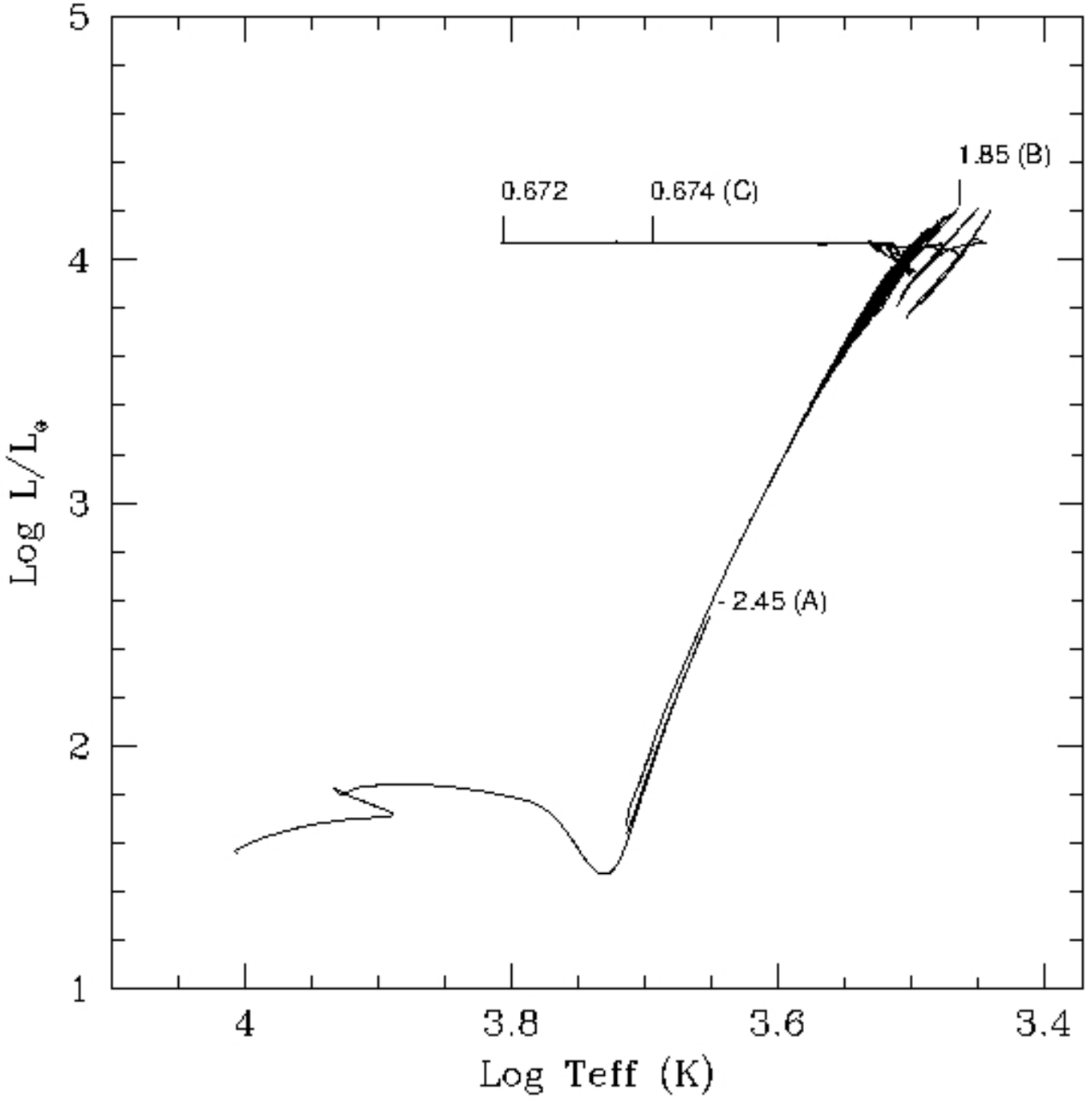
Single Rotating Stars and the formation of Bipolar Planetary Nebulae

Guillermo Garcia-Segura
Eva Villaver
Norbert Langer
Sung-Chul Yoon
Arturo Manchado

