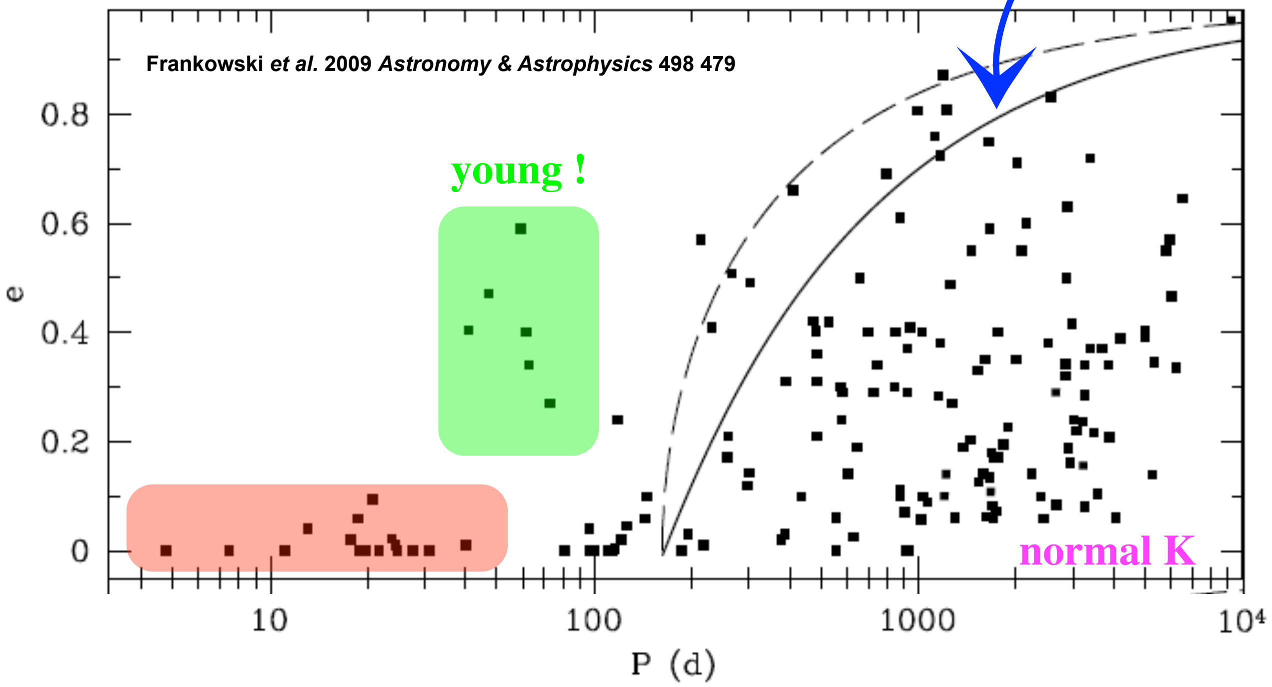


Eccentricity - period diagrams

RS CVn often confused with **pre-MS binaries,** because

- both have spectral type K
- they fall in the same P range

