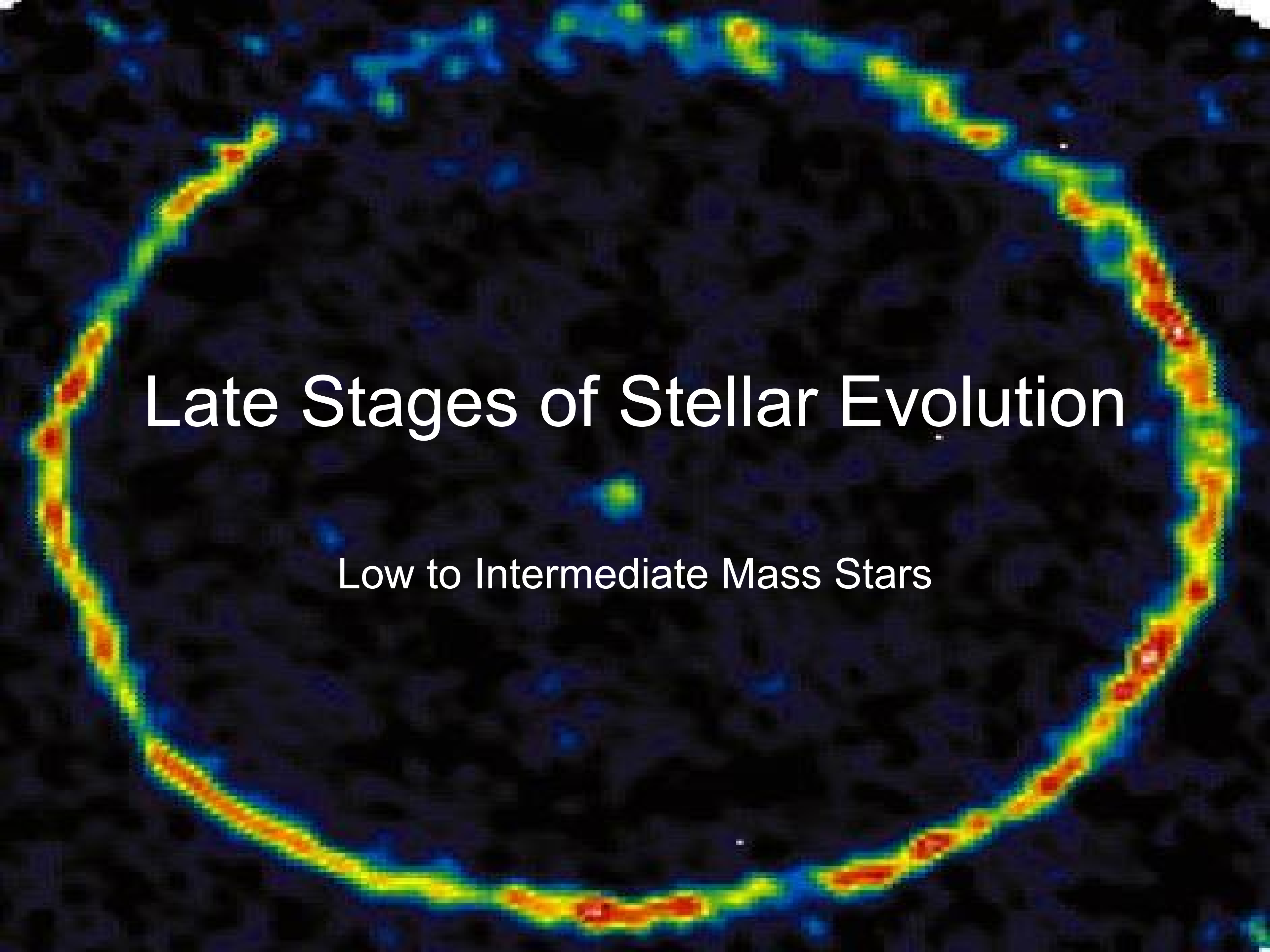
Late Stages of Stellar Evolution

Low to Intermediate Mass Stars



Introduction

- Stars evolve because of two (irreversible) processes:
  - Nuclear burning (in the core)
  - Mass loss (from the surface)
- Massive stars ($M > 9\ M_\odot$) lose mass during most of their lifes, and finally explode as supernovae.
- Low and intermediate mass stars ($M < 9\ M_\odot$) only lose large amounts of mass towards the end of their evolution, and end up as White Dwarfs.

- Without mass loss, stars with masses as low as $4\ M_\odot$ would explode as supernovae.

Relevance of Lower Mass Stars

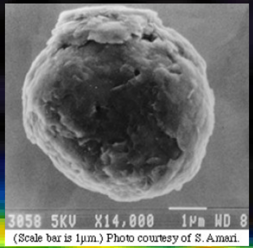
- Stars that end up as WDs may seem less spectacular than those that become SNe, but they are important in the lifecycle of gas/dust in galaxies.
- Most stars are low mass stars:
- The initial mass function of stars can be approximated with the Salpter function: $$\frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-2.35}$$
- Using this we see that >90% of stars have a mass between 0.8 and 8 $M_\odot$.
- The lower mass limit is set by the lifetime of stars:

$$t_{\mathrm{evol}} \propto M^{-2.5}$$

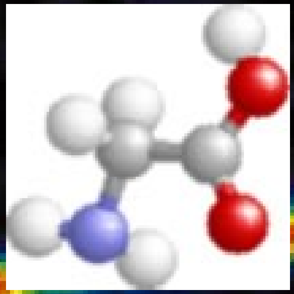
- Stars with a mass of 0.8 $M_\odot$ take longer than 14 Gyr to evolve off the Main Sequence.

The Life Cycle of Gas & Dust

- Stars form from the interstellar gas, which to a large extent comes from previous generations of stars. This is known as the life cycle of gas & dust.
- Although lower mass stars do not enrich the ISM as much as SNe, they still contribute substantially (and dominate the budget of certain elements).
- Lower mass stars are also the main producers of dust grains in galaxies, both Si-based and C-based.
- The complex chemistry in their circumstellar envelopes allows the formation of complex (organic even) molecules.

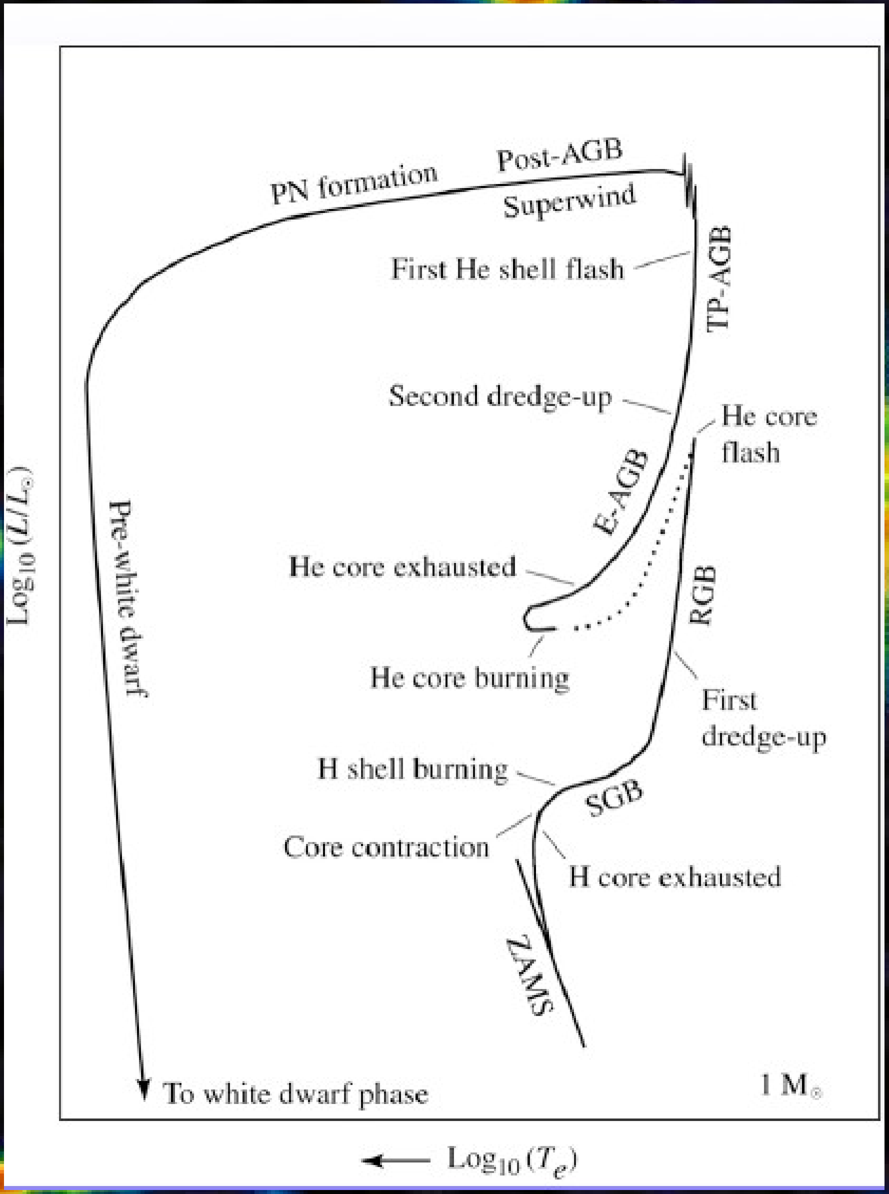


(Scale bar is 1μm.) Photo courtesy of S. Amari.



Evolution across the HR-Diagram

- After the MS, our stars evolve through 6 phases:
  - Sub-Giant Branch
  - Red Giant Branch (RGB) phase.
  - Horizontal Branch (HB) phase.
  - Asymptotic Giant Branch (AGB) phase.
  - Planetary Nebula (PN) phase.
  - White Dwarf (WD) phase.



Course Contents

- Review of Stellar Evolution
- Evolution on the AGB
- Thermal pulses, nucleosynthesis and dredge-up
- Pulsation
- Mass loss
- Circumstellar Envelope
- Post-AGB Evolution

Basic Stellar Evolution

- Equations:

Mass conservation:

$$\frac{\mathrm{d}M_r}{\mathrm{d}r} = 4\pi r^2 \rho$$

Hydrostatic equilibrium:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{G M_r \rho}{r^2}$$

Energy production:

$$\frac{\mathrm{d}L_r}{\mathrm{d}r} = 4\pi r^2 \rho \epsilon$$

Energy transport:

$$\frac{\mathrm{d}T_r}{\mathrm{d}r} = \begin{cases} -\frac{3}{4ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L_r}{4\pi r^2} & \text{if } \frac{\mathrm{d}\ln P}{\mathrm{d}\ln T} > \gamma/(\gamma-1) \text{ (radiative diffusion)} \\ -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_{\mathrm{H}}}{k_{\mathrm{B}}}\frac{G M_r}{r^2} & \text{if } \frac{\mathrm{d}\ln P}{\mathrm{d}\ln T} < \gamma/(\gamma-1) \text{ (adiabatic convection)} \end{cases}$$

