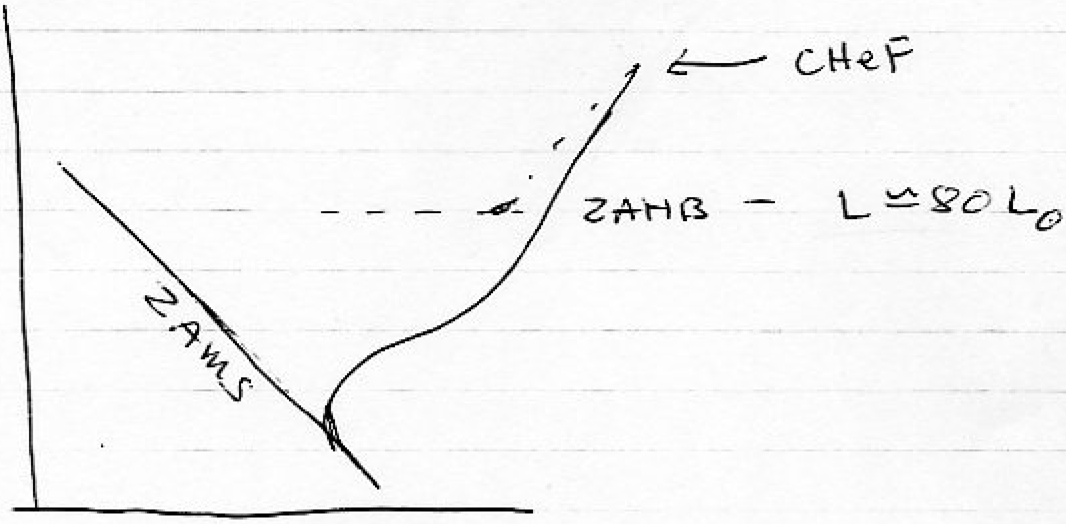
X4

HORIZONTAL BRANCH



Models evolved through the core flash have the wrong luminosity when compared to observations!

To get L correct we need to subtract $\sim 0.2 M_\odot$ from the ZAHB models.

$\Rightarrow$ mass-loss on the giant branch!

This was confirmed observationally.

$$\dot{M} \propto \frac{RL}{M}$$

larger $R \Rightarrow$ less bound

larger $L \Rightarrow$ higher radiation force

larger M means <u>more</u> bound

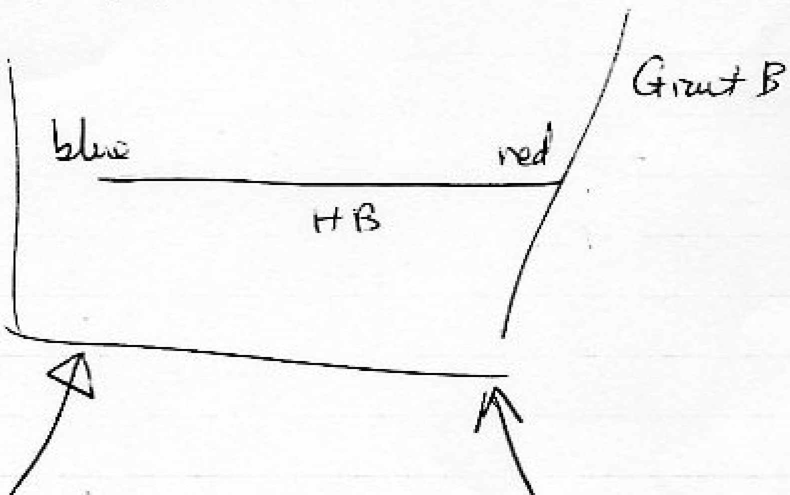
Fit to observations by Reimers: $\dot{M} \simeq 1.4 \times 10^{-11} \left(\frac{L}{L_\odot}\right)^{1.66} \left(\frac{M}{M_\odot}\right)^{-1} M_\odot/y$

Fit to observations by Reimers

$$\dot{m} \simeq -3.2\times10^{-13}\left(\frac{L}{L_\odot}\right)^{1.66}\left(\frac{M}{M_\odot}\right)^{-1} \; M_\odot/yr$$

Also, a given globular cluster shows a <u>SPREAD</u> on the HB ... should be <u>very</u> narrow range of masses ... seems to be more wide than that?!

Obs indicate a spread in total mass if we are to populate the HB



- thin envelope
- small M_{env}
- large $\dot{m}$ on GB

- thicker envelope
- higher M_{env}
- lower $\dot{m}$ on GB

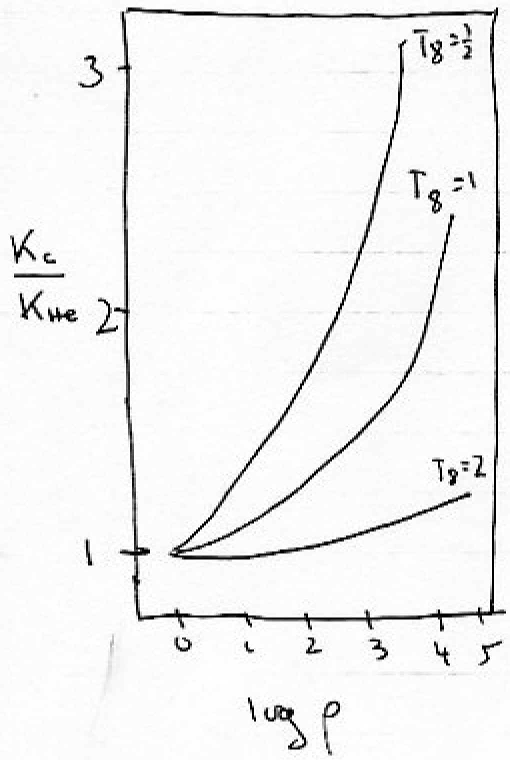
$$M = M_{env} + M_{core}$$

M_{env} ← depends on $\dot{m}$ ← can vary with ... rotation?

M_{core} ← depends on nuclear physics ← Same for <u>all</u> stars!