New Stellar Model 2.5 Mo vrot=250 km/s at ZAMS



B-field included

New Stellar Evolution Codes with Rotation and Magnetic Fields

Thanks to:
Norbert Langer
Sung-Chul Yoon
Alexander Heger
Hartmut Braun

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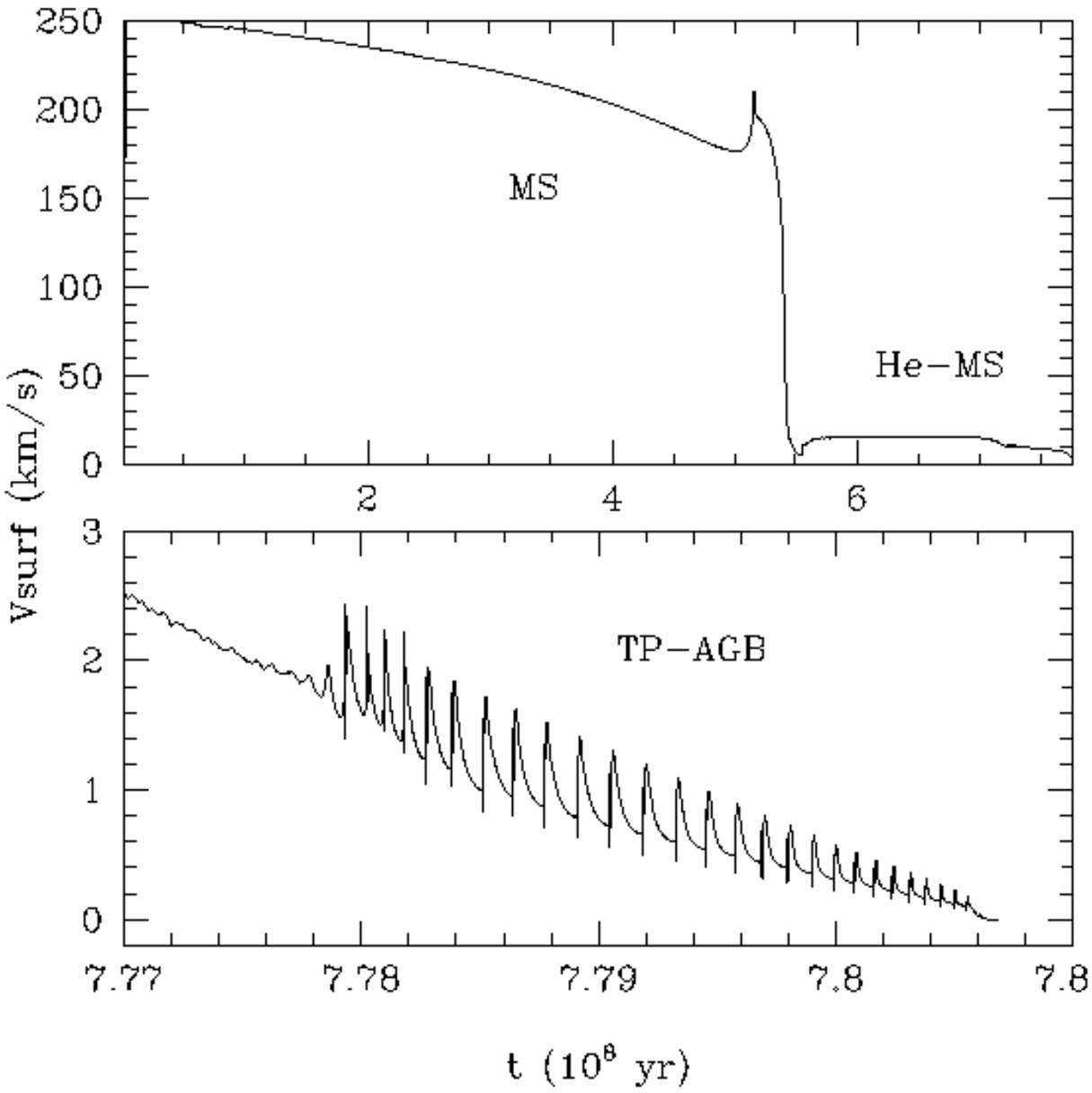
Thanks to GRBs and Pulsars !!