combined with

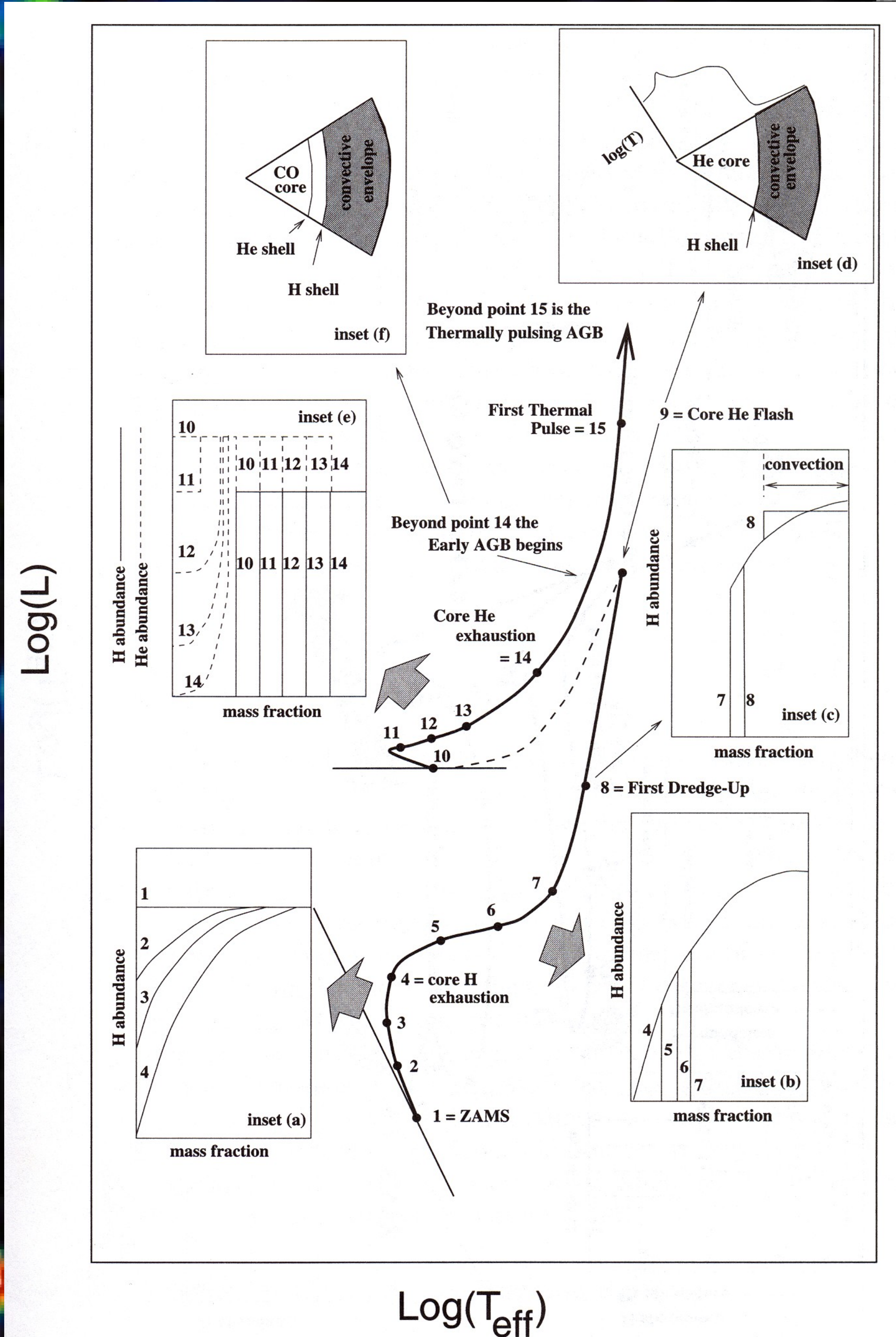
Equation of state: $p = p(\rho, T, \text{composition})$

Opacity: $\bar{\kappa} = \bar{\kappa}(\rho, T, \text{composition})$

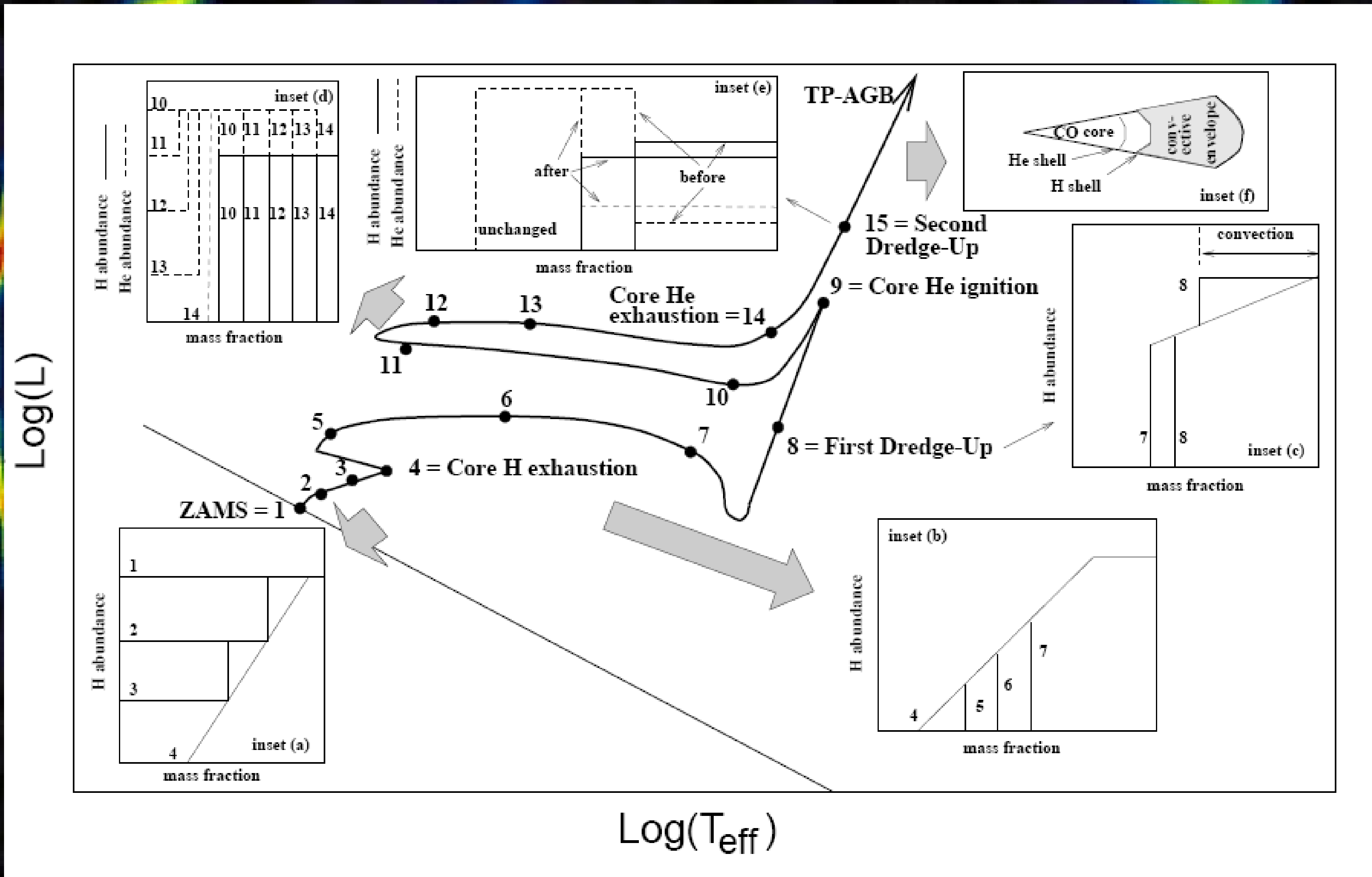
Nuclear reactions: $\epsilon = \epsilon(\rho, T, \text{composition})$

1 $M_\odot$ Star

- 1-4: Core H-burning
- 4-8: H-shell burning
- 8: Convection, 1st dredge-up
- 9: He-core flash
- 9-14: Core He-burning
- 14- : AGB



5 $M_\odot$



Log(L)
Log(T_eff)
ZAMS = 1
2
3
4 = Core H exhaustion
5
6
7
8 = First Dredge-Up
9 = Core He ignition
10
11
12
13
Core He exhaustion =14
15 = Second Dredge-Up
TP-AGB
inset (a)
inset (b)
inset (c)
inset (d)
inset (e)
inset (f)
H abundance
He abundance
mass fraction
unchanged
after
before
convection
CO core
He shell
H shell
conv-ective envelope

Some Mass Limits

$$\text{Main Sequence: } M_{\text{ZAMS}} \begin{cases} < 1.3 M_\odot & \text{pp-chain dominates} \\ > 1.3 M_\odot & \text{CNO-cycle dominates} \end{cases}$$

$$\text{RGB: } M_{\text{ZAMS}} \begin{cases} < 2.3 M_\odot & \text{electron-degenerate He-core} \\ > 2.3 M_\odot & \text{non-degenerate He-core} \end{cases}$$

$$M_{\text{ZAMS}} < 0.6 M_\odot \quad \text{He-burning never starts}$$

$$M_{\text{ZAMS}} \begin{cases} < 9 M_\odot & \text{electron-degenerate C/O core} \\ > 9 M_\odot & \text{non-degenerate C/O core} \end{cases}$$

Shells Sources

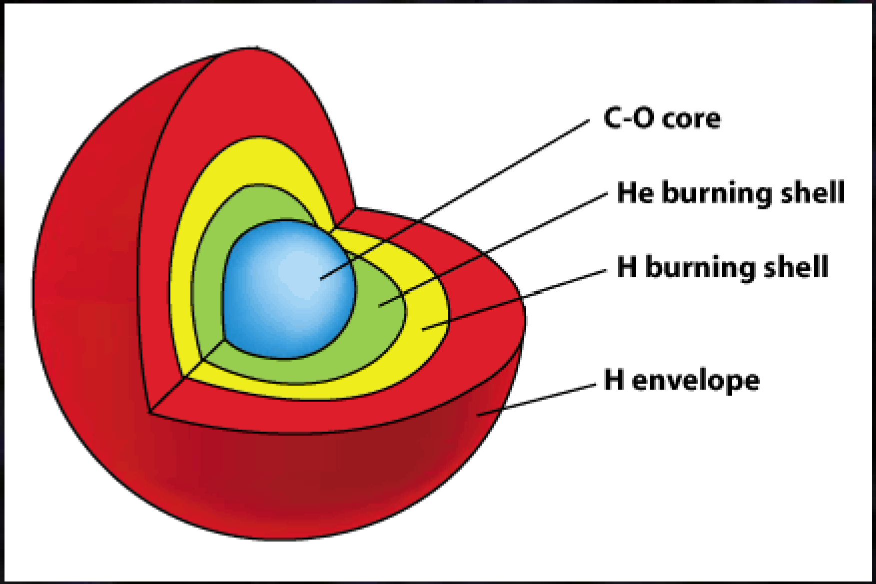
- The three rules of thumb for active shell sources:
  - Associated with a density jump (due to composition difference between core and shell)
  - Position fixed in time (due to thermal feedback). For example $r_{shell}=0.03R_{\odot}$ throughout most of the post-MS evolution of a 1 $M_{\odot}$ star.
  - Shells mirror the expansion/contraction of their interiors.

Core contraction (Active Shell) Envelope expansion

Core expansion (Active Shell) Envelope contraction

Stellar Evolution on AGB

- Once on the AGB, all stars have a similar structure:
  - C/O core
  - He-shell
  - Intershell region
  - H-shell
  - H-envelope



Not to scale!!!

- Their evolution is therefore also similar, although still mass-dependent.
- The evolution is dominated by occasional activity of the He-shell: thermal pulses.

Early AGB

- The period before the first thermal pulse is known as the early AGB (E-AGB).
- Stars with $M > 4\ M_{\odot}$ lose their active H-shell during this period, and the convective envelope can reach down and mix up processed material: Second Dredge Up.
- Both 1st and 2nd Dredge-Up bring up CNO-processed material: ^{4}He↑ ^{12}C↓ ^{13}C↑ ^{14}N↑
- At the end of the E-AGB all stars have an active H-shell and an inactive, but growing He-shell.

Thermally Pulsing AGB

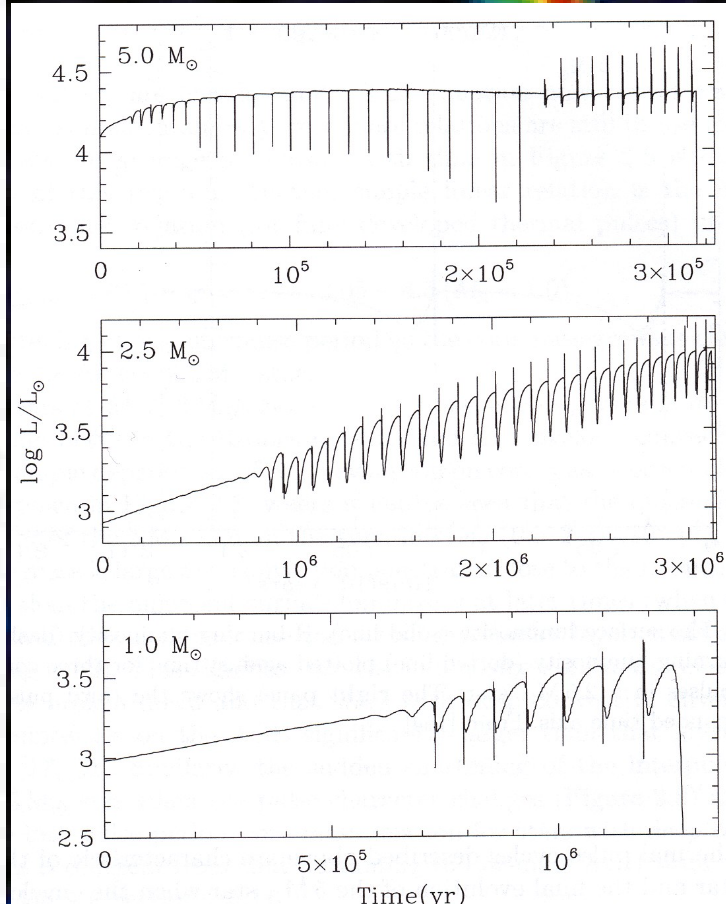
- The rest of the AGB is known as the TP-AGB, as the evolution is dominated by a series of TPs: short outbursts of the He-shell, separated by longer periods of H-shell activity.
- At the same time the star starts to lose material from its surface, with rates of the order $10^{-7}\ M_{\odot}$/yr.
- The luminosity of these stars ranges from 10^{3} to $10^{4}\ L_{\odot}$, so they consume something like $10^{-8}\ M_{\odot}$/yr in nuclear fusion.
- The conclusion is that mass loss dominates the evolution on the AGB!