Semiconvection — He-burning for $m \lesssim 2\text{-}5 M_\odot$

Core He burning produces C^{12} ($\& O^{16}$) from He^4. The opacity of C-rich material usually exceeds that of He-rich matter by factors of a few at the T & ρ found at the edge of convective cores in He-burning stars

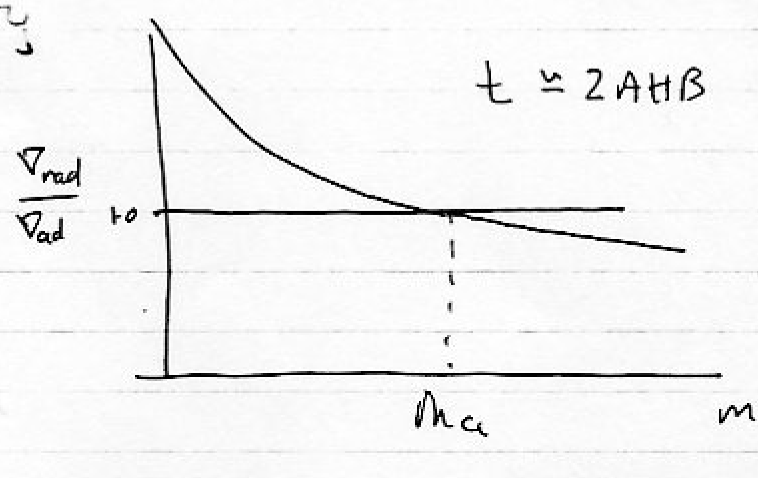


$K_c = K$ for $Z = 0.001$ and $C = 0.999$
K_{He} = " " " " $He = 0.999$

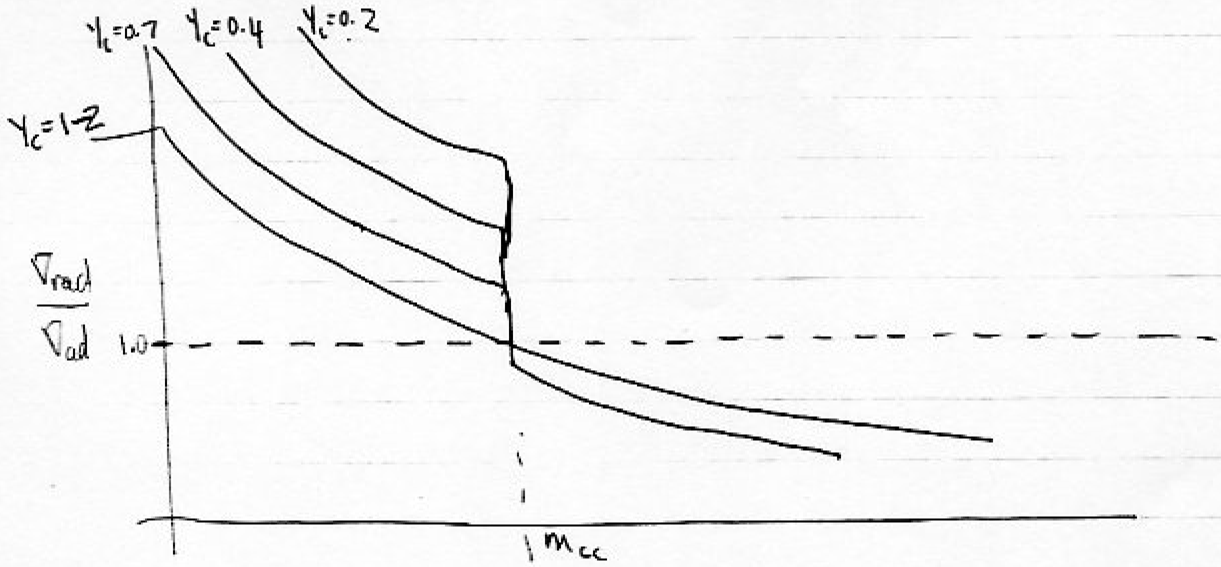
$T_8 = T/10^8 K$

At this stage of the evolution the effects of opacity are much greater than changes in the physical parameters. Nuclear burning changes He ~~and~~ into C in the convective core. So there is a growing chemical discontinuity at the edge of the convective core.

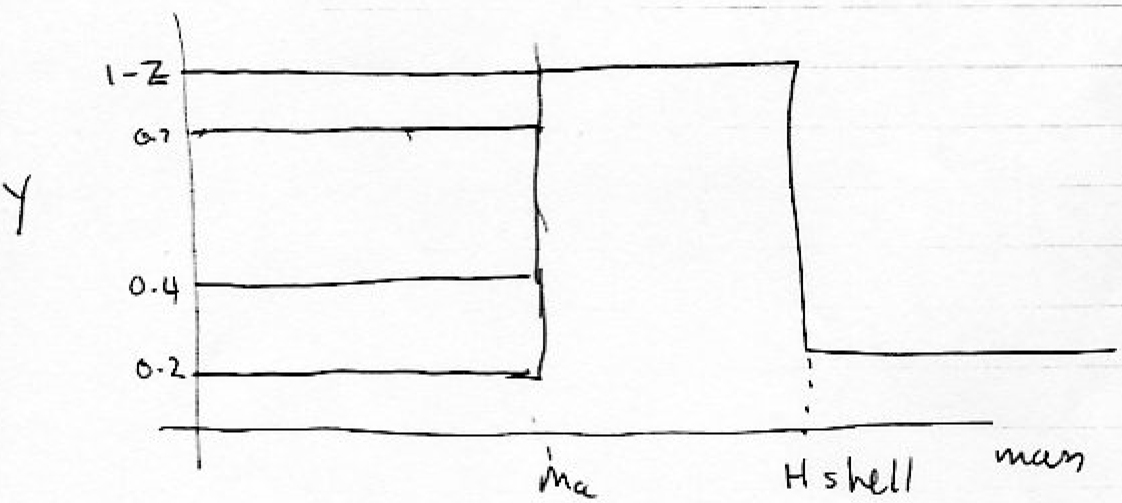
$t \simeq 2AHB$



As He → C we find κ of core increases. Thus ∇_{rad} ↑.