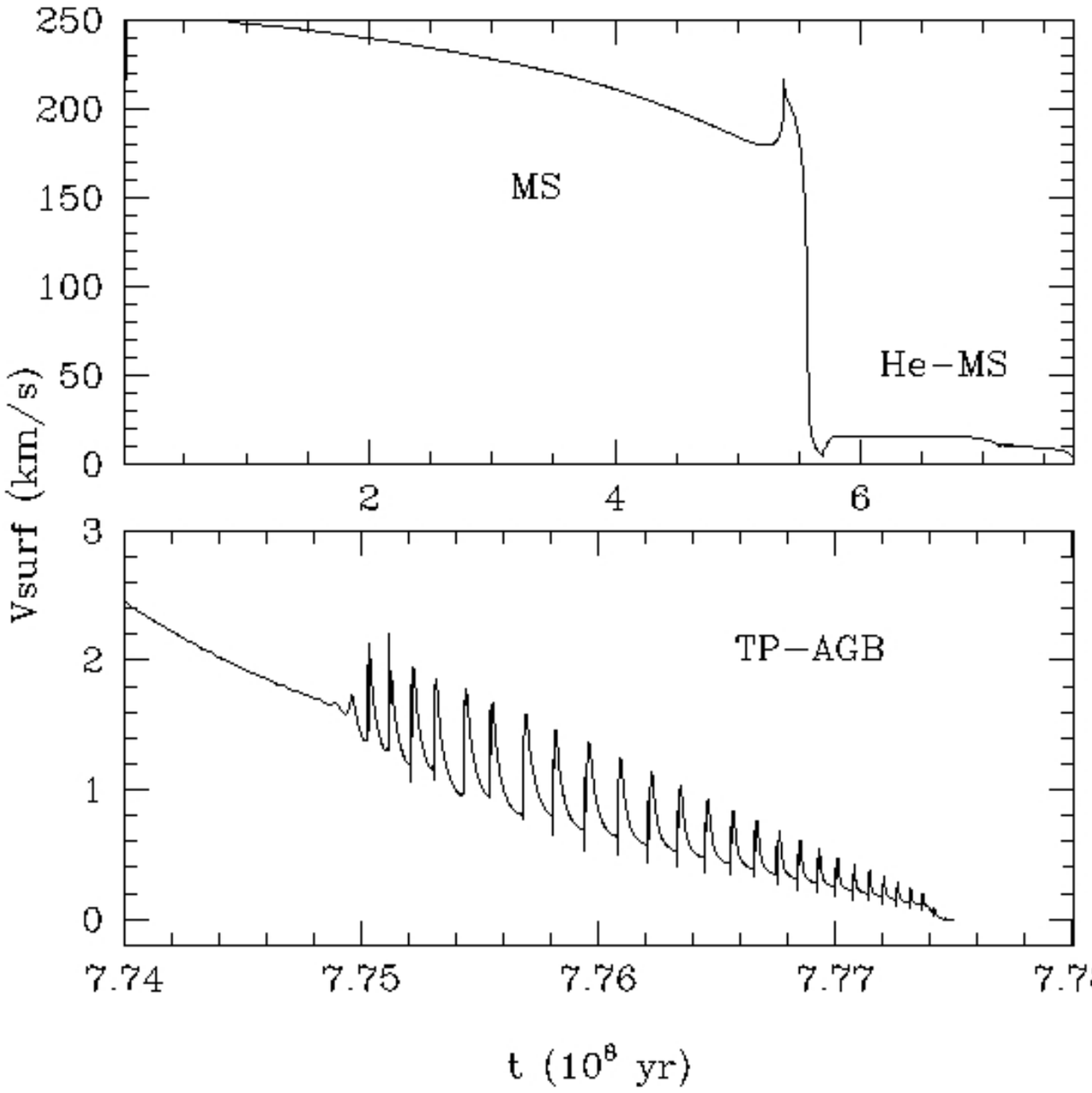
Mass Loss Rate by Vassiliadis & Wood 93

Stellar model 2.5 Mo vrot=250 at ZAMS

With no B



With B-field



Surface Rotation ~ 0 at Post-AGB !!

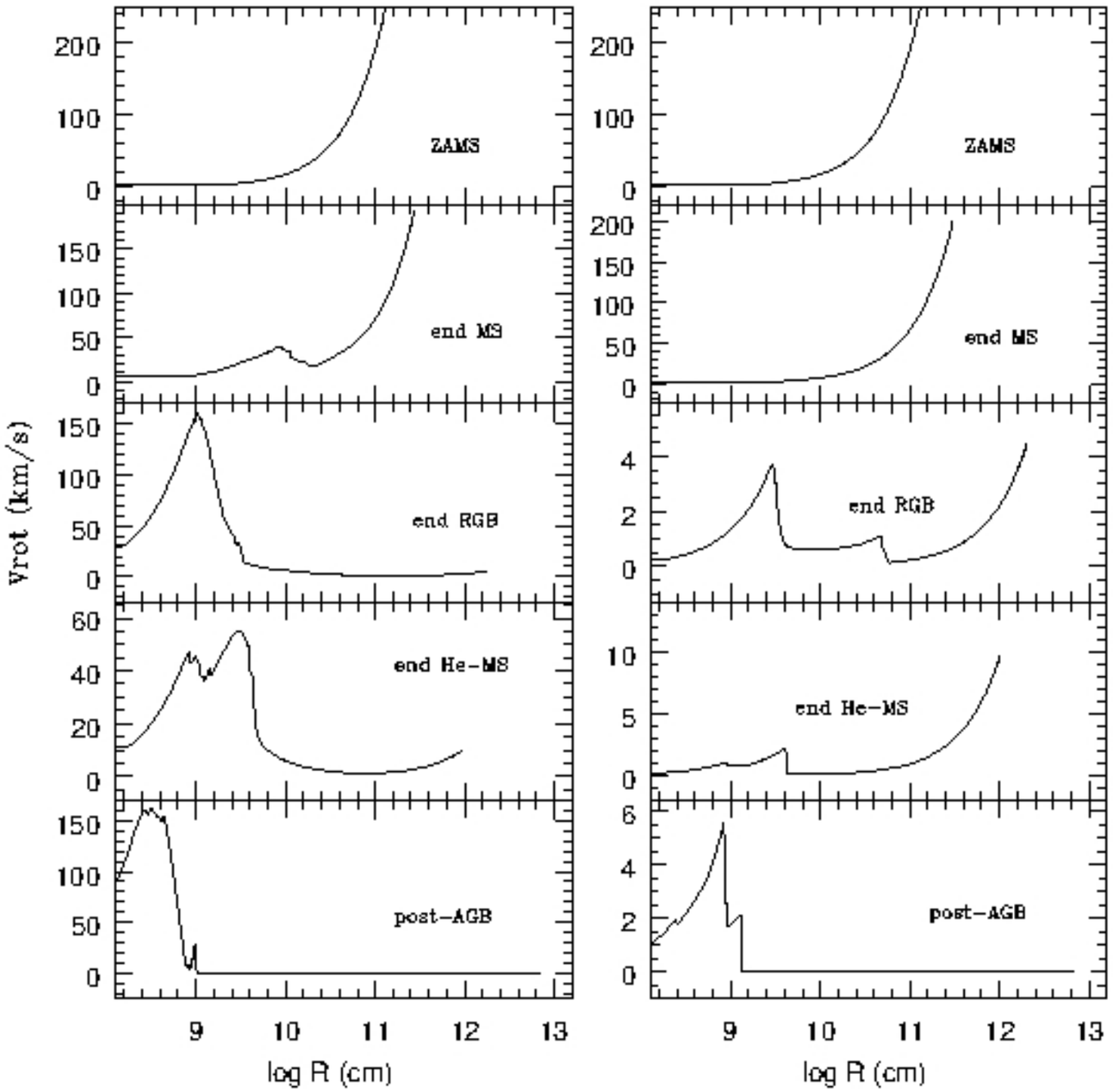
Vsurf = 9.7e-6 km/s

Vsurf = 8.4e-6 km/s

Internal Rotation Very Different

With no B

With B-field



in line with WD observations !