AGB Evolution

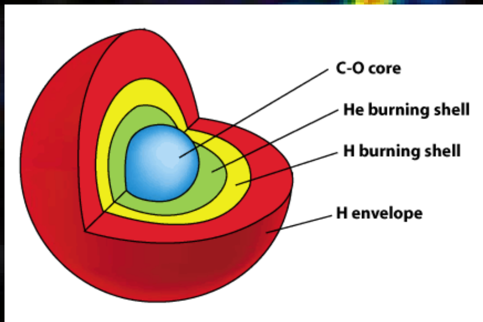
Time Scales

M_i [$M_\odot$]	M_f [$M_\odot$]	M_{bol}	t_{MS} [Gyr]	t_{EAGB} [Myr]	$\frac{t_{EAGB}}{t_{MS}}$ [%]	t_{TPAGB} [Myr]	$\frac{t_{TPAGB}}{t_{MS}}$ [%]
			Z=0.016				
1.0	0.57	−4.0	11.3	12	0.16	0.50	0.004
1.5	0.60	−4.5	2.7	9.2	0.34	0.83	0.03
2.0	0.63	−4.9	1.2	7.9	0.66	1.20	0.10
2.5	0.67	−5.1	0.62	1.1	0.18	2.20	0.35
3.5	0.75	−5.7	0.23	2.8	1.2	0.43	0.19
5.0	0.89	−6.2	0.10	1.2	1.2	0.26	0.27
			Z=0.004				
1.0	0.59	−4.5	6.7	8.0	0.12	0.87	0.01
1.5	0.64	−4.9	2.1	6.3	0.30	0.97	0.05
2.0	0.67	−5.2	0.89	6.7	0.75	1.60	0.18
2.5	0.69	−5.5	0.46	5.2	1.1	1.30	0.27
3.5	0.85	−6.0	0.18	2.2	1.2	0.25	0.14
5.0	0.94	−6.5	0.08	0.6	7.3	0.31	0.39

Luminosity Evolution

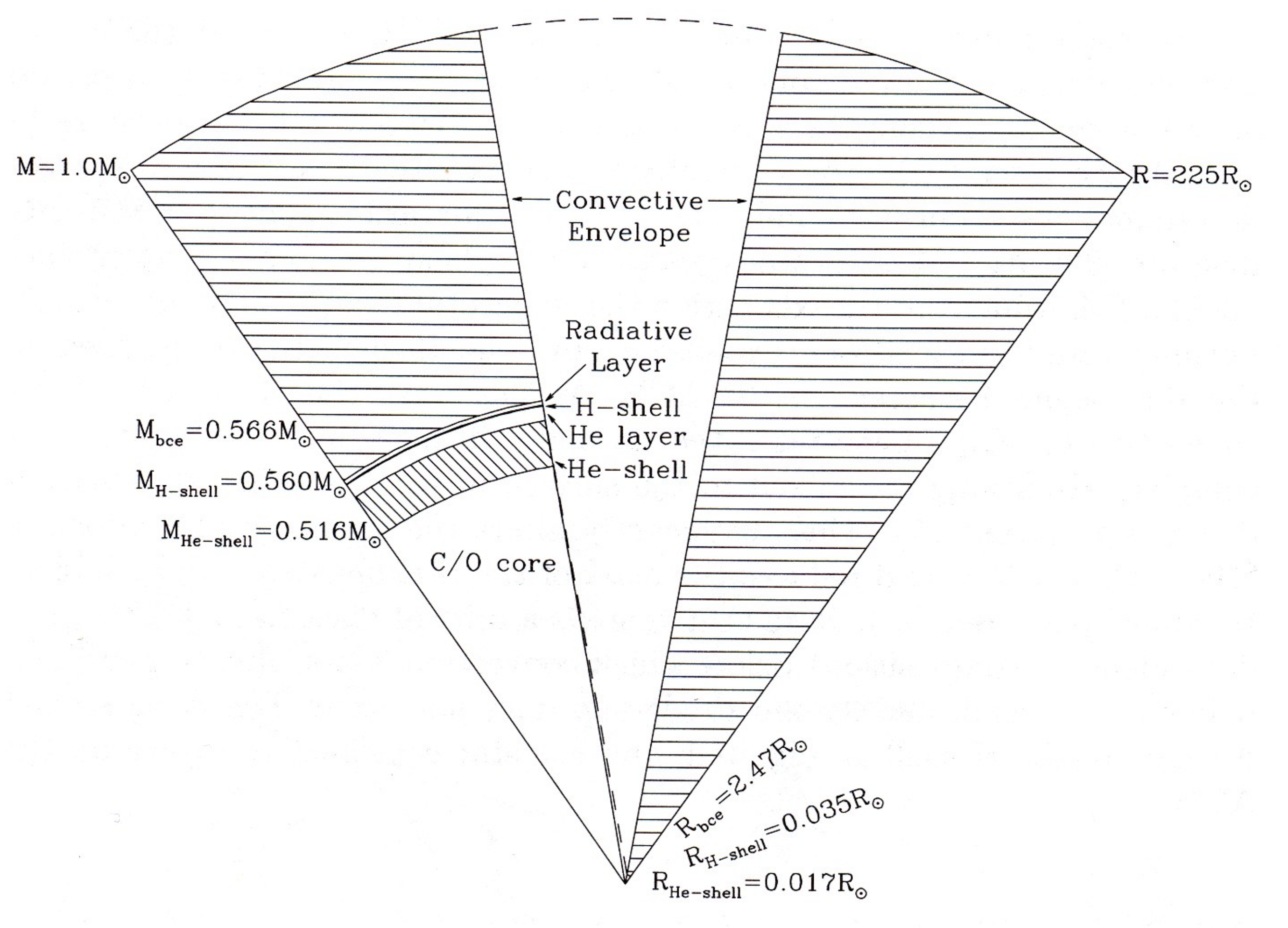


Internal Structure



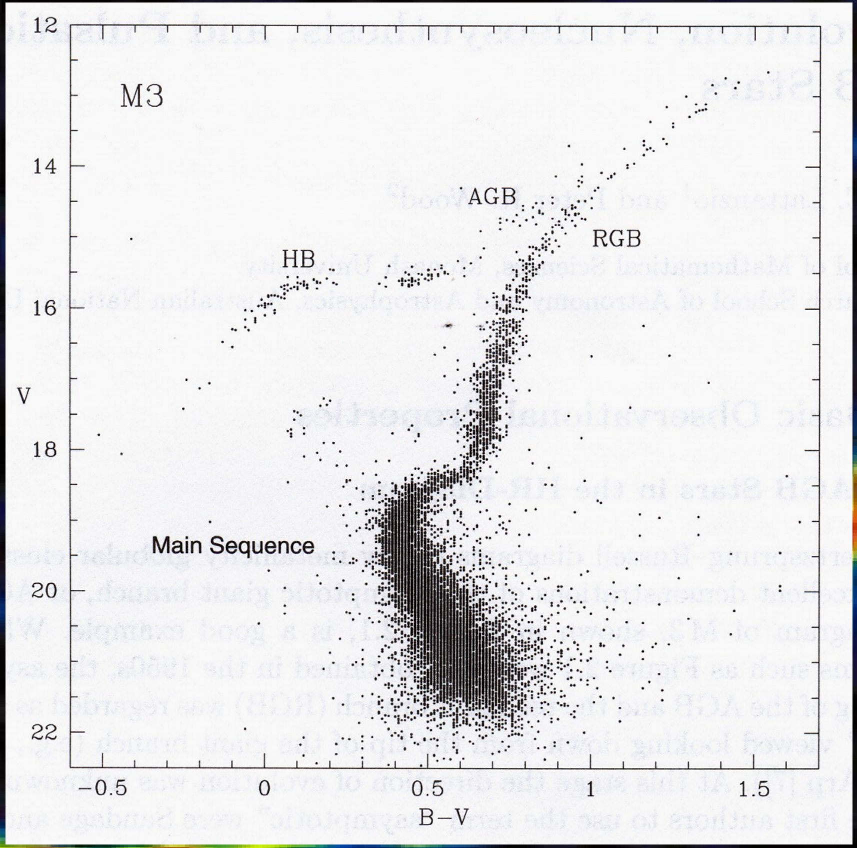
Not to scale!

To scale: very inhomogeneous!



History

- The name Asymptotic Giant Branch was introduced by Sandage & Walker (1966) to describe the observed bifurcation of the Red Giant Branch in HR-diagrams of Globular Clusters:



- Nowadays we use the term AGB for the evolutionary phase when stars become Red Giants for the second time

Thermal Pulses

- The He-core flash is a run-away process because the core is supported by the pressure of degenerate electrons, decoupling the pressure from the temperature.
- The He-shell in AGB stars is non-degenerate. Why then does the ignition of the He-shell lead to a thermal run-away?
- The process was first discovered by Schwarzschild & Härm (1965) in their stellar evolution calculations.
- They also identified the cause:
  - Temperature dependence of the 3α process ($\propto T^{40}$).
  - Small width of the shell region.

Gravothermal Specific Heat

- When a certain amount of heat is added to a pocket of gas, its temperature will change according to:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{1}{C}\frac{\mathrm{d}q}{\mathrm{d}t}$$

- Under isolated circumstances *C* the specific heat depends only on the gas properties.
- If in addition we require that the gas is part of a system in hydrostatic equilibrium, we obtain instead

$$C_* = C_p\left(1 - \nabla_{\mathrm{ad}}\frac{4\delta}{4\alpha - 3}\right)$$

$$\rho \propto p^{\alpha}T^{-\delta}$$

$$\nabla_{\mathrm{ad}} = \left(\frac{\mathrm{d}\ln p}{\mathrm{d}\ln T}\right)_S$$

- For a monatomic gas ∇_{ad}=0.4, α=δ=1, so C_*=-0.6C_p<0.
- Adding heat brings down the temperature!
- Explanation: upon heating, the gas pocket will expand, pushing the upper layers out, doing work, losing energy.

Adding Energy Production & Opacity

- A more complete picture requires that we take into account the energy production rate ε and the energy transport (proportional to the opacity κ):

$$\epsilon \propto \rho^{\lambda} T^{\nu} \qquad \kappa \propto \rho^{p} T^{q}$$

- This gives an expression: $$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{K}{C_*}\frac{\mathrm{d}T}{T}$$

$$K = \frac{L}{M}\left[(\nu + q - 4) + \frac{\delta}{4\alpha - 3}(3\lambda + 3p + 4)\right]$$

- For negative feedback *K* and C_* need to have opposite signs, for positive, the same.

Feedback and Stability

- For a stable situation we need negative feedback: a small temperature increase will lead to higher energy production due to nuclear processes. If this leads to an even higher temperature, we have a run-away process.
- For the pp-chain: v=4, λ=1, for Kramer's opacity q=-3.5, p=1, so $K>0$ and $C_*<0$, and the situation is stable.
- For 3α in a degenerate core: v=40, λ=2, making K still positive, but now α=3/5, δ=0, so $C_*>0$, and we have positive feedback, and a thermal run-away (until the equation of state is changed).