At this stage the He profiles look like this:



In Asst 1 we saw that, for *any* value of U,

$$x \uparrow \text{ as } \omega \uparrow$$

$$\text{ie } \nabla - \nabla_{ad} \uparrow \text{ as } \nabla_{rad} - \nabla_{ad} \uparrow$$

$$\text{ie } \nabla \uparrow \text{ as } \nabla_{rad} \uparrow$$

So the growing $\nabla_{rad} / \nabla_{ad}$ at the core edge leads to a larger ∇. And the buoyancy is?

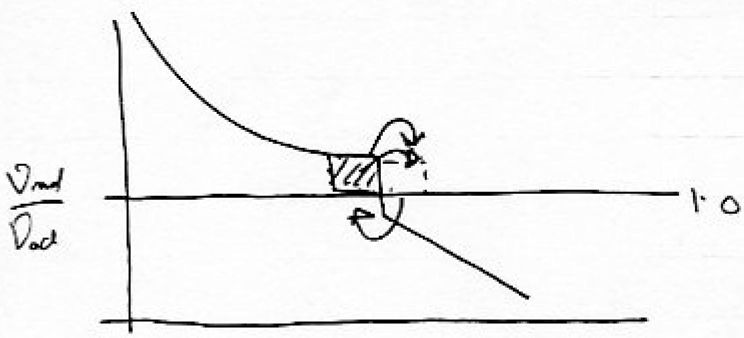
$$k = -g \frac{D\rho}{\rho}$$

$$= \frac{g\delta\, l_m}{2H_p} (\nabla - \nabla_e) \propto (\nabla - \nabla_{ad}) > 0$$

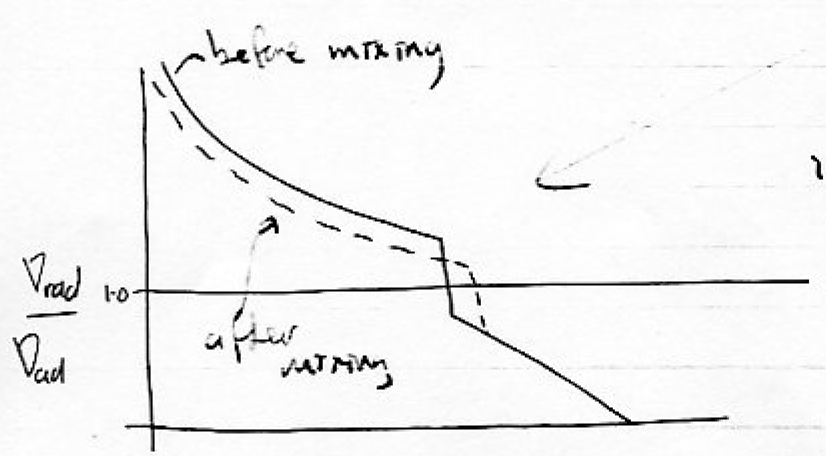
i.e. the buoyancy increases, & the acceleration $\neq 0$. Thus material is driven <u>across</u> the Schwarzschild barrier.

(This is different to the usual overshooting: in that we have $k = 0$ but $v \neq 0$. Here <u>both</u> v and k are > 0.)

Thus we expect some overshooting / mixing across the formal edge, as determined by the Schwarzschild criterion.



Thus a "lump" of C-rich matter is mixed out, and the equal mass of He-rich matter is mixed inward.
This raises K <u>outside</u> the core, and <u>lowers</u> it <u>inside</u>



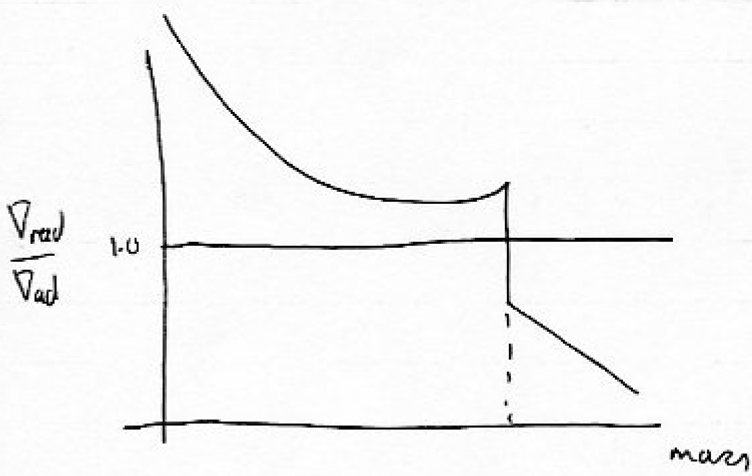
i.e. the convective core grows. Radiative shells are added to the convective core.

<u>NB</u> This assumes that the timescale for the propagation of the convective boundary τ_p is less than the nuclear burning time-scale τ_N for He depletion in the core:

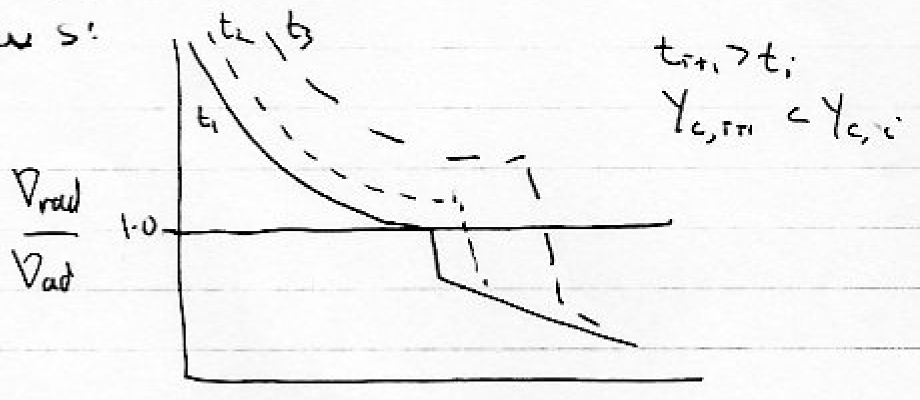
$$\tau_p < \tau_N .$$

The situation is actually more complicated, because there is in fact a local <u>minimum</u> in ∇_{rad}! This is due to a complex variation of the quantities in its definition:

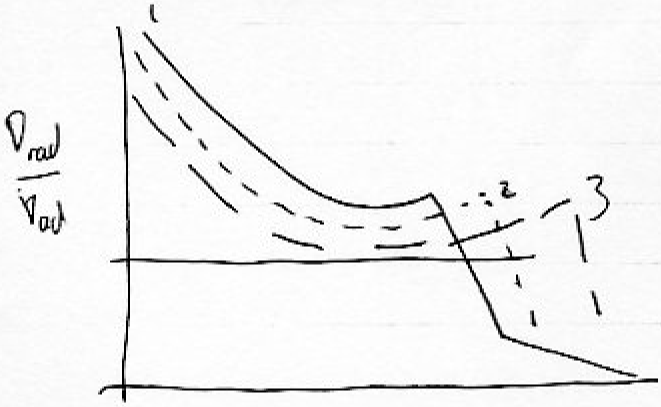
$$\nabla_{rad} = \frac{3KLP}{16\pi ac G m T^4} \sim \frac{KLP}{mT^4}.$$



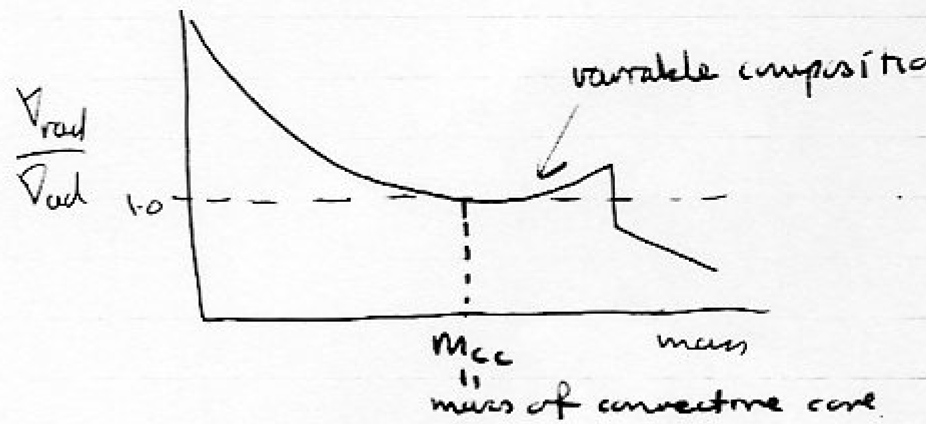
During early evolution $\tau_p > \tau_N$ so that the production of C^{12} dominates and the extent of the convective core actually grows:



It is not until $Y_c \lesssim 0.6$ that $\tau_p < \tau_N$. Then the overshooting extends the core, as discussed above.



As ∇_{rad}/∇_{ad} drops below unity at the minimum, it "pinches-off" the convective core.



Just beyond the convective core we have

$$\nabla_{ad} < \nabla_{rad} < \nabla_{ad} + \frac{\varphi}{\delta} \nabla_\mu$$

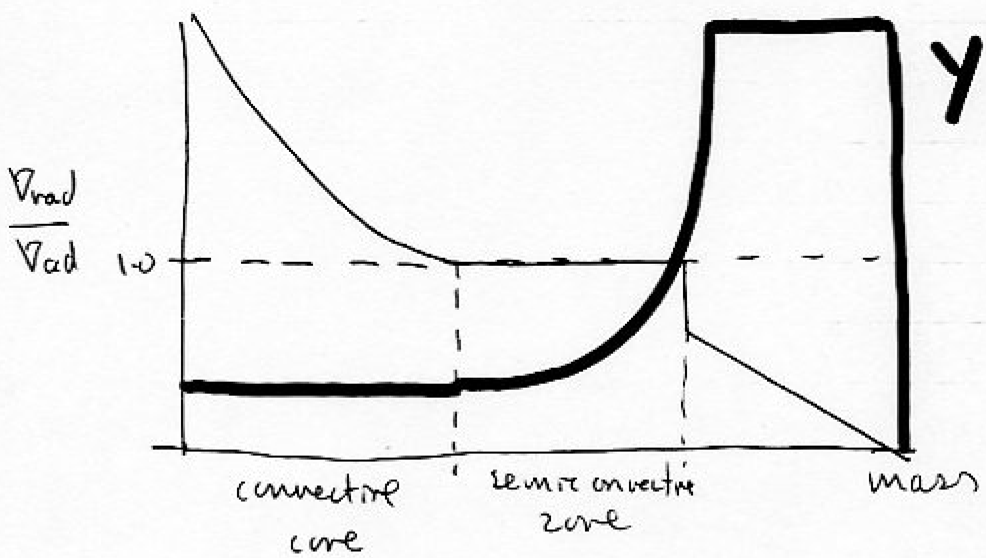
Schwarzschild criterion — Ledoux criterion

ie the zone is STABLE by Schwarzschild, yet it is UNSTABLE by Ledoux!