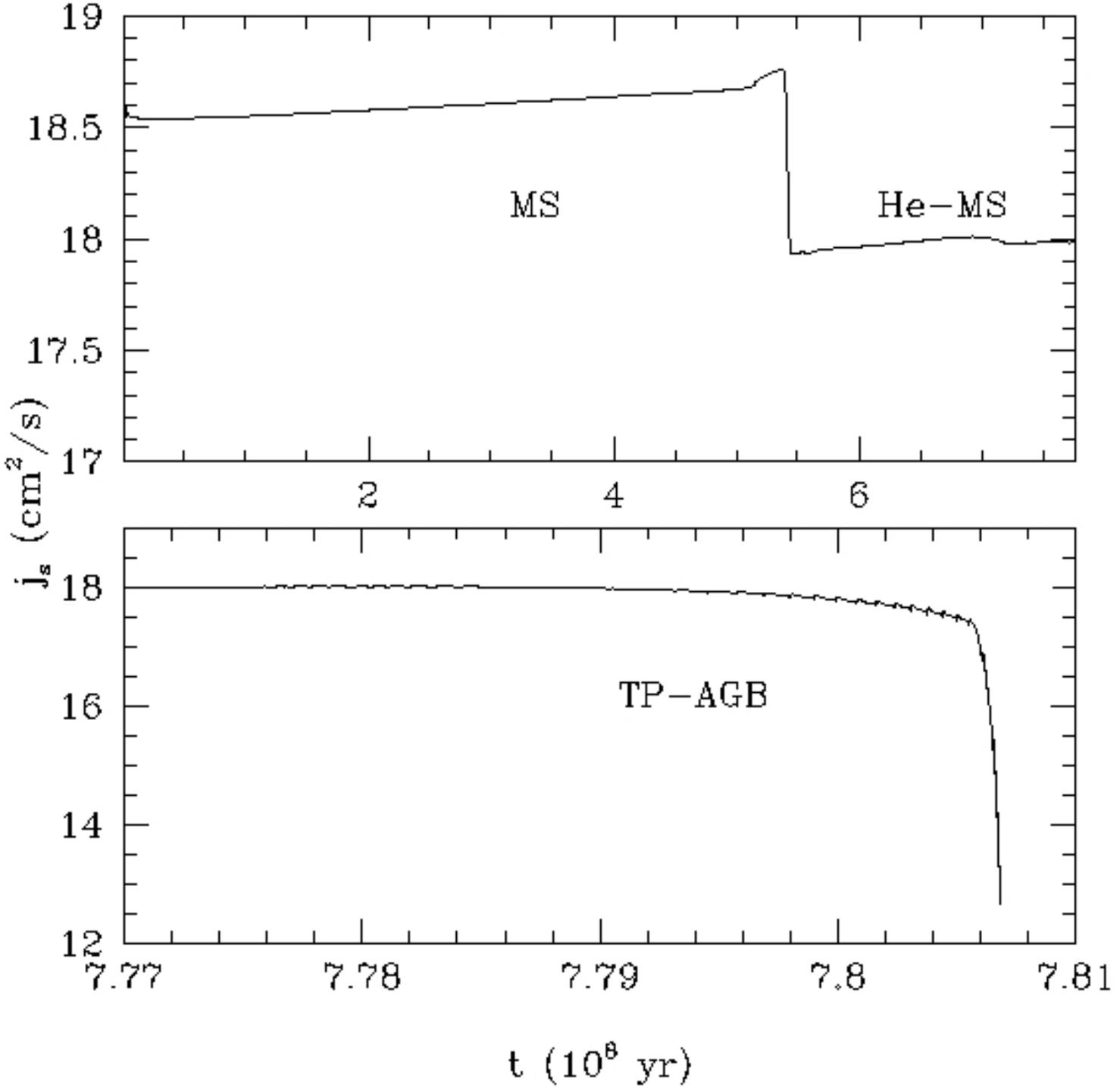
Garcia-Segura et al. 1999

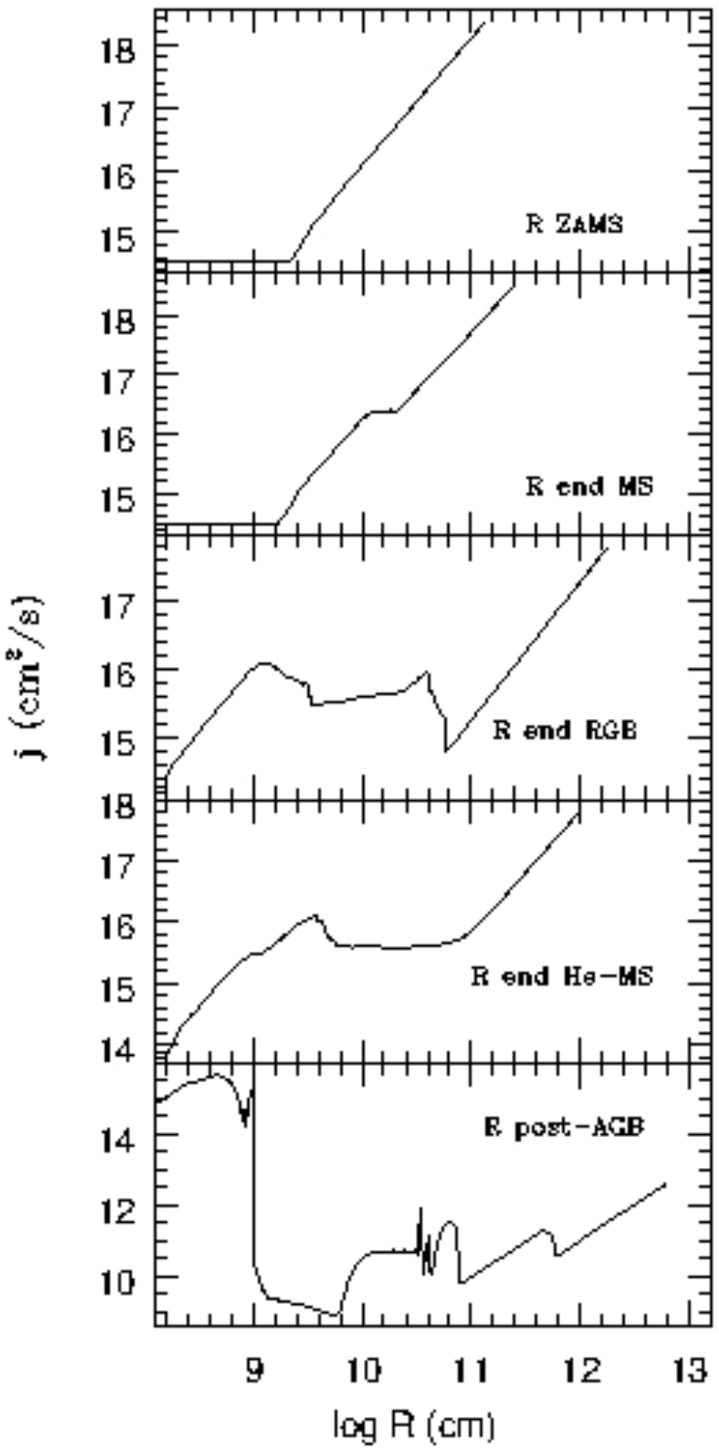
Two Scenarios:

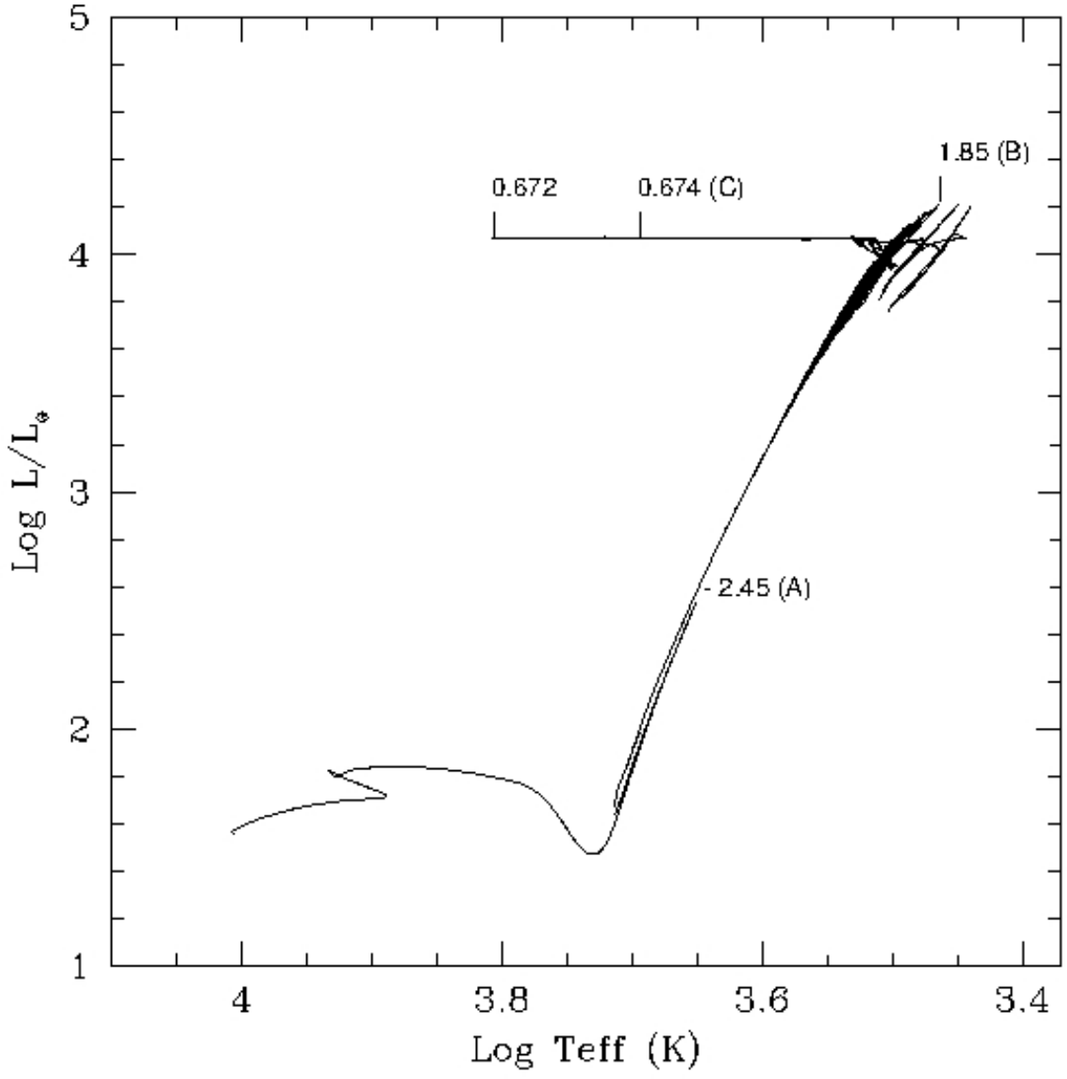
1) Pessimistic: Post-Main Sequence Stars above 1.6 Mo suffer magnetic braking and their helium cores are spun down