Shell Sources

- If we want to apply this to shell sources, we have to realize that they have a much smaller volume than a spherical core region.
- A small expansion of a shell region will lead to a drop in the density, but will not consume much energy in pushing away the outer layers.

$$\mathrm{d}V = \frac{3}{r} V \,\mathrm{d}r$$

$$\mathrm{d}V = \frac{1}{D} V \,\mathrm{d}D = \frac{r}{D}\frac{V}{r}\mathrm{d}D$$

$$C_* = C_p \left(1 - \nabla_{\mathrm{ad}} \frac{4\delta}{4\alpha - 3}\right)$$

$$C_*^{\mathrm{shell}} = C_p \left(1 - \nabla_{\mathrm{ad}} \frac{4\delta}{4\alpha - r/D}\right)$$

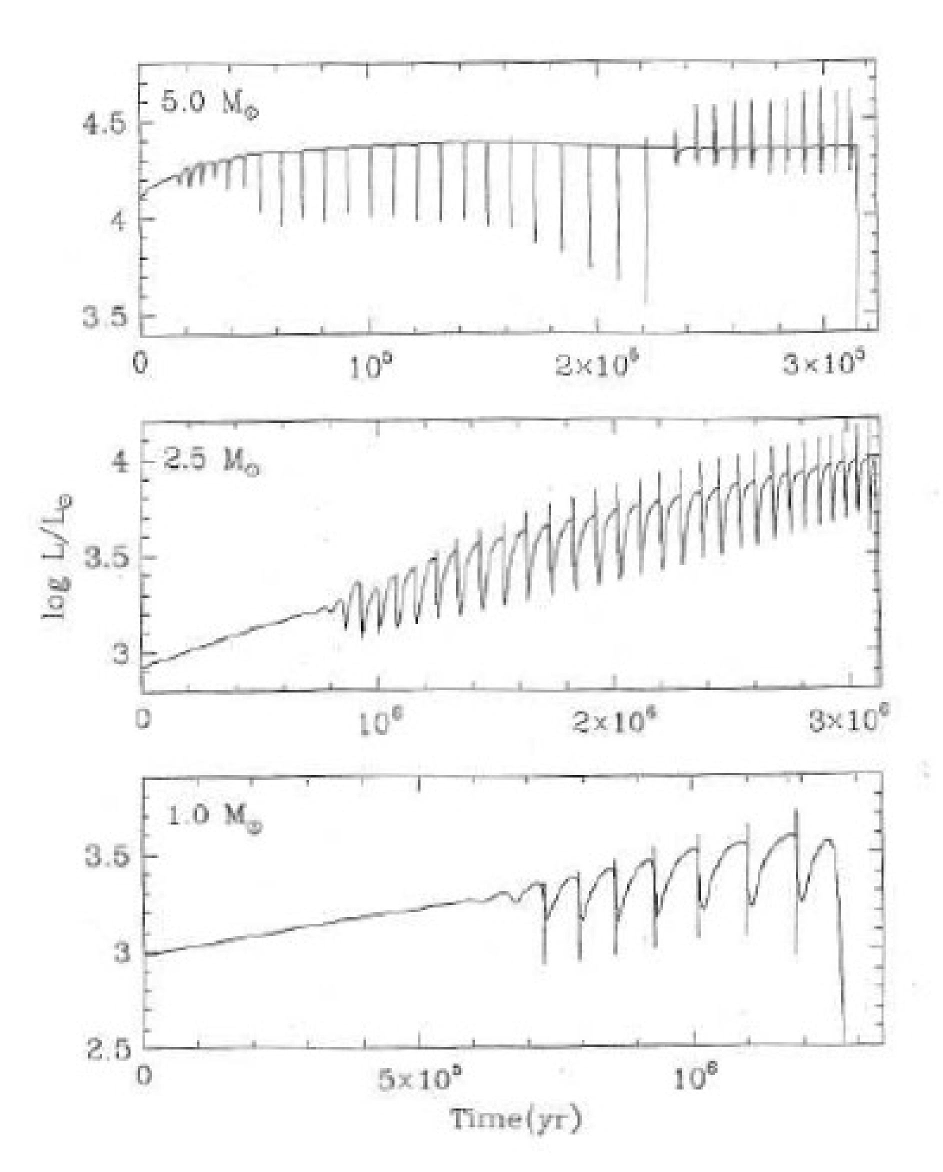
- If $D<r/4$ then C_* will still be *positive! Unstable!*

Interpulse Times

- The time between thermal pulses depends on the mass of the star.
- Numerical modelling shows

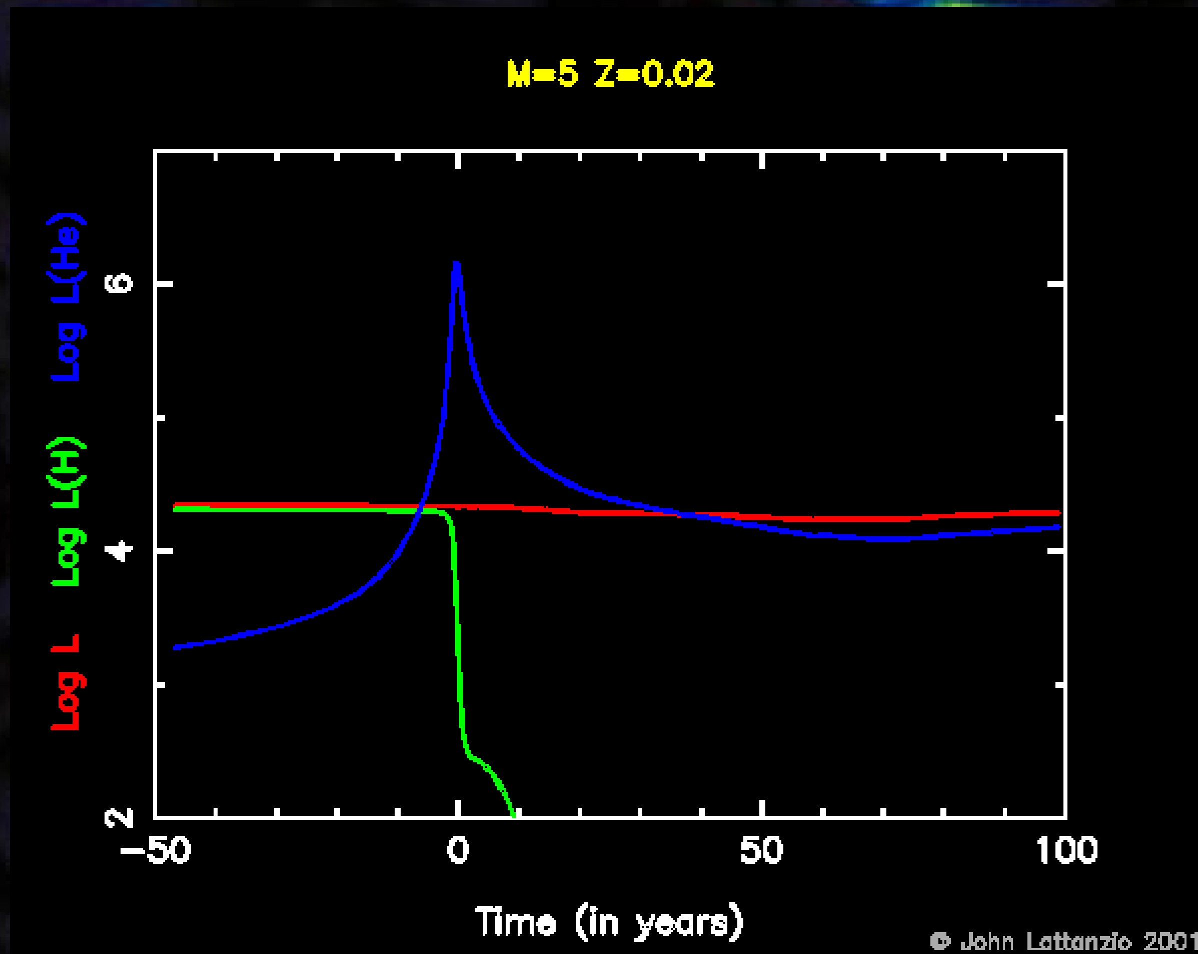
$$\log \tau_{\rm p} = 4.5(1.678 - \frac{M_{\rm core}}{M_\odot}) \qquad \text{(years)}$$

- For 1 $M_\odot$ with M_c=0.6 $M_\odot$: 70,000 years
- For 5 $M_\odot$ with M_c=1.0 $M_\odot$: 1,100 years
- Peak luminosity: 10^9 $L_\odot$.



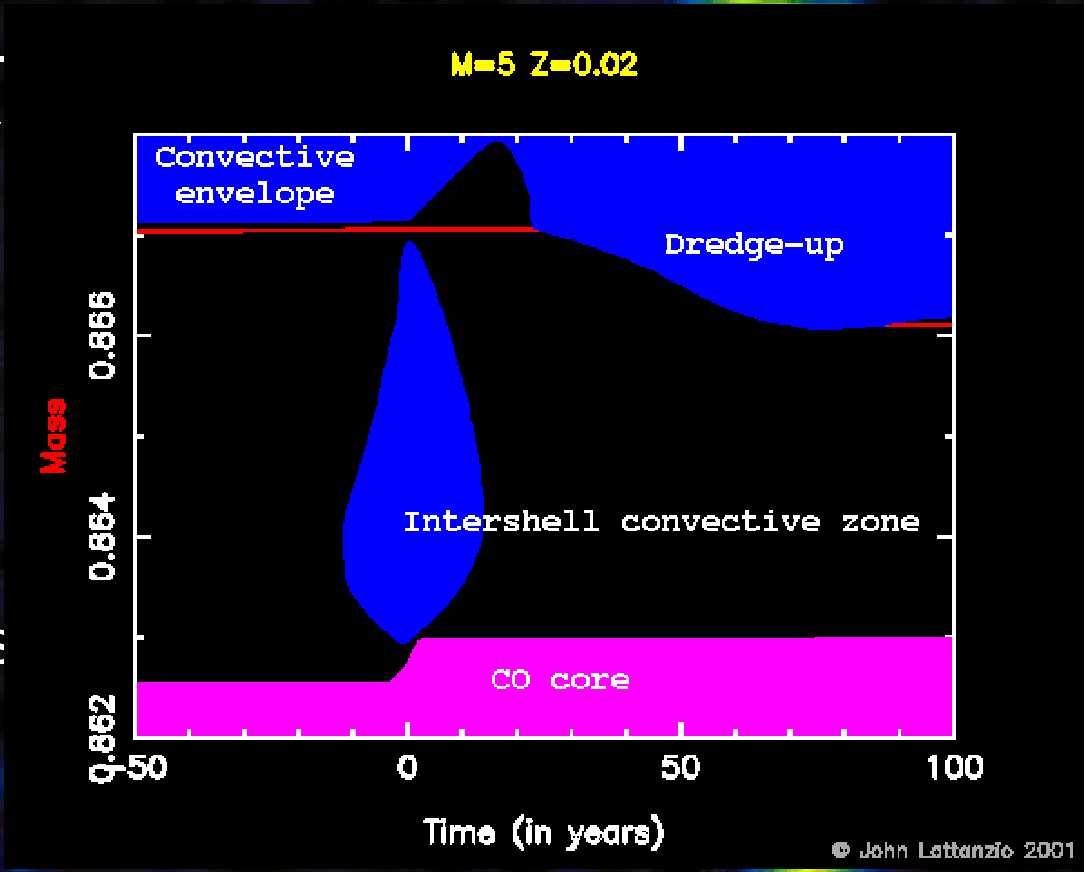
What Happens During a TP

- He-luminosity goes up many order of magnitude.
- H-luminosity goes down (H-shell extinguished).
- Total luminosity remains almost constant.