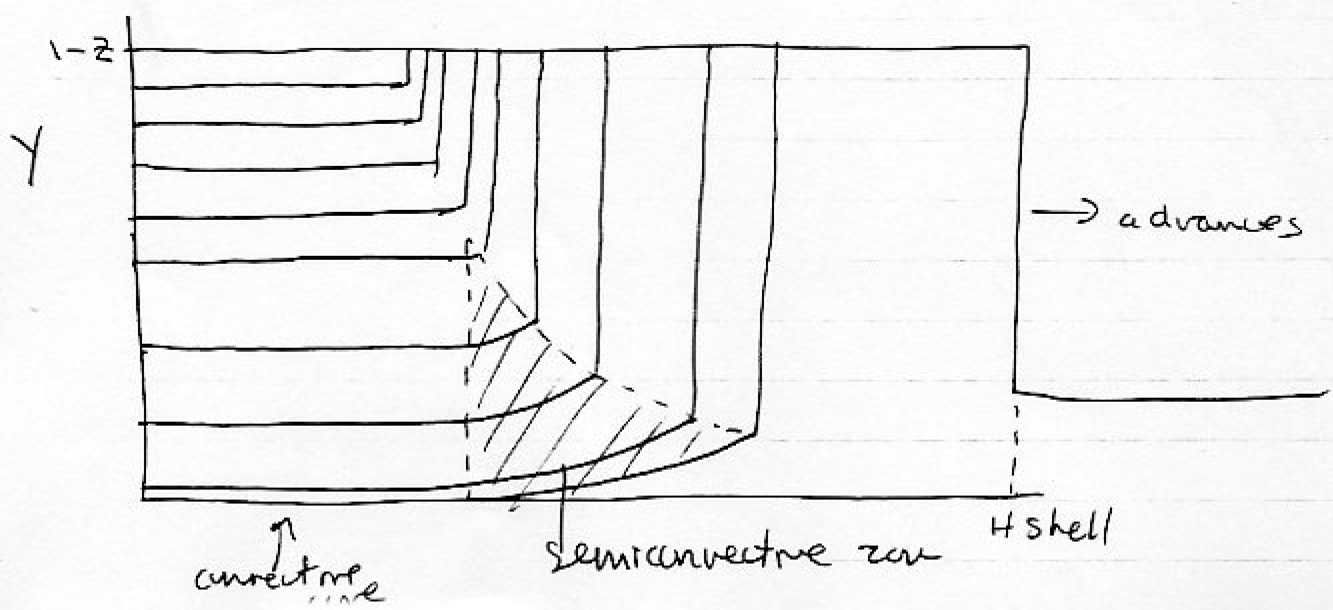
Also note the shape of the ∇_{rad}/∇_{ad} plot: there is finite buoyancy driving o/shoot.

Clearly this unstable situation results in mixing. This adjusts the compositions. Wherever there is mixing the opacity is lowered and $\nabla_{rad} \to \nabla_{ad}$. If it drops below ∇_{ad} the mixing stops. Clearly the only stable situation is that mixing continues until the composition is such that

$$\nabla_{rad} = \nabla_{ad}.$$



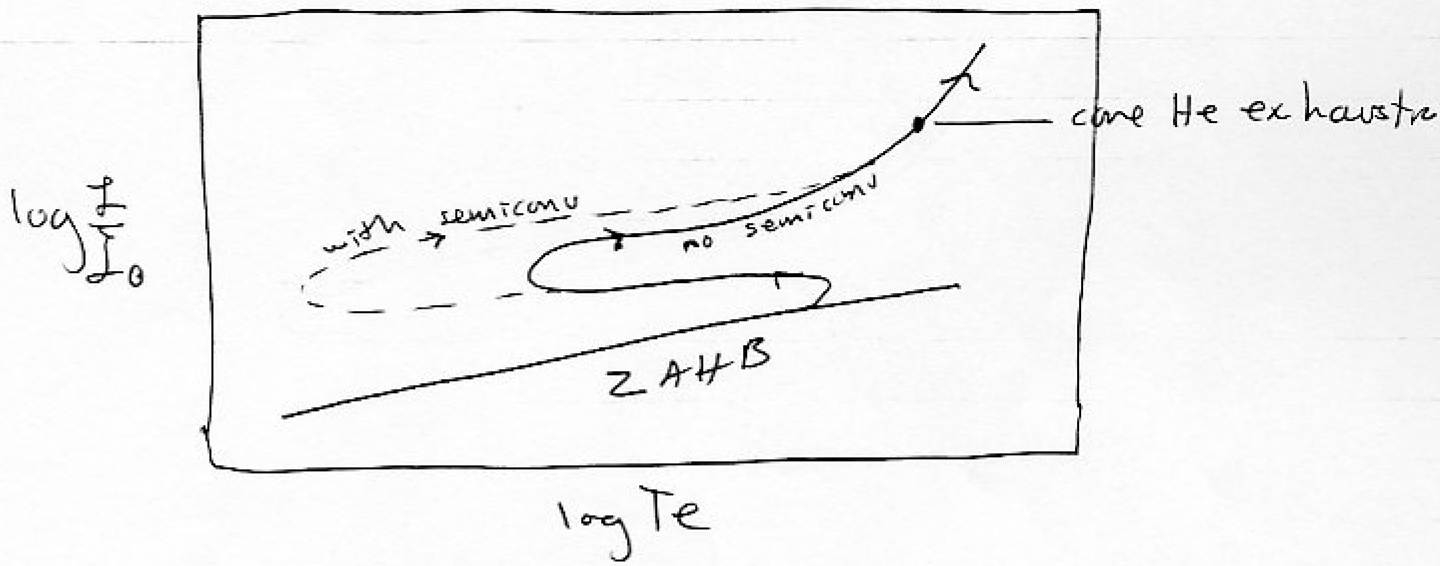
So for a typical He burning star of $M \lesssim 2$ this occurs when $Y_c \lesssim 0.0$. : $Y_c \gtrsim 0.6$ sees convective core which grows. When $Y_c \lesssim 0.6$ the convective core remains approx constant in mass but a semi-convective zone develops, and grows.



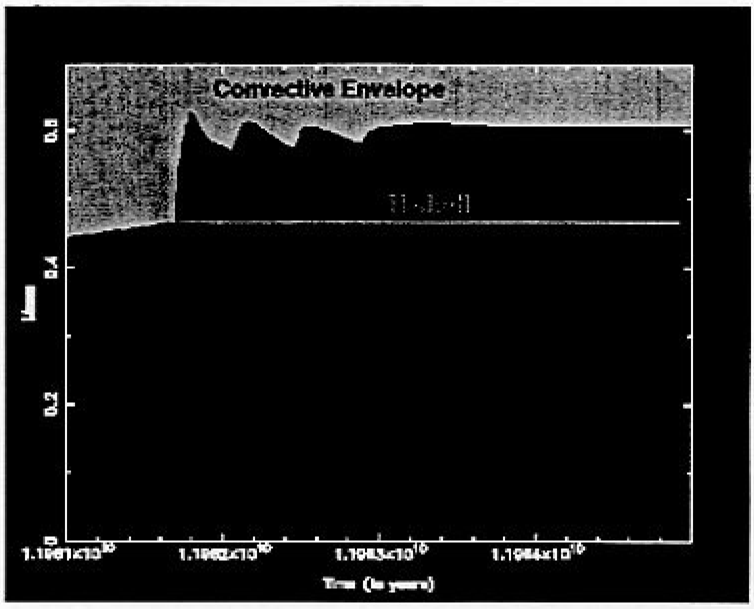
A numerical method to study semiconvection in core-He-burning stars was devised by two people at Mt. Stromlo Observatory:

John Robertson & Don Faulkner
Ap. J., 1972, 171, 309.