Tidal circularization limit for ‘old’ stars



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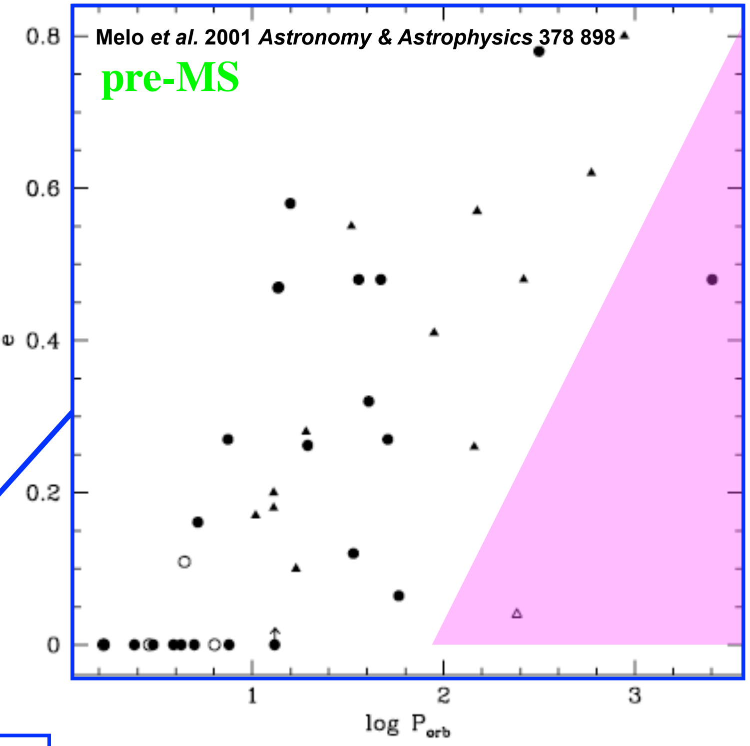
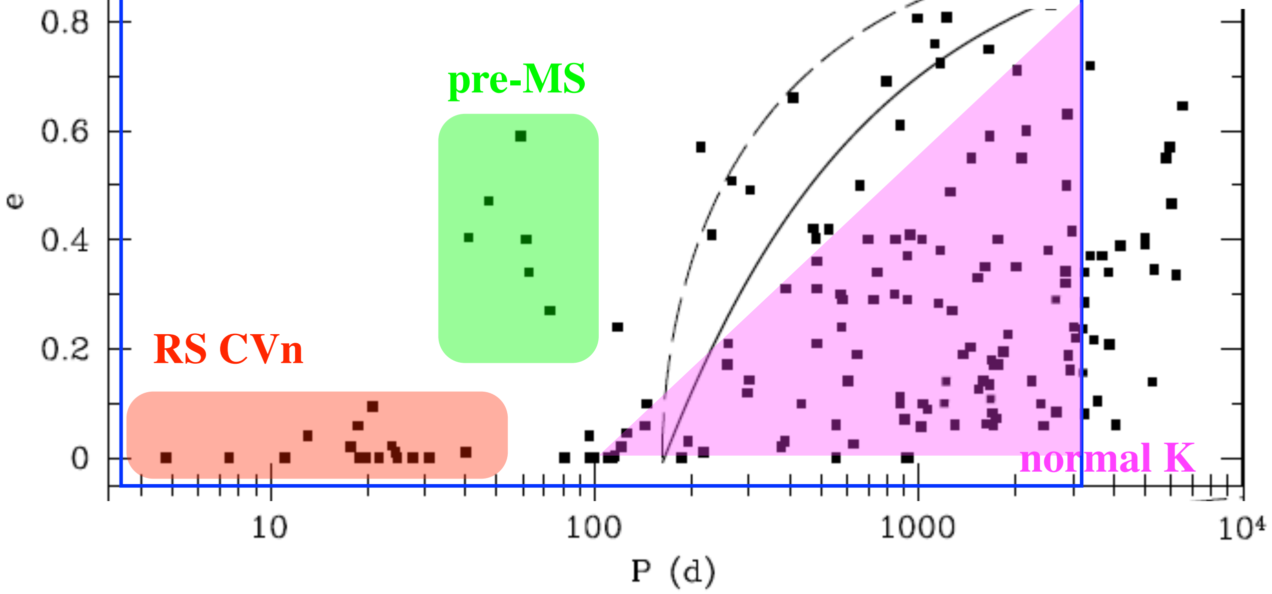
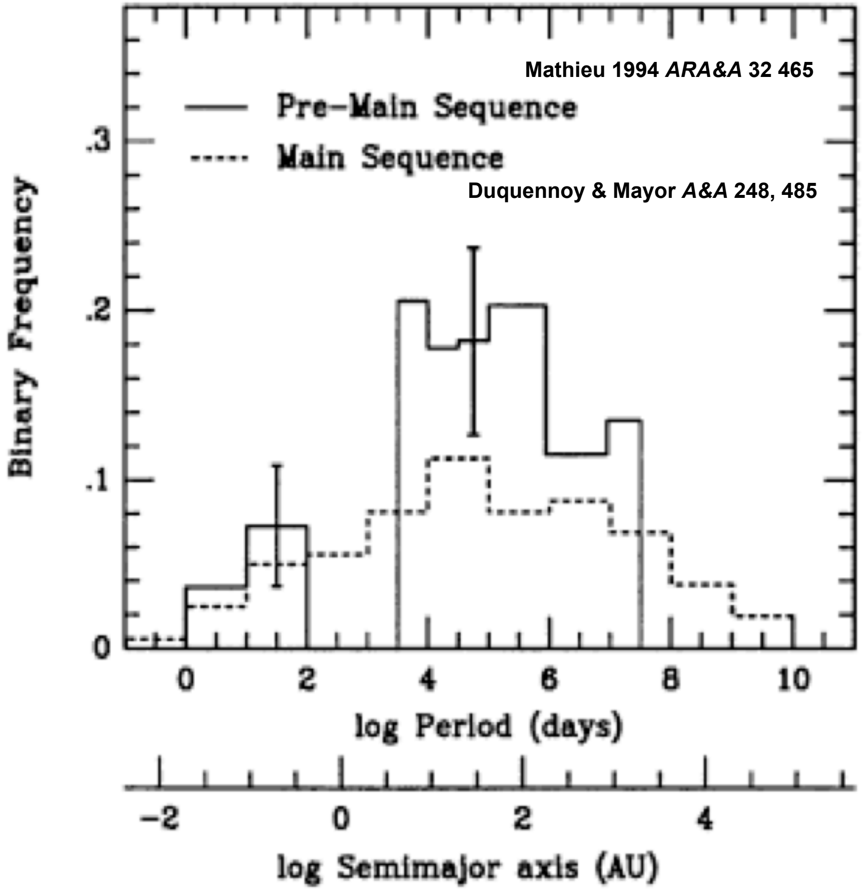