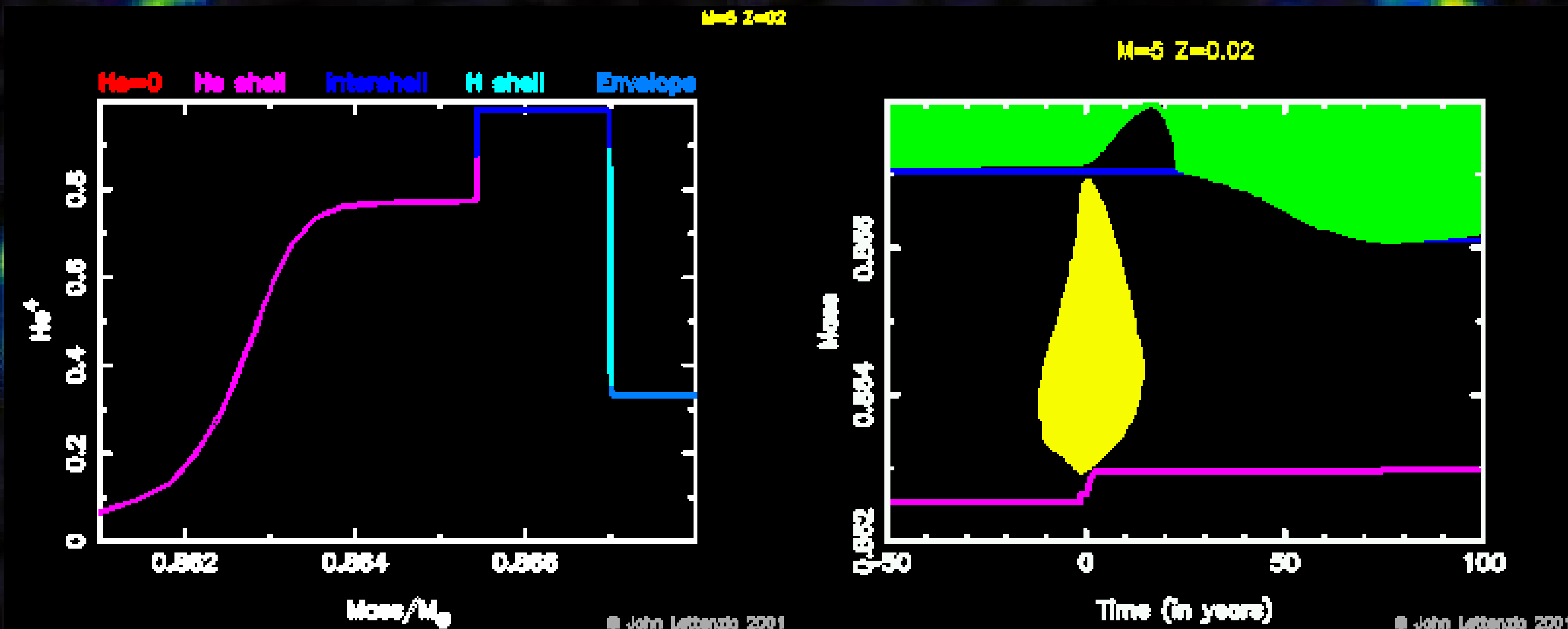


Interior Structure During TP

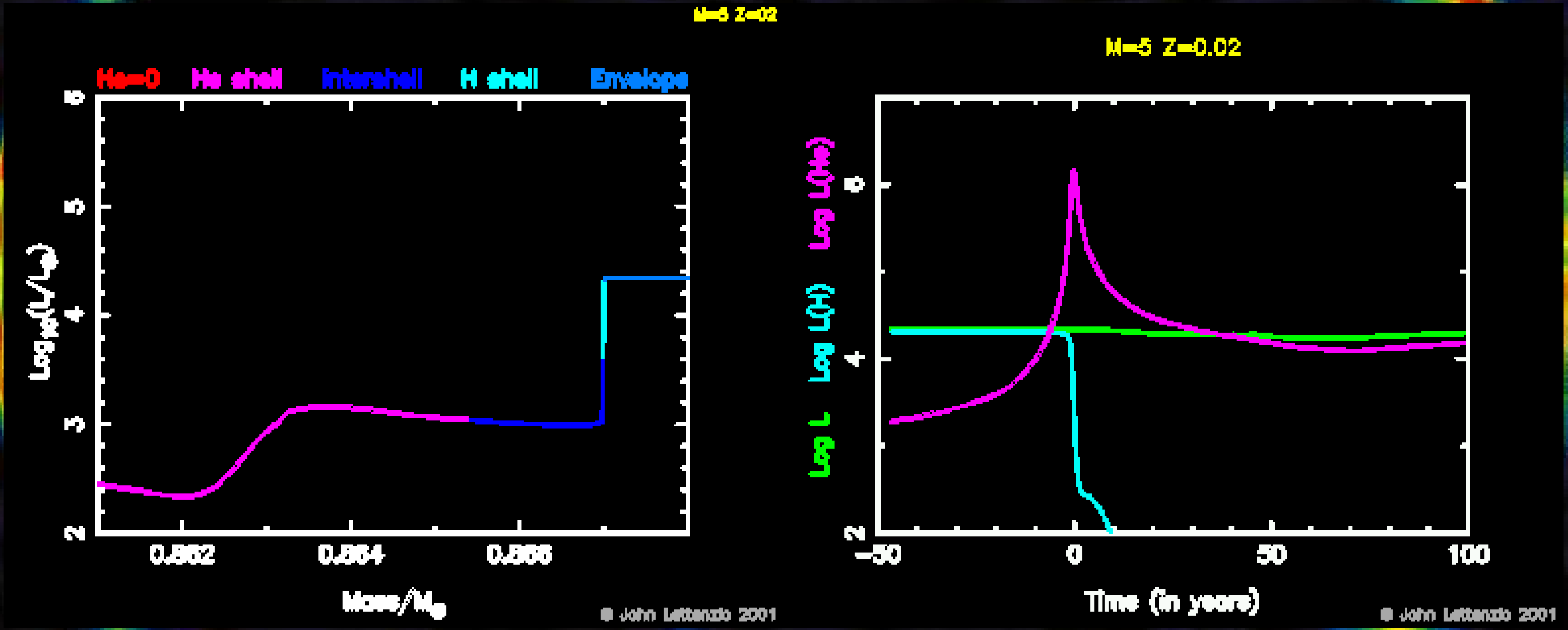
- Blue areas: convective.
- C/O core grows rapidly
- Convective envelope pushed out.
- Intershell convective zone develops.
- After end of pulse, convective zone moves back in.



Animated TP Evolution: ^{4}He



Animated TP Evolution: L



Anatomy of a TP

- **"Off"**: He-shell is inactive, H-shell is active.
- **"On"**: He-shell ignites, $10^8 L_\odot$. Convective zone develops in ISR. Lasts 10-100 years.
- **"Power-down"**: L_{He} declines, expansion of ISR extinguishes H-shell. Overall L drops. Lasts 10-100 years.
- **"Dredge-up"**: Convective envelope moves in, mixing up processed material. Lasts 10-100 years.

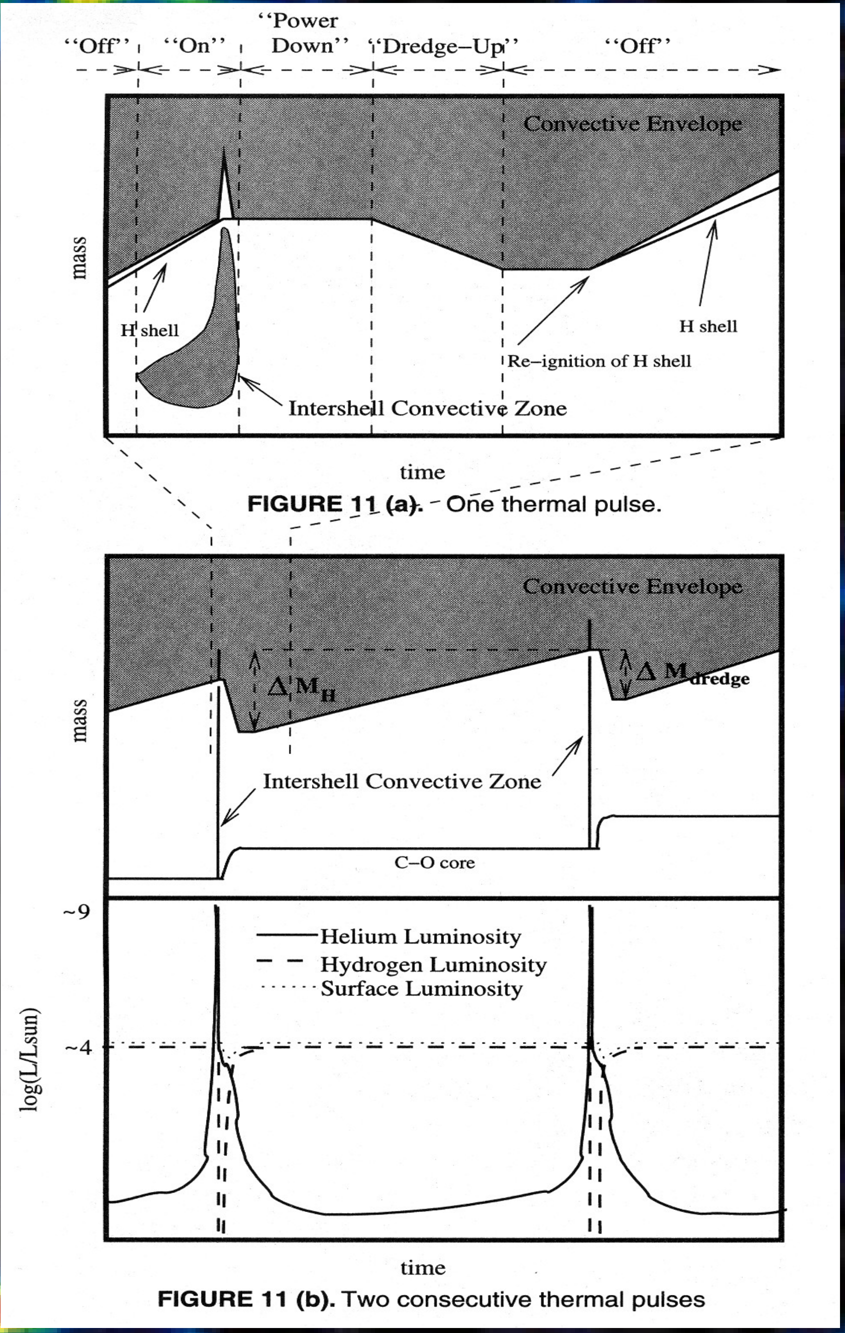
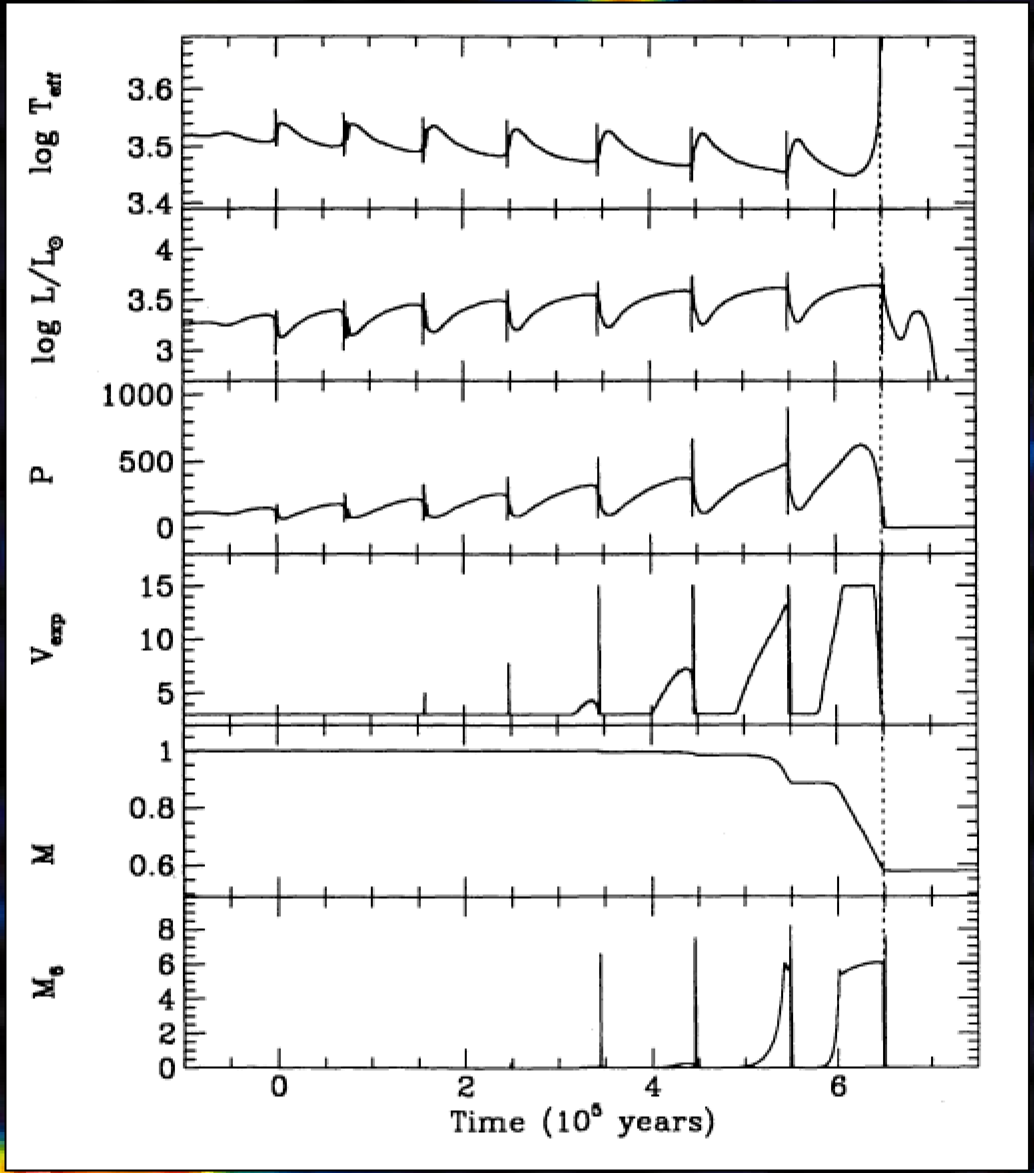


FIGURE 11 (a). One thermal pulse.