As semiconvection mixes more He into the core, where it is burnt, the effect of semiconvection is to extend the He-burning lifetime. By up to a factor of 2! This lifetime is supported by counts of the ratio of stars in He-burning phase to those phases just before and after



steadily burning helium core.



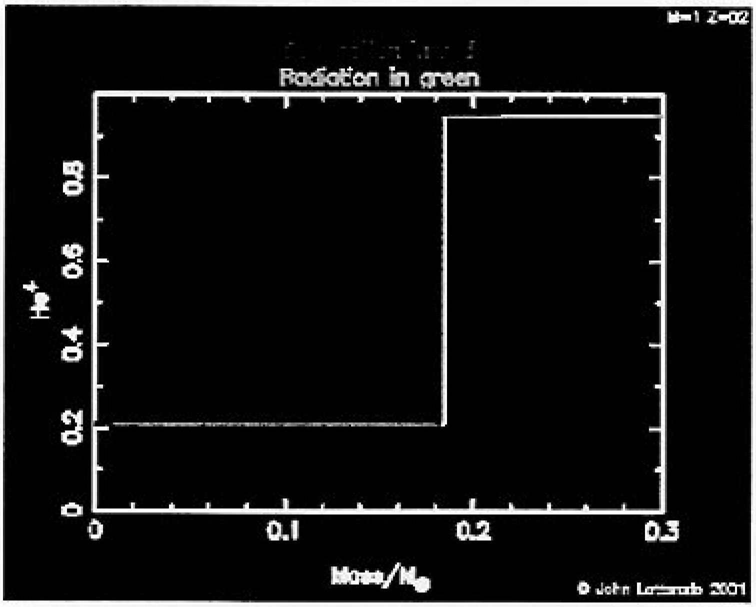
7. **Core Helium Burning (M=1 Msun, Z=0.02)**

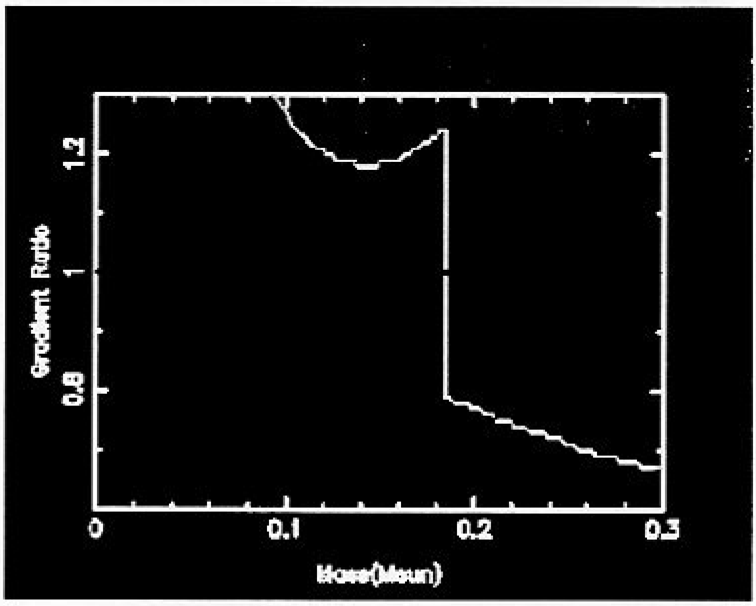
    1. The star now begins evolution with two energy sources: a He-burning core and a H-burning shell. This movie (horizontal or vertical) shows the interior profiles of He as the star proceeds through the HR diagram. Note that we have colour-coded the He profiles here according to the H and He abundances

    2. Semiconvection: now comes the fun bit!

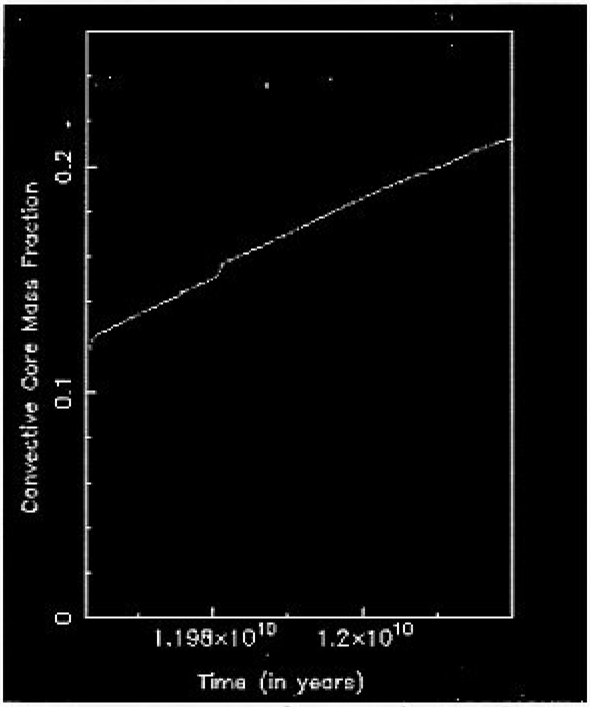
    3. It is not our aim here to go through all the details of semi-convection. Rather, as with the rest of this page, we use results to illustrate the principles. You are referred to the Castellani, Giannone and Renzini papers from 1970 for an excellent discussion. But here we show the latter stages of the core helium burning evolution of out M=1 Z=0.02 model.

    4. Initially the burning of He into C-12 increases the opacity in the core. Hence the radiative gradient increases, and hence the ratio of the gradients increases. But on the other side of the convective border there is no change in the composition (recall that the burning is happening in the very centre, but convection covers a much larger mass than the burning zone, so that there is a discontinuity in the composition at the edge of the convective core: just outside is a radiative region where there is no nuclear burning). SO we have a discontinuity in the composition and also the ratio of the radiative to adiabatic temperature gradients, as shown below.