Melo *et al.* 2001 *Astronomy & Astrophysics* 378 898


Frankowski *et al.* 2009 *Astronomy & Astrophysics* 498 479

e - P diagram for systems with KIII primaries from SB9 [The 9th Catalogue of Spectroscopic Binary Orbits]

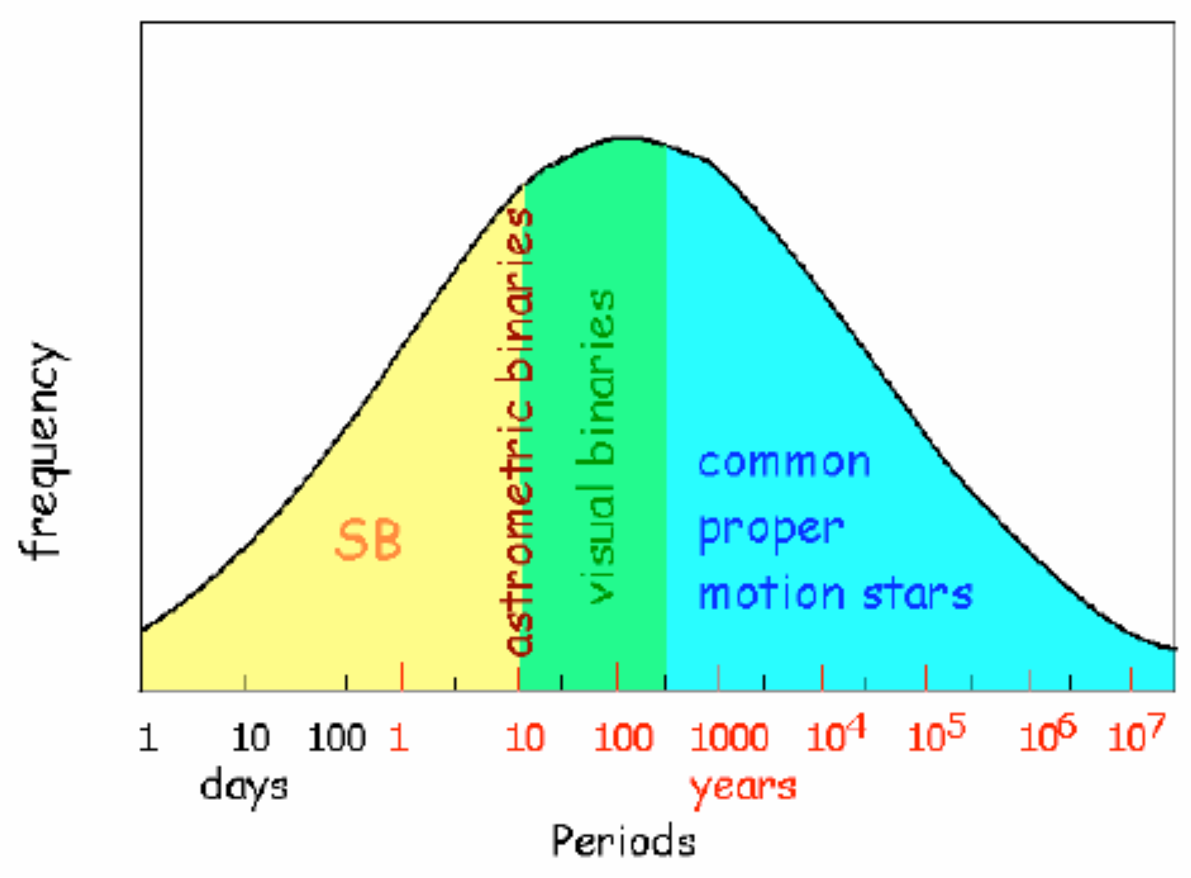
`http://sb9.astro.ulb.ac.be`

pre-main-sequence versus main-sequence period distribution


Mathieu 1994 *ARA&A* 32 465

Duquennoy & Mayor *A&A* 248, 485

period distribution for all kinds of binaries



Photometric binaries:
eruptive

novae : dwarf + WD (low accretion rate)
a few: giant + WD ('symbiotic nova')
thermonuclear outbursts (non-destructive explosive H-burning on the WD)