FIGURE 11 (b). Two consecutive thermal pulses

Evolutionary Calculations 1 $M_\odot$

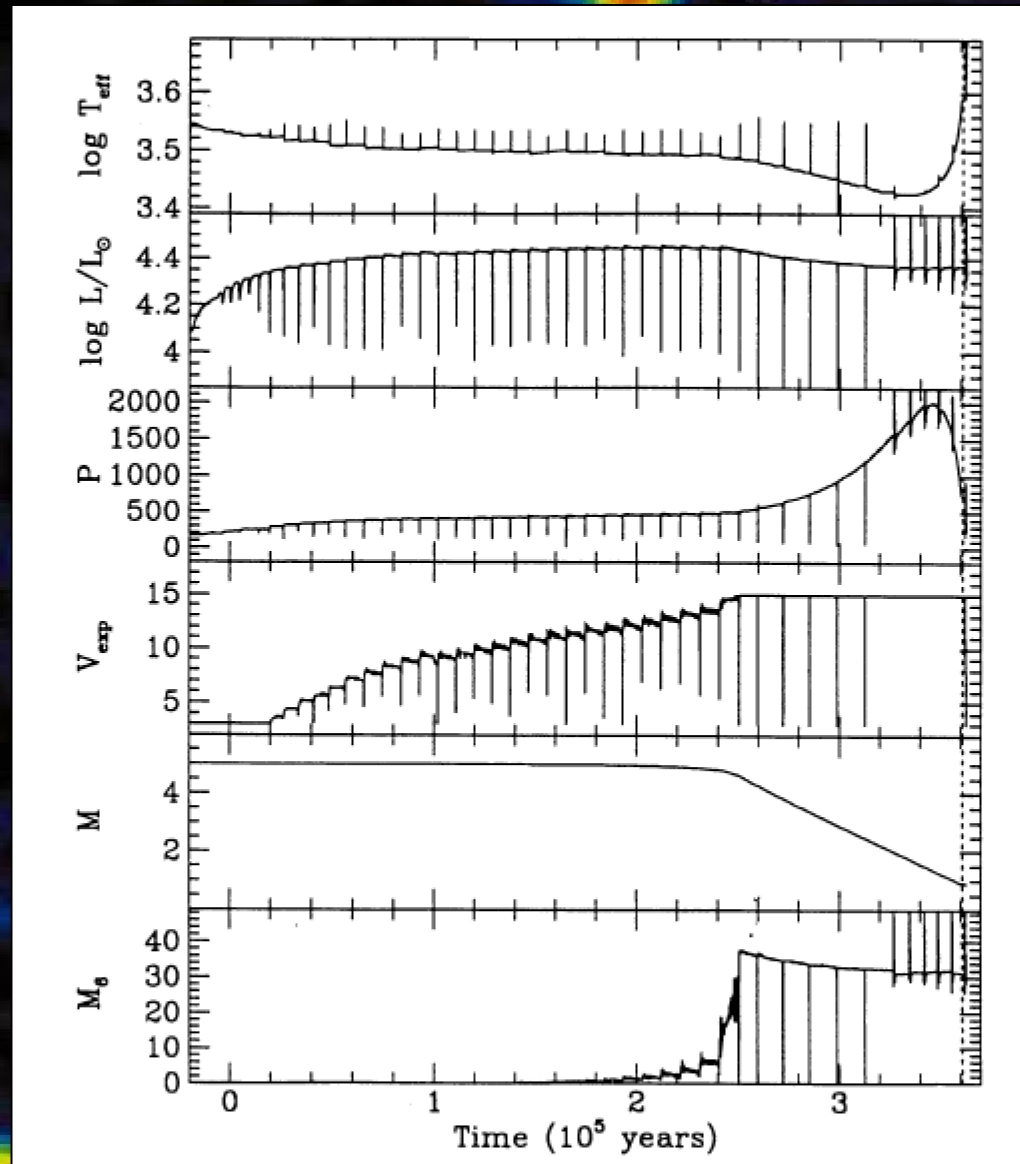
- Evolution of a 1 $M_\odot$ star on the TP-AGB.
- (Y,Z)=(0.25,0.008).
- 8 TPs.
- Total TP-AGB lifetime: 650,000 years.
- From Vassiliadis & Wood (1993).



Evolutionary Calculations 5 $M_\odot$

- Evolution of a 5 $M_\odot$ star on the TP-AGB.
- (Y,Z)=(0.25,0.008).
- ~40 TPs.
- Total TP-AGB lifetime: 360,000 years.

- From Vassiliadis & Wood (1993).



Core Mass – Luminosity Relation

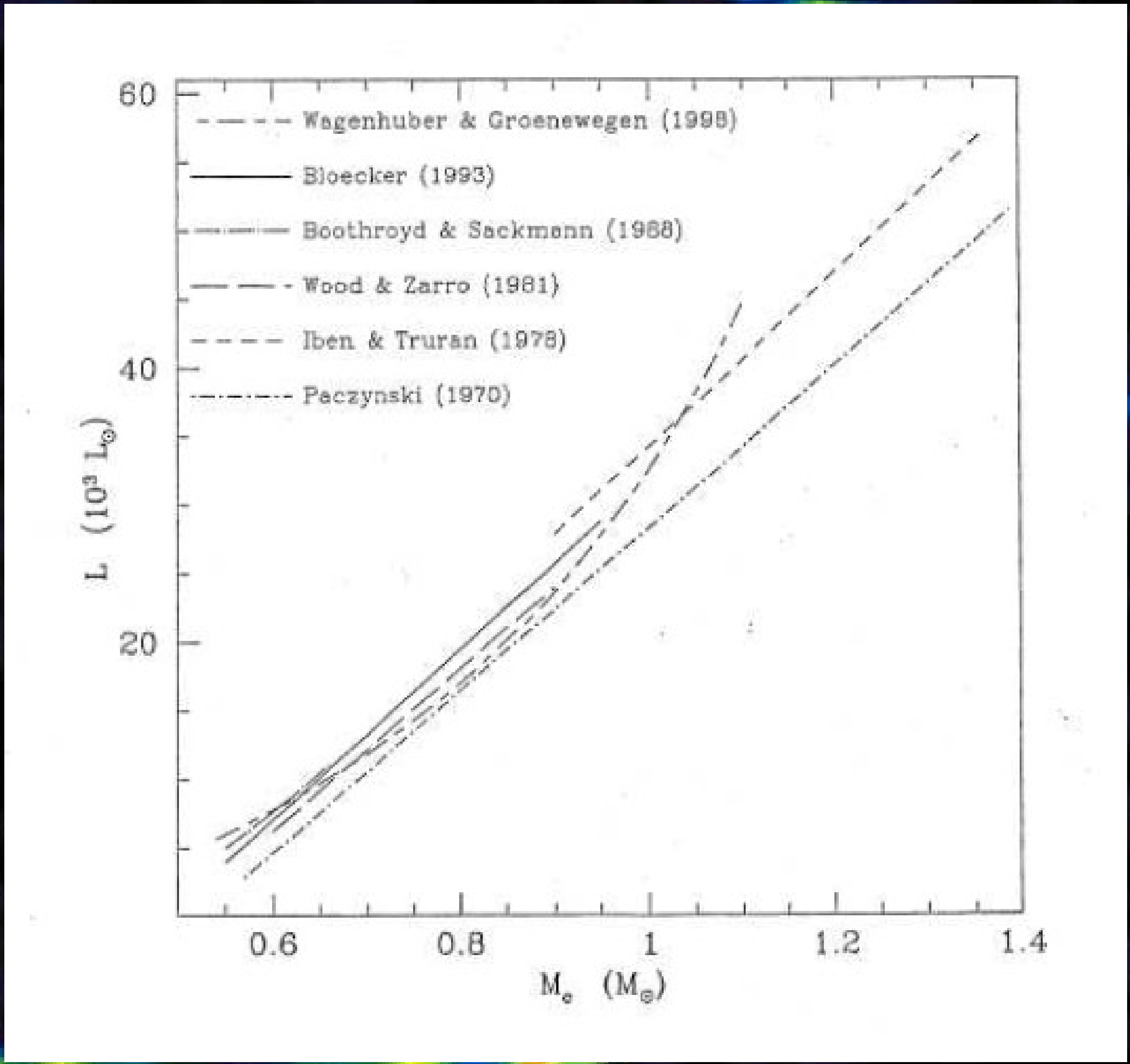
- The luminosity during the ”off” phase keeps going up as the star evolves along the TP-AGB.
- This is connected to the growth of the core mass:

$$L_{\mathrm{AGB}} = 5.9 \times 10^4 (M_{\mathrm{c}} - 0.52) \qquad L_{\odot}$$

- The relation is due to the fact that the envelope is so extended that it becomes irrelevant for the energy producing region.
- L-M_c relations exist for all giant phases, but on RGB: $L \propto M_c^{8}$. On the AGB this becomes $L \propto M_c$ because the higher luminosity leads to a domination of radiation pressure.

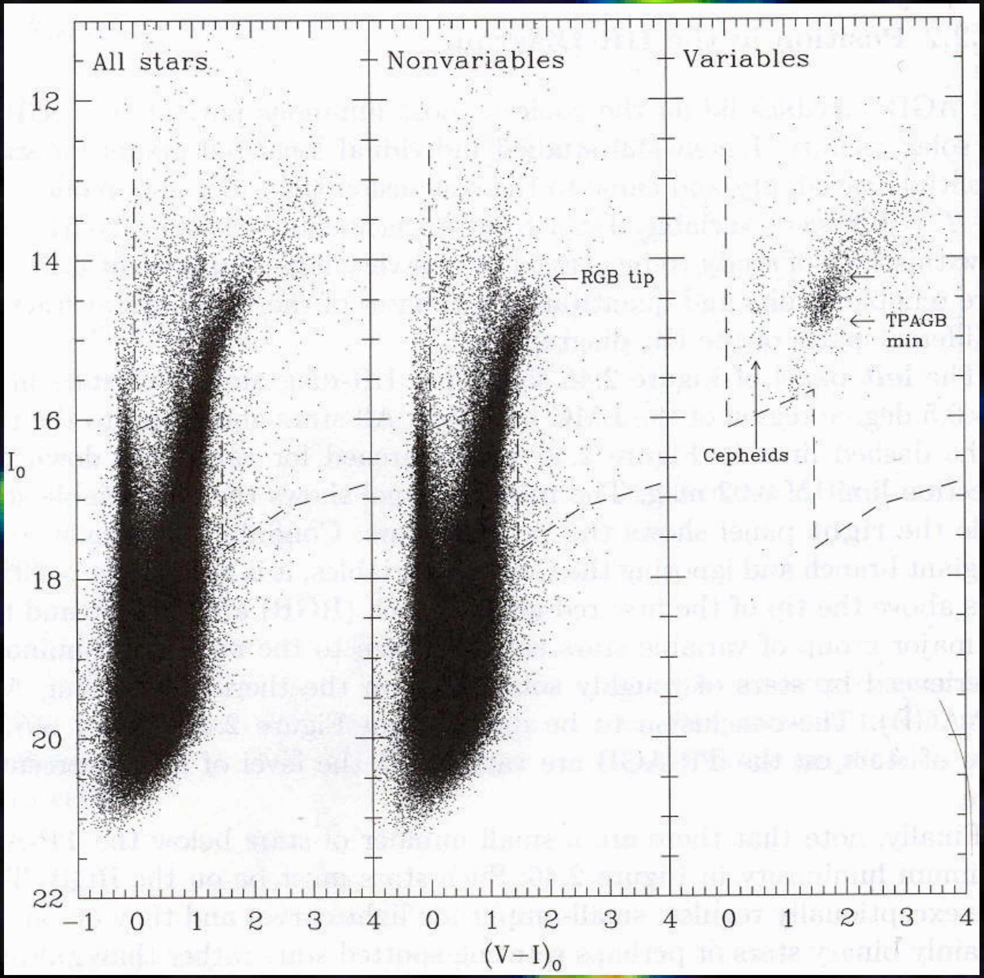
L-M_c Relations

- Paczynski's relation was theoretically derived.
- Later L-M_c relations followed from stellar evolution calculations or 'synthetic evolution calculations', fitted to observations.



Luminosities Limits

- AGB:
  - $L_{min} = 2800\ L_\odot$
  - $L_{max}=51000\ L_\odot$
- RGB:
  - $L_{max}= 2900\ L_\odot$
- Tip of the RGB is a useful concept for studying populations in other galaxies, but confusion with AGB stars may occur.