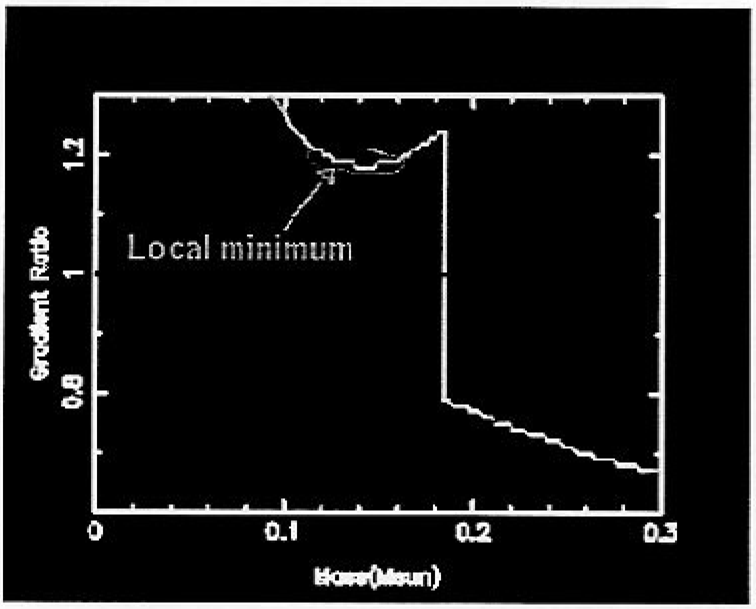


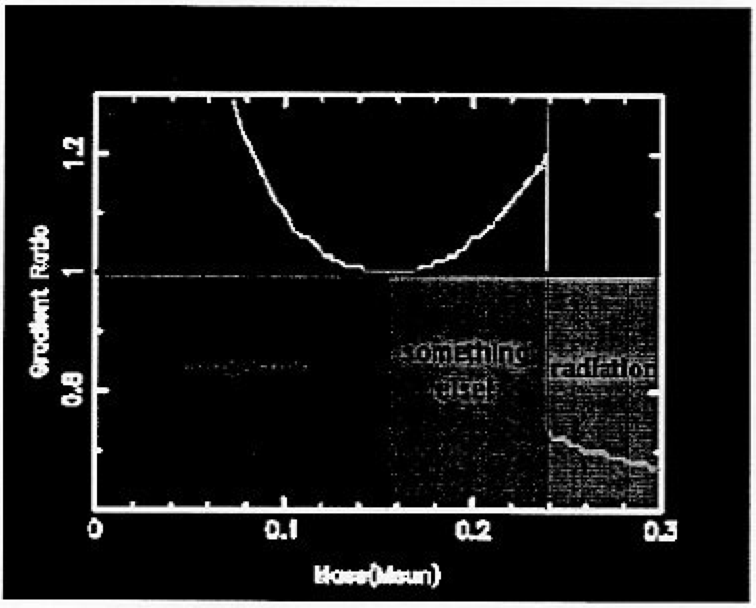
5. But note that the edge of the core has a large discontinuity in the ratio of the gradients. This means that there is a finite acceleration (buoyancy) on the inside. The point where the gradients are equal may be neutral (and hence define the Schwarzschild boundary) but there is no such neutral point here. On the inner side there is a positive acceleration outward, and on the opposite side there is a restoring force back inward. Surely in this case the core will grow, due to overshoot beyond the theoretical Schwarzschild boundary. This is seen in the evolution, the mass extent of the convective core grows due to the conversion of He into the more opaque C-12.



6. But look again at the ratio of the gradients. Do you see how it turns up at the outer edge? So although the size of the core progresses through overshoot, something strange will happen. As we mix more He into the core (the outer region is rich in He as there is no burning there) then we gradually lower the entire value of the ratio of the gradients throughout the core. As a region falls below unity, of course, then the convection disappears and radiation carries the energy. Due to the local minimum in the ratio of the gradients (in the core region) the first point to become radiative will be this local minimum. What will happen then? Do we have a convective zone on either side?

7. Well, no. The growth of the convective core is being driven by the mixing of carbon rich material to the edge. Once the convection is "pinched off" at the local minimum in the gradients the inner region can continue to be convective, but the outer region is now separated.