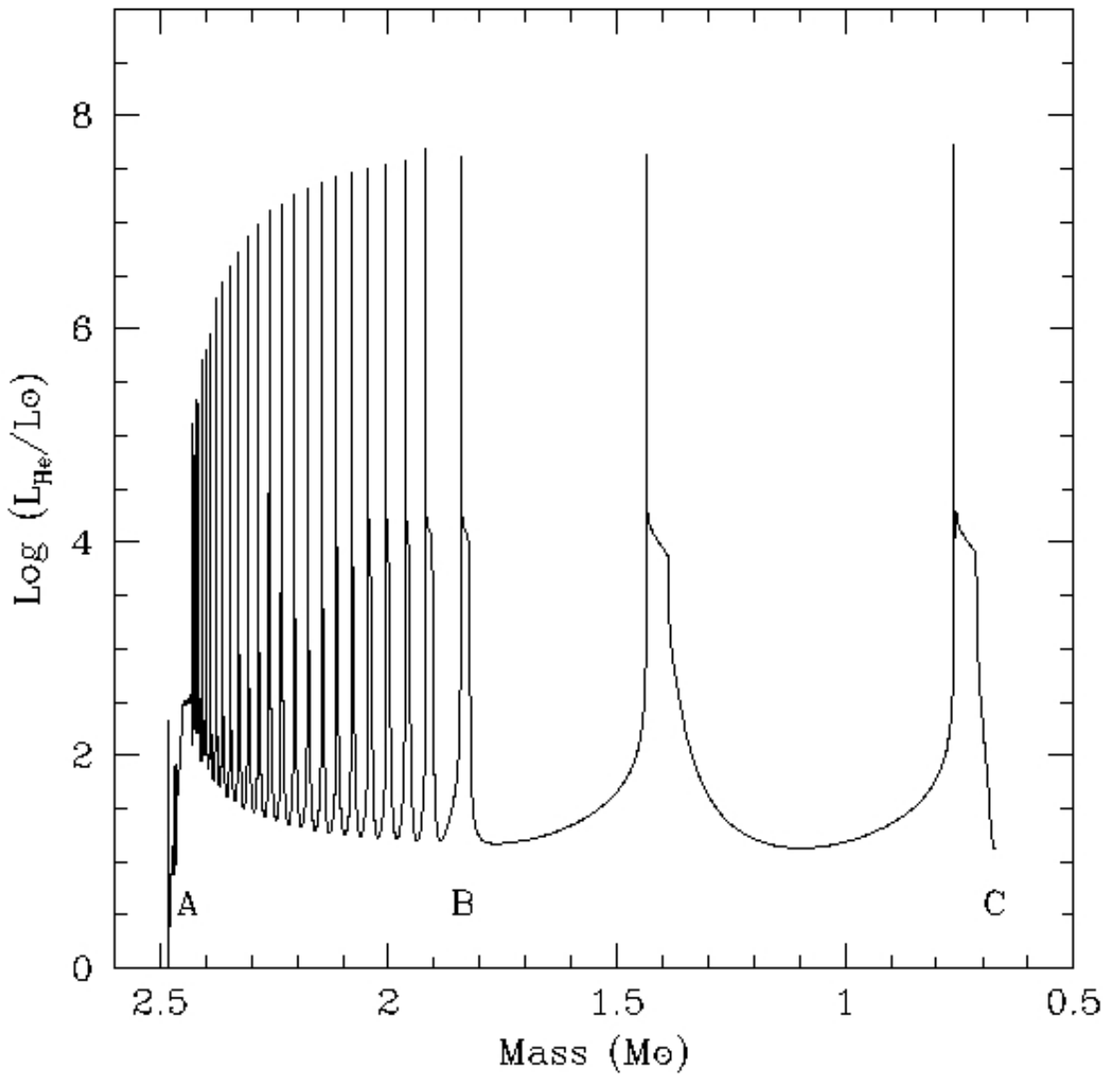
2) Optimistic : The helium core evolves decoupled from the envelope and retains its angular momentum. But, core-envelope angular momentum exchange must occur at some point previous to White Dwarf.