Luminosity – Colour Diagram

Life Times

TABLE 1

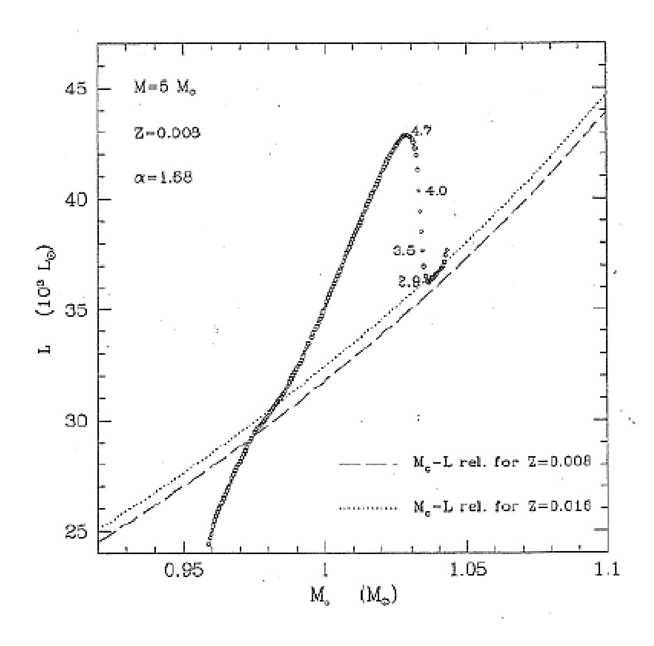
LIFETIMES OF MAJOR EVOLUTIONARY PHASES

M ($M_\odot$)	Z	τ_{MS} (yr)	$\tau_{FGB\text{-}C}$ (yr)	τ_{FGB} (yr)	τ_{HeB} (yr)	τ_{EAGB} (yr)	τ_{TPAGB} (yr)	τ_{AGB} (yr)	$\frac{\tau_{FGB\text{-}C}}{\tau_{HeB}}$	$\frac{\tau_{AGB}}{\tau_{FGB\text{-}C}}$	$\frac{\tau_{TPAGB}}{\tau_{EAGB}}$	$\frac{\tau_{AGB}}{\tau_{HeB}}$
1.0	0.016	1.125E+10	5.786E+07	3.563E+09	1.416E+08	1.209E+07	4.946E+05	1.258E+07	0.409	0.218	0.041	0.089
1.5	0.016	2.742E+09	5.197E+07	7.570E+08	1.359E+08	9.191E+06	8.266E+05	1.002E+07	0.373	0.193	0.090	0.038
2.0	0.016	1.236E+09	5.454E+07	1.648E+08	1.509E+08	7.933E+06	1.175E+06	9.108E+06	0.361	0.167	0.148	0.060
2.5	0.016	6.192E+08	1.429E+08	4.283E+07	2.805E+08	1.084E+07	2.184E+06	1.303E+07	0.051	0.911	0.201	0.046
3.5	0.016	2.307E+08	1.669E+06	1.110E+07	9.142E+07	2.793E+06	4.270E+05	3.220E+06	0.018	1.929	0.153	0.035
5.0	0.016	9.560E+07	3.638E+05	2.578E+06	2.353E+07	1.145E+06	2.624E+05	1.408E+06	0.015	3.869	0.229	0.060
0.945	0.008	1.052E+10	6.094E+07	3.038E+09	1.356E+08	1.057E+07	5.704E+05	1.114E+07	0.449	0.183	0.054	0.082
1.0	0.008	8.129E+09	4.860E+07	2.776E+09	1.336E+08	9.600E+06	6.502E+05	1.025E+07	0.364	0.211	0.068	0.077
1.5	0.008	2.461E+09	3.450E+07	5.140E+08	1.304E+08	7.783E+06	9.385E+06	8.721E+06	0.265	0.253	0.121	0.067
2.0	0.008	1.018E+09	4.458E+07	1.286E+08	1.520E+08	1.340E+07	1.339E+06	1.474E+07	0.293	0.331	0.100	0.097
2.5	0.008	5.170E+08	9.028E+06	3.355E+07	2.209E+08	1.035E+07	1.827E+06	1.217E+07	0.041	1.349	0.177	0.055
3.5	0.008	2.009E+08	1.100E+06	9.042E+06	6.388E+07	3.032E+06	3.509E+05	3.383E+06	0.017	3.075	0.116	0.053
5.0	0.008	8.567E+07	2.496E+05	2.426E+06	2.161E+07	8.036E+05	3.601E+05	1.150E+06	0.012	4.662	0.448	0.053
0.89	0.004	1.096E+10	6.276E+07	2.617E+09	1.294E+08	1.127E+07	7.711E+05	1.204E+07	0.485	0.192	0.068	0.093
1.0	0.004	6.650E+09	5.872E+07	2.111E+09	1.279E+08	8.008E+06	8.684E+05	8.875E+06	0.459	0.151	0.108	0.069
1.5	0.004	2.088E+09	3.650E+07	4.202E+08	1.268E+08	6.302E+06	9.667E+05	7.269E+06	0.288	0.199	0.153	0.057
2.0	0.004	8.930E+08	3.693E+07	1.082E+08	1.539E+08	6.705E+06	1.559E+06	8.264E+06	0.240	0.224	0.233	0.054
2.5	0.004	4.604E+08	5.953E+06	2.745E+07	1.669E+08	5.149E+06	1.248E+06	6.397E+06	0.036	1.075	0.242	0.038
3.5	0.004	1.844E+08	7.070E+05	6.868E+06	5.355E+07	2.150E+06	2.524E+05	2.402E+06	0.013	3.398	0.117	0.045
5.0	0.004	8.058E+07	1.759E+05	2.180E+06	1.864E+07	5.924E+05	3.123E+05	9.205E+05	0.009	5.143	0.527	0.049
1.0	0.001	5.737E+09	3.436E+07	1.344E+09	1.211E+08	7.737E+06	1.357E+06	9.094E+06	0.284	0.265	0.175	0.075
1.5	0.001	1.603E+09	3.633E+07	3.606E+08	1.222E+08	4.962E+06	1.127E+06	6.088E+06	0.297	0.168	0.227	0.050

Vassiliadis & Wood (1993)

Hot Bottom Burning

- This process happens in the more massive AGB stars (>5 $M_\odot$, for solar metallicity $Z=Z_\odot$, lower for lower metallicity).
- It involves the base of the convective zone being involved in H-burning.
- HBB breaks the L-M_c relation, so the higher mass stars do not follow this relation.
- The observational evidence for this process comes from certain abundance variations.
- As well as the lack of high mass C-stars (see later).



HBB: Abundance Effects

- Since the H-burning occurs at the base of the convective envelope, it leads to changes in the surface abundances. Partly these are similar to the effects of the 1st and 2nd dredge-up, $^{4}He\uparrow$ $^{12}C\downarrow$ $^{13}C\uparrow$ $^{14}N\uparrow$
- The reduction of ^{12}C influences the formation of C-stars (see below).
- However, also partial products can now enter the stellar envelope. The most interesting one is ^{7}Li, which is an intermediate product of the pp-chain. Stars with increased ^{7}Li have been found in both the MW and the Magellanic Clouds. The cosmic abundance of ^{7}Li is important because it connects to big bang nucleosynthesis.

PP Chain

$$^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{2}_{1}H + e^{+} + \nu_e$$

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He + \gamma$$

69%

$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + 2\,^{1}_{1}H$$

(PP I)

31%

$$^{3}_{2}He + ^{4}_{2}He \longrightarrow ^{7}_{4}Be + \gamma$$

99.7%

$$^{7}_{4}Be + e^{-} \longrightarrow ^{7}_{3}Li + \nu_e$$

$$^{7}_{3}Li + ^{1}_{1}H \longrightarrow 2\,^{4}_{2}He$$

(PP II)

0.3%

$$^{7}_{4}Be + ^{1}_{1}H \longrightarrow ^{8}_{5}B + \gamma$$

$$^{8}_{5}B \longrightarrow ^{8}_{4}Be + e^{+} + \nu_e$$

$$^{8}_{4}Be \longrightarrow 2\,^{4}_{2}He$$

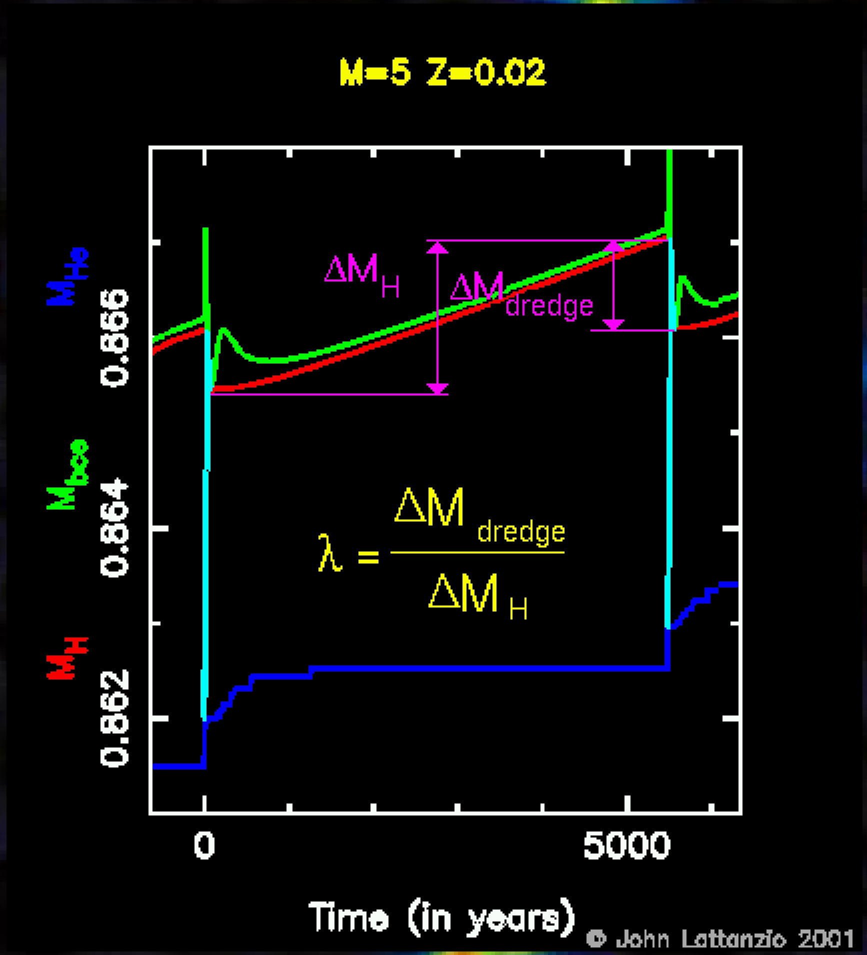
(PP III)

Third Dredge-Up

- As the convective envelope gets pushed out during a TP, and later moves back in again, formerly intershell material may end up in the stellar envelope. This is known as the 3rd Dredge-Up.
- The difference with the other dredge-up events is that this material has been involved in He-burning, so the types of isotopes that are dredged up are very different.
- The most notable of these are
  - ^{12}C
  - s-process elements

3DUP Efficiency

- The efficiency of the 3rd dredge-up is parametrized via $$\lambda = \frac{\Delta M_{\mathrm{dredge-up}}}{\Delta M_c}$$
- This efficiency is not well known, but falls in the range 0.3 – 1.0.
- It can be calibrated with measured abundances in AGB star populations.



Formation of Carbon Stars

- The most dramatic effect of the 3DUP is the formation of Carbon stars.
- Since the early days of stellar spectroscopy (1860s, A. Secchi) a group of red stars with spectra dominated by lines of carbon molecules, has been known. This is peculiar since usually C/O < 1.
- Only in the 1970s it was shown that the 3DUP can bring so much C that the abundance ratio C/O>1.
- This requires a minimum number of TPs, so there is a minimum mass, ~1.5 $M_{\odot}$.
- HBB can turn the ^{12}C in the envelope into ^{14}N, so there is also a maximum mass, ~5 $M_{\odot}$.