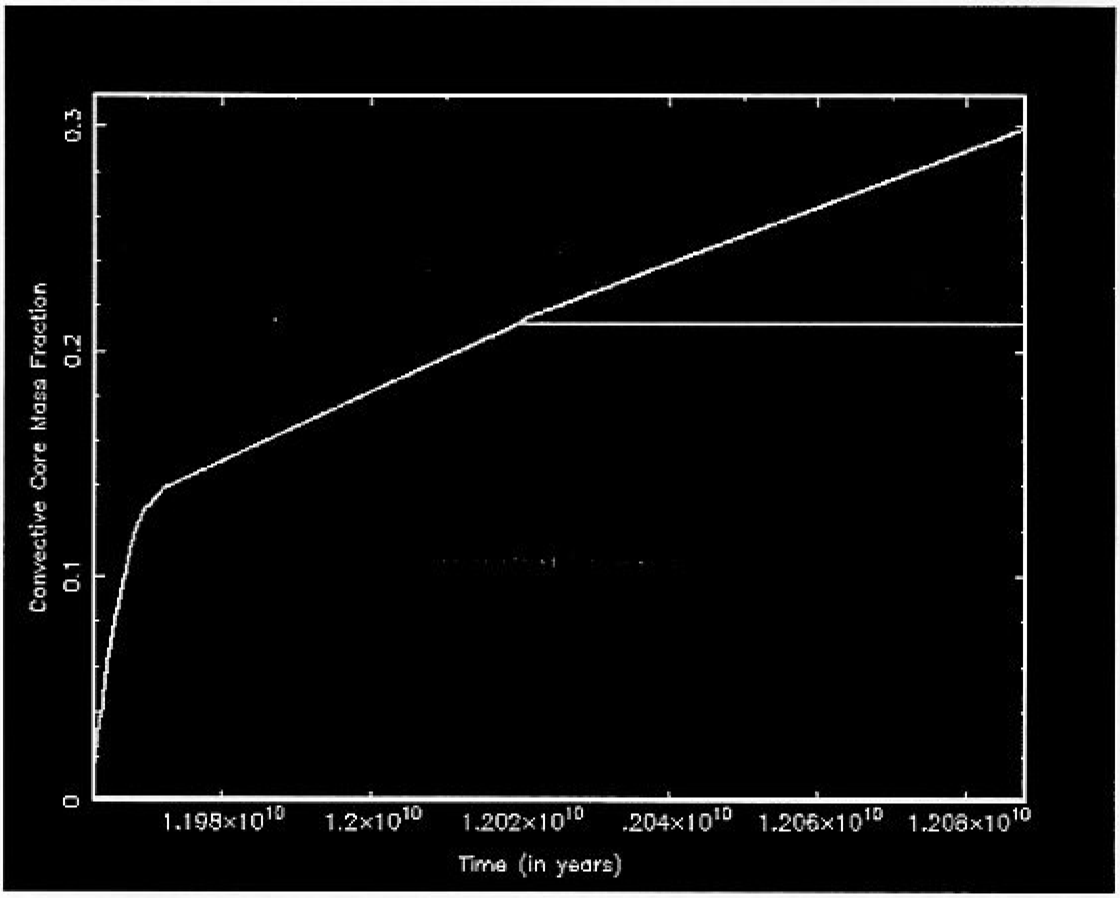


8. A little thought will reveal that the only stable configuration is one where the region is partially mixed, so that it maintains neutrality. If it is unstable it will mix, and this will decrease the opacity and hence the ratio of the gradients, until neutrality is achieved. The convective core will continue to face the same problem at its edge, however: the opacity inside the core will again produce the same result. The edge of the core will go through this minor crisis continually. The result is the propagation of helium inward to the core. In fact, the region will mix small zones until convective neutrality is achieved. We call this "semiconvection". The details are perhaps not so well understood. On average we expect a nice smooth profile, but in reality there will many distinct mixing events, but on what length-scale? I have calculated an approximate solution using zones of width no smaller than 0.006Msun in this region. This is for illustration.

9. The next movie (horizontal and vertical) shows the helium profile and the ratio of the

gradients. Watch the growth of the core by overshooting, and then the lowering of the ratio of the gradients until the semiconvective region forms. Then you can see small radiative and convective zones work to mix He into the core.

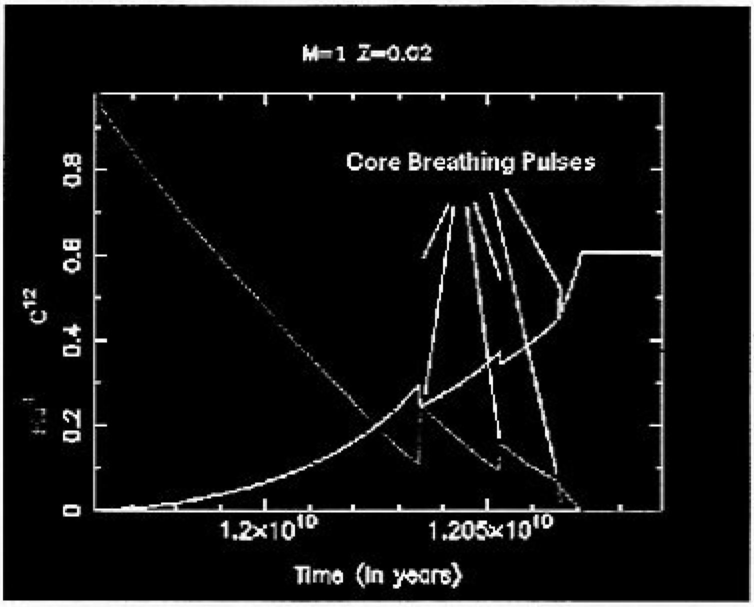
10. What usually happens is that the convective core grows till it reaches some value, and then the semiconvection begins to appear (when the local minimum in the ratio if the gradients reaches unity). The semiconvective zone grows in size as the evolution proceeds, until it usually encompasses about half as much matter as the convective core (on average), as shown in the schematic diagram below. Note that there are many ways to calculate the semiconvection and the associated abundance profile. Most of these give smooth abundance profiles, unlike shown above. But I have done this deliberately because I think it illustrates the physics of the phenomenon, even if on average it is rather smooth in reality.



11. As He-4 burns it initially produces C-12. But once there is a substantial amount of C-12 then we get O-16 from

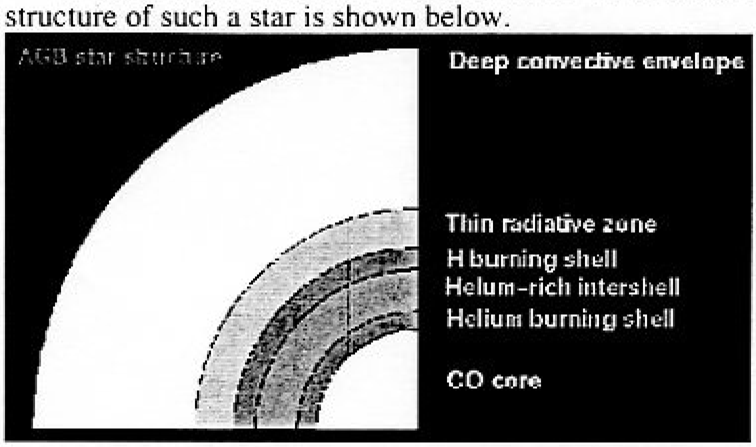
C-12(alpha,gamma)O-16

as shown in the C and O profiles movie.
The time dependence of the central abundances of He, C-12 and O-16 are shown below. The strange spikes are caused by "core breathing pulses", a discussion of which will be added "soon".



8. **Toward the Asymptotic Giant Branch (M=1 Msun, Z=0.02)**

   1. Once the central helium abundance is exhausted the star will begin its ascent of the second, or asymptotic, giant branch. Details of this evolution can be found here. The schematic structure of such a star is shown below.



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