Specific Angular Momentum

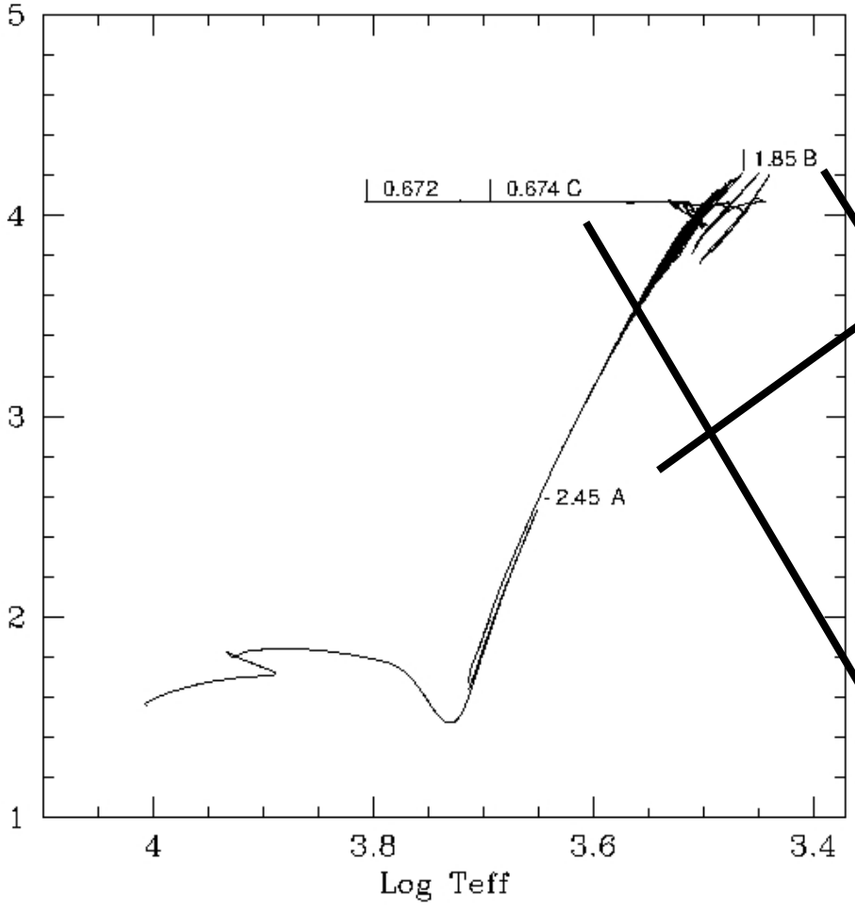


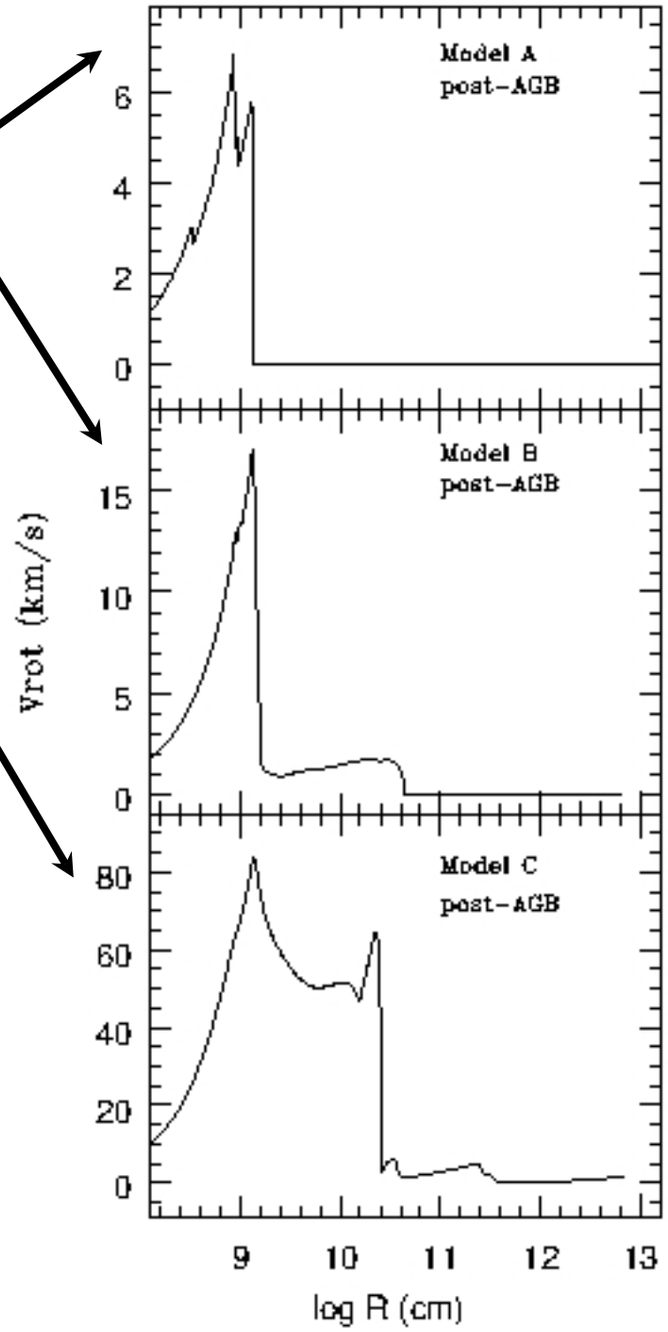


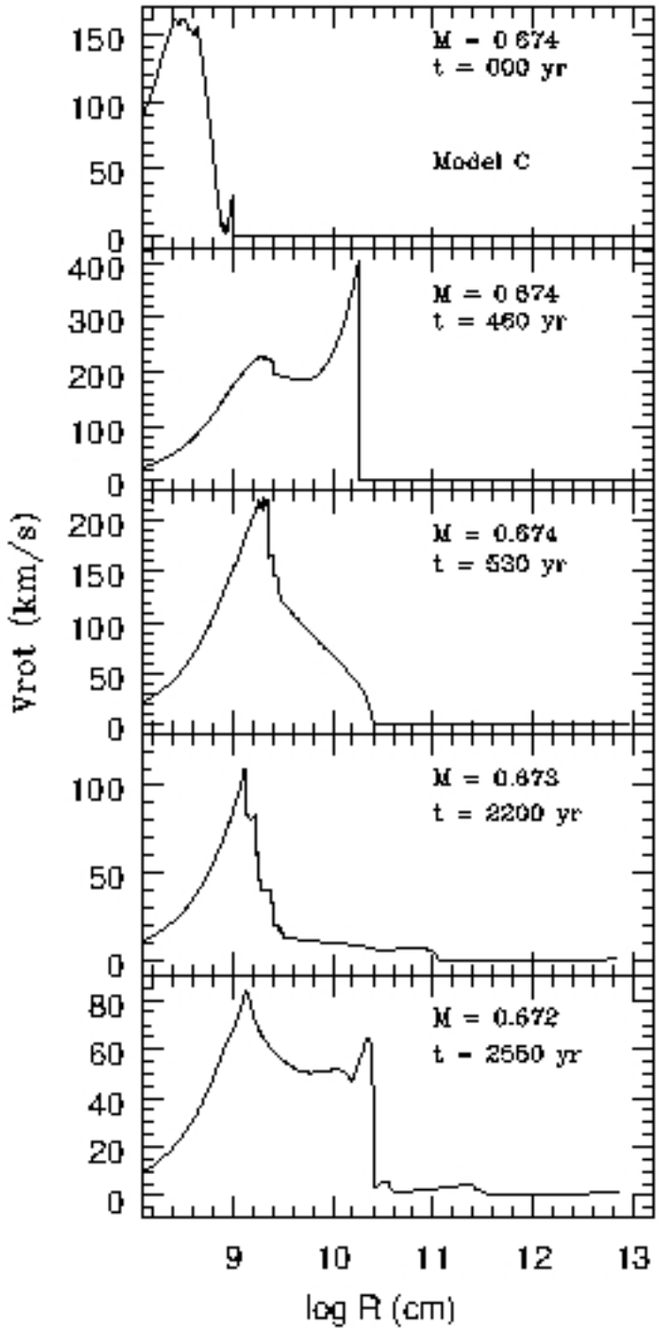




3 experiments that suddenly include B-field to allow transport of angular momentum


0.672
0.674 C
1.85 B
2.45 A
Log L
Log Teff


Model A
post-AGB
Model B
post-AGB
Model C
post-AGB
Vrot (km/s)
log R (cm)


M = 0.674
t = 000 yr
Model C
M = 0.674
t = 460 yr
M = 0.674
t = 530 yr
M = 0.673
t = 2200 yr
M = 0.672
t = 2550 yr
Vrot (km/s)
log R (cm)

Some Numbers (J = Angular Momentum)

$$J_{\rm ZAMS} = 7.095 \times 10^{50}\ {\rm g\ cm^2\ s^{-1}}$$
$$J_{\rm AGB} = 5.667 \times 10^{48}\ {\rm g\ cm^2\ s^{-1}}$$

} f=125 (by $\dot{M}$)

$$J_{\rm core} = 4.018 \times 10^{48}\ {\rm g\ cm^2\ s^{-1}}$$
$$J_{\rm env} = 1.649 \times 10^{48}\ {\rm g\ cm^2\ s^{-1}}$$

Mtot=1.008 Mo
Mcore=0.656 Mo
Menv=0.352 Mo
R=463 Ro

Vsurf = 296 cm/s → V'surf = 2 km/s
f=676 larger

→ $J_{\rm ideal} = 1.115 \times 10^{51}\,{\rm g\ cm^2\ s^{-1}}$

f=1.57 larger than ZAMS !!

(just 6 Jupiters at 5 A.U. !!)

Conclusions:

1) It is really hard to get SINGLE stars rotating
at the late AGB and post-AGB stage
that could form Bipolar Planetary Nebulae
(with the actual tools)

2) External Angular Momentum is welcome
(from planets, brown dwarfs,.....)
to spin-up late AGBs

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As Noam Soker always said.....