Surface Abundance Changes: 2.5 $M_\odot$

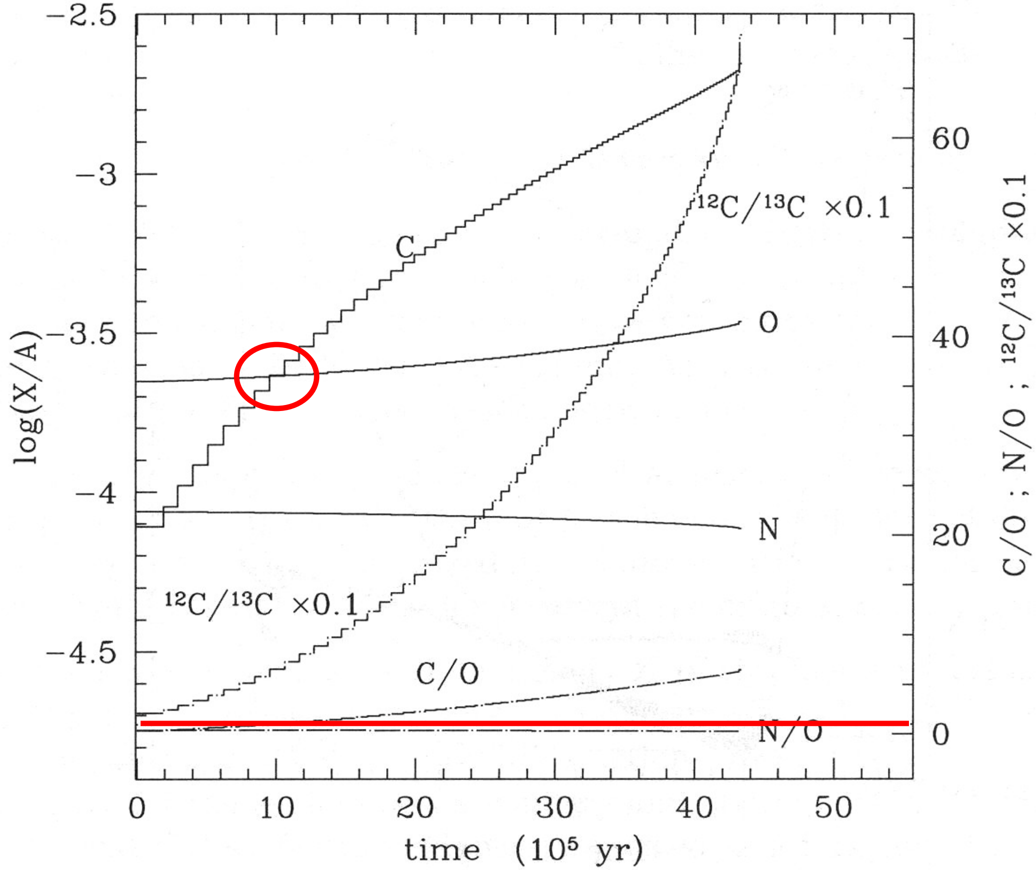


Fig. 3.5. Evolution of CNO surface abundances (by number, mole gr^{-1}) and ratios from the first thermal pulse until the complete ejection of the stellar envelope for $Z = 0.008$ TP-AGB model with initial mass of 2.5 $M_\odot$. The efficiency parameter for the third dredge-up is assumed to be $\lambda = 0.5$; the mixing-length parameter is $\alpha = 2.0$. Based on synthetic calculations by [63]

Surface Abundance Changes: 5 $M_\odot$

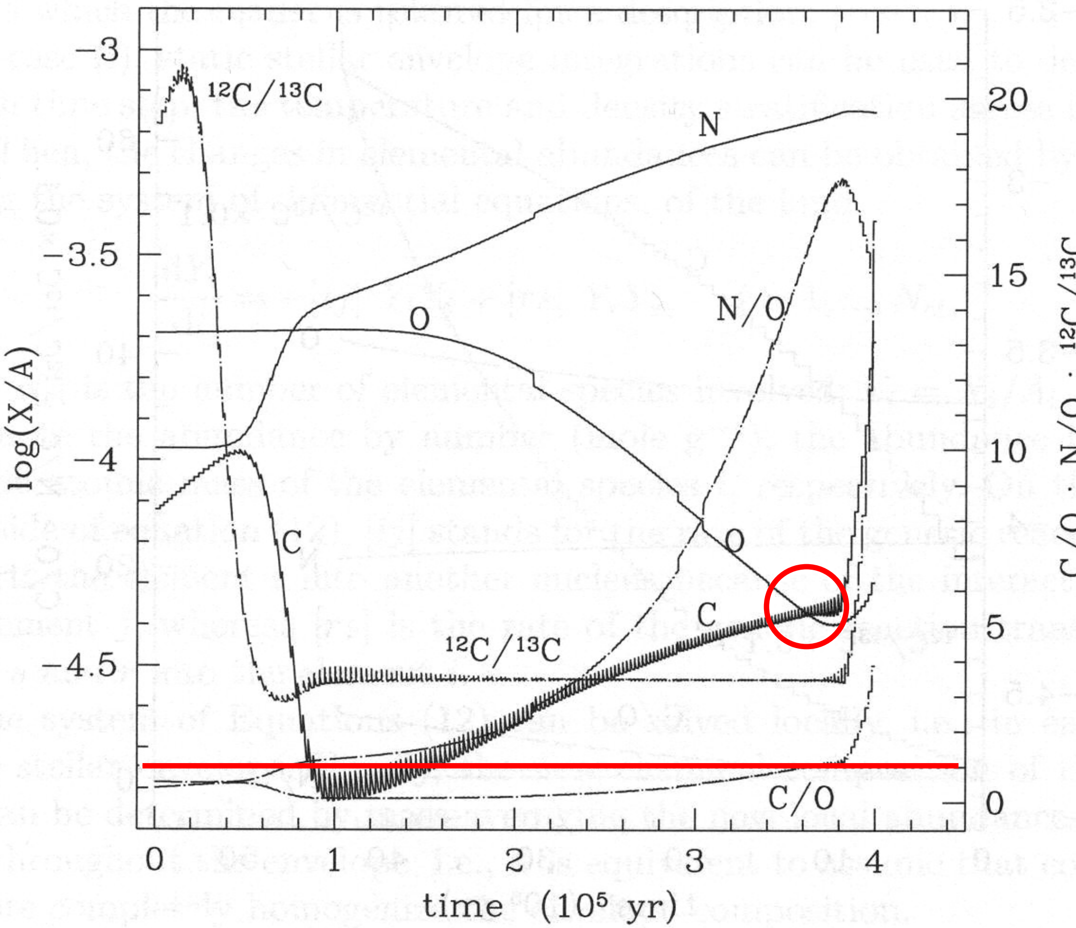


Fig. 3.6. The same as in Figure 3.5 but for a $Z = 0.008$ TP-AGB model with initial mass of $5.0\,M_\odot$

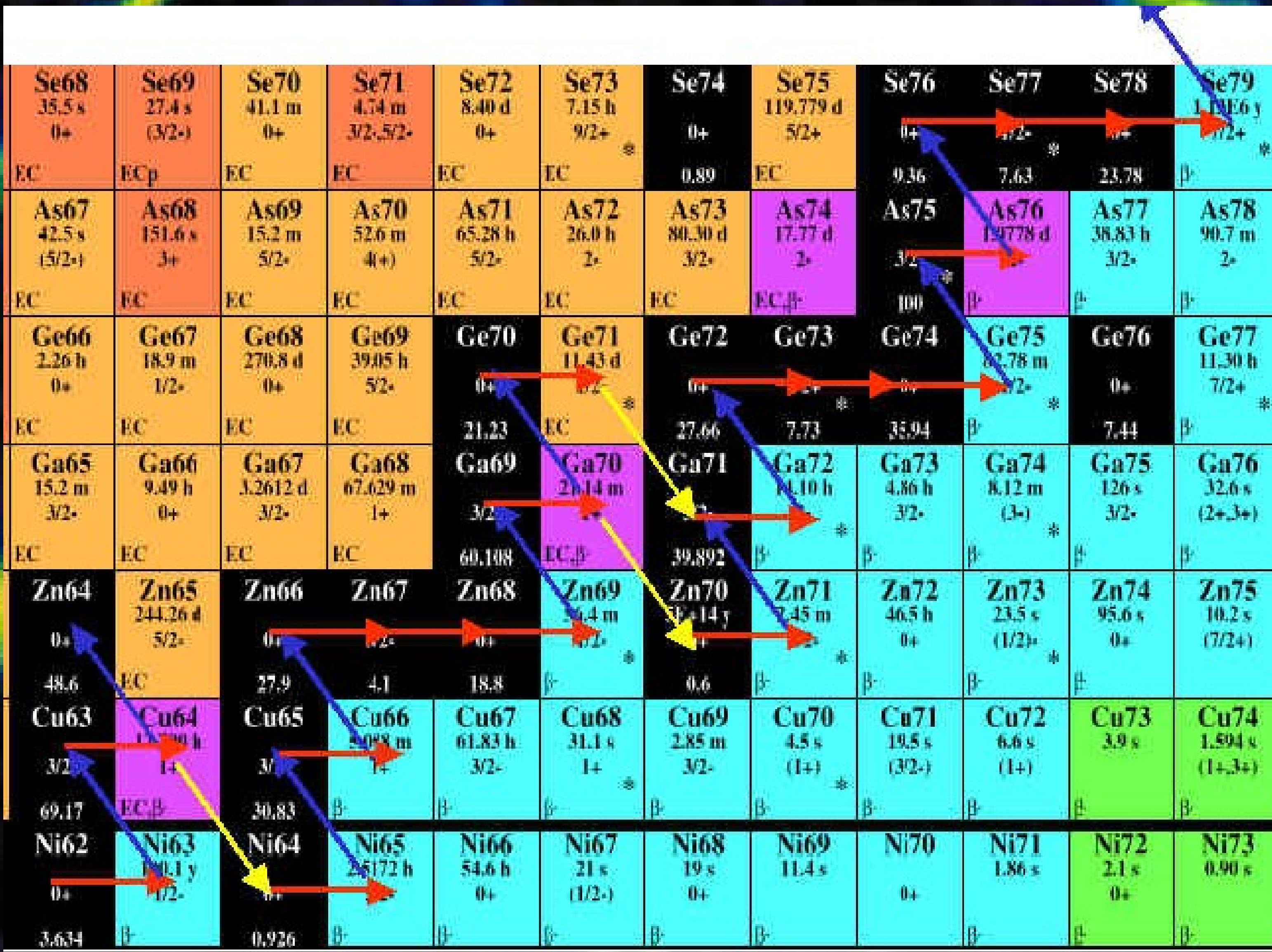
The s-process

- Spectra of AGB stars also can show increased abundances of elements heavier than Fe: Zr, Ti, Tc.
- Nuclear burning does not produce elements heavier than Fe/Ni, since these have the highest binding energy per nucleon.
- These elements can only form through *neutron capture.*
- If the neutron flux is low, unstable nuclei will decay before capturing another neutron: slow neutron capture or s-process. Produces most stable isotopes.
- Decay through β decay or inverse β decay:

$$^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \bar{\nu}_e$$

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e$$

Stepping through the Isotopes



Limit of the s-process

- The s-process cannot produce elements heavier than Pb (Z=82) since at Pb there is a closed loop in the decay scheme:

$$
\begin{aligned}
{}^{209}\mathrm{Bi} + n &\rightarrow {}^{210}\mathrm{Bi} + \gamma \\
{}^{210}\mathrm{Bi} &\rightarrow {}^{210}\mathrm{Po} + e^{-} + \bar{\nu}_e \\
{}^{210}\mathrm{Po} &\rightarrow {}^{206}\mathrm{Pb} + {}^{4}\mathrm{He} \\
{}^{206}\mathrm{Pb} + 3n &\rightarrow {}^{209}\mathrm{Pb} \\
{}^{209}\mathrm{Pb} &\rightarrow {}^{209}\mathrm{Bi} + e^{-} + \bar{\nu}_e
\end{aligned}
$$

- Heavier elements require the r-process (operating in SN explosions).

Spectroscopic Evidence

- AGB stars can show clear signs of s-process elements: ZrO, TiO. Stars which show these lines particularly prominently get a special spectroscopic classification: S-stars.
- The most convincing evidence for the s-process in AGB stars is the detection of Tc lines. Tc (Z=43) does not have any stable isotopes. The stablest isotope is ^{99}Tc with a half life of 2×10^5 years.
- As s-process elements have the same origin as the increase in the C abundance, it is thought that there is an evolutionary sequence M → S → C.

Neutron Source

- Although the evidence for the operation of the s-process is convincing, the process itself is not fully understood.
- The problem lies with the source of neutrons which is needed for the s-process.
- Best candidates:

$$^{13}\mathrm{C} + ^{4}\mathrm{He} \rightarrow ^{16}\mathrm{O} + n$$

$$^{22}\mathrm{Ne} + ^{4}\mathrm{He} \rightarrow ^{25}\mathrm{Mg} + n$$

← Only in higher mass stars

- To make ^{13}C we need protons, but only just enough!!

$$^{12}\mathrm{C} + p \rightarrow ^{13}\mathrm{N} + \gamma \rightarrow ^{13}\mathrm{C} + e^{+} + \nu_e$$

$$^{13}\mathrm{C} + p \rightarrow ^{14}\mathrm{N} + \gamma$$

← and gone it is!!!

The ^{13}C Pocket

- Two consecutive TPs needed to get the s-process elements out.