cataclysmic variables: dwarf + WD (high accretion rate with accretion disk):
- dwarf novae
- AM Her (highly magnetic, no accretion disc)
- DQ Her (moderately magnetic, accretion disc)

accretion or disc instabilities

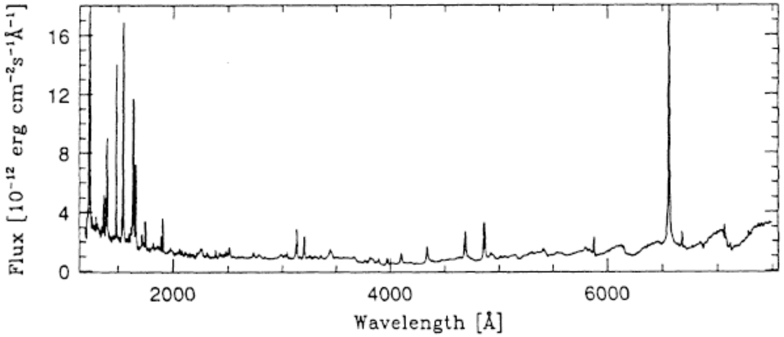
Symbiotic : giant + WD (neutron star in one case)
sometimes accretion disc (Z And, X-ray flickering)
most often no X-ray flickering (-> X-ray origin ?)
accretion or disc instabilities

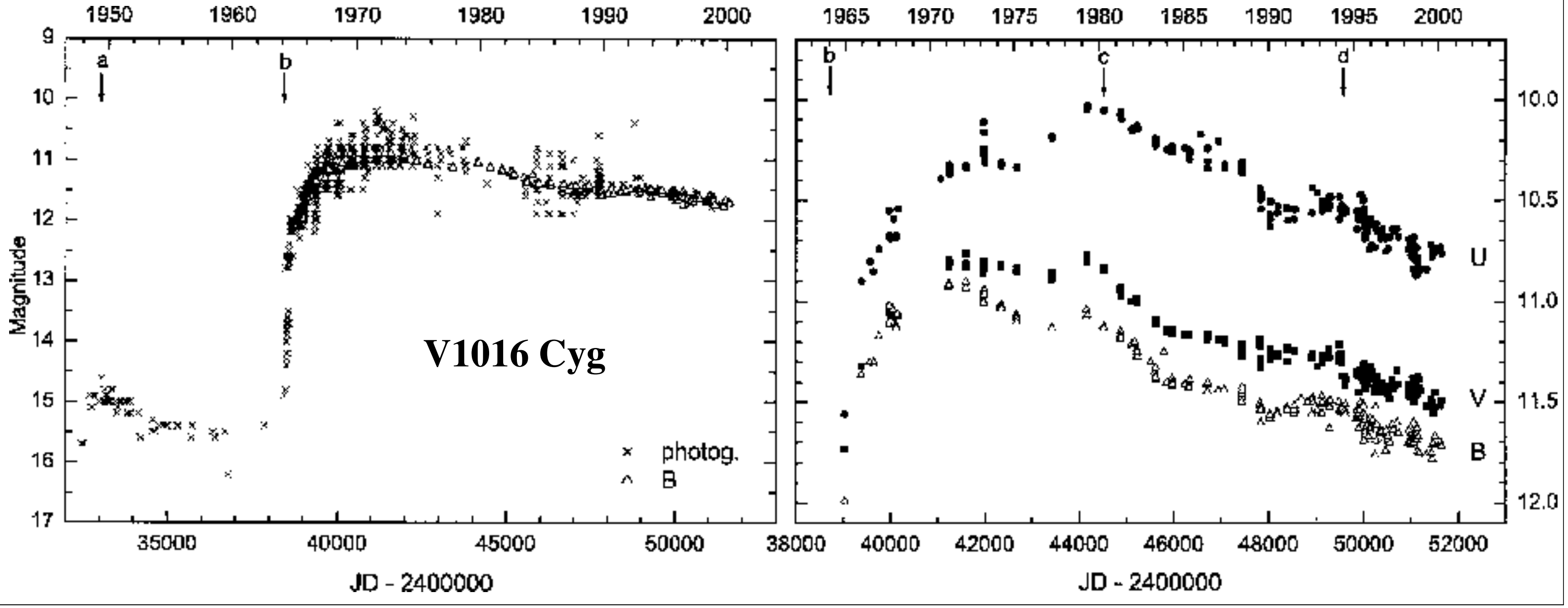
supernovae type Ia : WD + WD
thermonuclear outbursts (destructive explosive C-burning in merging WDs ?)

Photometric binaries: eruptive

Symbiotic :

eruptions + composite spectrum
(hot + cool + nebula)

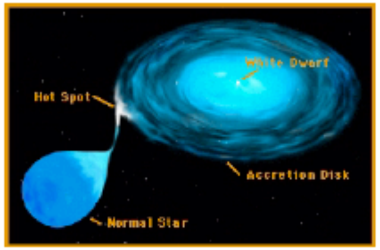




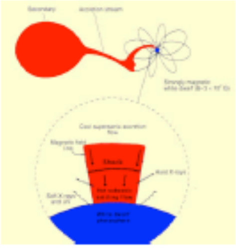
X-rays

Basics on X-ray binaries (III)

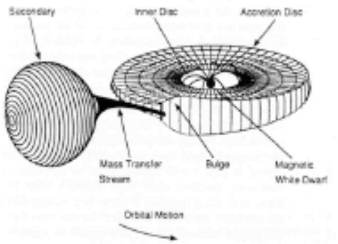
CVs = dwarf star + white dwarf in a short P, semi-detached system



Dwarf novae



Polars (AM Her systems):
Highly magnetized white dwarfs



Intermediate Polars
(DQ Her systems)
longer P and wider separation: there is room for an accretion disk

X-rays

Basics on X-ray binaries (IV)

X-rays (photons with $h\nu > 0.1$ keV requiring $T > 10^6$ K) may come from:

- hot stellar coronae (either single star or RS CVn binary)

  RS CVn: dynamo caused by fast, synchronous rotation
- nuclear fusion (nova or symbiotic star)
  - Classical novae: explosive H-burning ($10^{33} - 10^{34}$ ergs/s)
  - Super soft sources : quiescent H-burning ?
- accretion
  - CVs = dwarf star + white dwarf in a short P, semi-detached system
    - Dwarf novae
    - Polars (AM Her systems)
    - Intermediate Polars (DQ Her systems)
  - Algols = subgiant (less massive) + main sequence (more massive)

    in a semidetached system
  - Symbiotics = giant star + white dwarf in a long P system

    but accretion-driven X-rays challenged !
- wind collision
  - Symbiotics

X-rays from binaries :

The case of symbiotic stars

Origin of X-rays not clear:
accretion disk, nuclear fusion, wind collision or fast rotation ?

Accretion-driven X-rays are accompanied by flickering with periods of minutes to days, as observed in Z And
Sokoloski 2003, ASP Conf. Ser. 303, p. 202
but flickering not often observed in symbiotic X rays!

→ fast rotation as for RS CVn, with X-rays due to dynamo activity?
Soker 2002, MNRAS 337, 1038

Intriguing possibility,
because it requires a high incidence of fast rotation !

The WIRRING stars, or 'Wind-Induced Rapidly RotatING',
Jeffries & Stevens, 1996, MNRAS 279, 180
are post-mass-transfer systems rotating fast, due to the accretion of spin angular momentum during the mass transfer !

Photometric binaries:
X-rays

Low-mass X-ray binaries (related to dwarf novae and CVs)

High-mass X-ray binaries : neutron star or black hole companions

What should you have learned ?

The bestiary

DQ Her, AM Her
RS CVn, pre-main sequence
Algols, β Lyr, SV Cen, W Ser
Z And (symbiotic)
VV Cep, zeta Aur, eps Aur, MACHO sequence D
CH (giants and subgiants), S (no-Tc), Ba, dwarf Ba, WIRRING, Abell 35
post-AGB
SN Ia
novae, dwarf novae
LMXRB, HMXRB

The concepts

cases A, B, C
RLOF, Bondi-Hoyle, common envelope
dynamical, thermal, nuclear time scales
astrometric, interferometric, spectroscpic (SB1, SB2)
eclipsing, ellipsoidal binaries
e - P, mass function, deriving masses