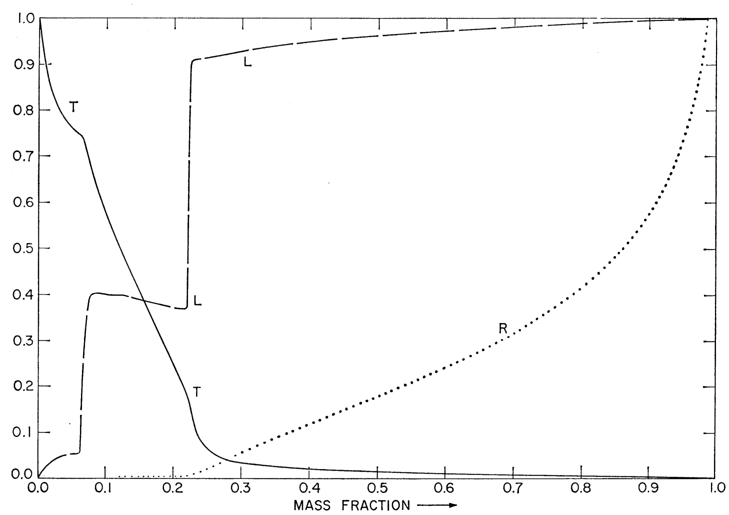

Figure 5.12: Interior quantities (scaled) for a $5M_\odot$ model. The radius here is $44R_\odot$. From Iben [1966].

November 12 ....

5.3.4 Horizontal branch evolution

- In general, the H-burning shell decreases in efficiency and the He-burning core increases.
- If the luminosity from the shell is greater than that of the core, the star goes blueward on the HR diagram.
- When the core starts to dominate, the star moves redward.
- One starts to see "loops" that depend strongly on the parameters.
- There are also internal "breathing" phases from convective overshoot that influence the observable properties, but we won't discuss these.
- Also note the *Instability Strip* crosses the horizontal branch, where stars pulsate in long periods (RR Lyrae stars, more later).
- Very massive stars ignite carbon very quickly (more later).
- Consider again a $5M_\odot$ model, as most stars behave similarly now.
- Still refer to Figure 5.3 and Figure 5.4.
- The star is going to go left-right-left.
- There is core He burning and still shell H burning (E-F).
- The convective envelope is now gone after point E.
- More than half of the luminosity still comes from shell burning.
- Central He burning lasts about $1 - 2 \times 10^7$ yr.
- The move from E to F represents a "loop."
- It's similar to the B to C movement, except that was for after H burning.

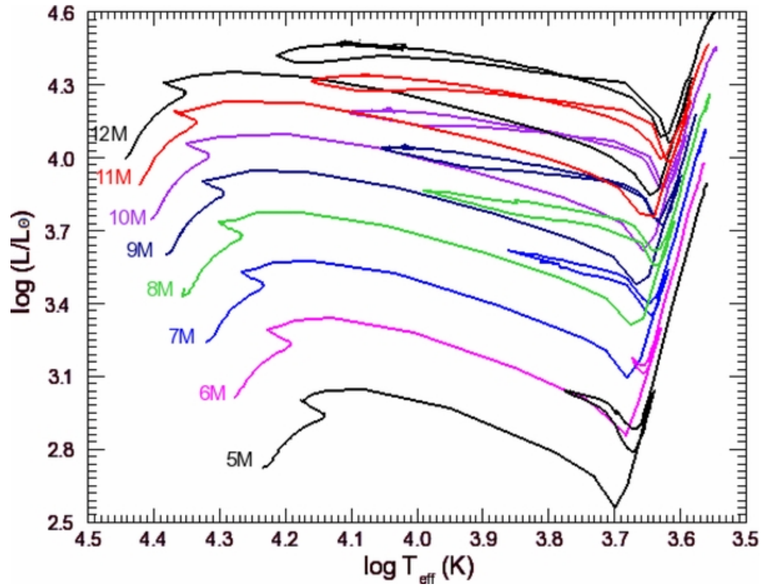

Figure 5.13: Evolutionary tracks for intermediate-mass stars and higher, showing the extent of the blue loops.

- He burning is getting stronger, and the core is expanding/envelope shrinking.
- At point F, the central He abundance is 0.5.
- The 3α energy fraction is about 20 percent.
- The number of loops, and how far "blue" they go, depends on stellar mass.
  - The more massive a star, the longer the loop to the blue.
  - That's because the H-burning shell contributes a significantly greater amount of energy in intermediate-mass stars than for low-mass stars.
  - Lower-mass stars don't have significant loops.
  - Increasing He abundance extends the blue loop, as does lowering the metallicity. However, models show nonlinear behaviors here.
  - Increasing core convective efficiency reduces the extension of the blue loop.
  - These loops are slow because of nuclear burning and therefore can be expected to be observed (and are: Cepheids!)
  - See Figure 5.13.

5.3.5 Asymptotic giant branch

- At point F or point 10 (in Figure 5.3 and Figure 5.4), He is less and less available for fusion.
- As C and O builds up in the core, the mean molecular weight increases.
- The core contracts and increases in temperature (as before, in the Hertzsprung Gap).
- The shell-burning law kicks in and the envelope expands, star moves to the red.
- The star starts moving redwards as the H-burning shell loses its dominance.
- Regardless of the mass, with low He abundances, the stars move back toward the Hayashi track.
- As He burning in the core exhausts, a new shell of He burning takes over (point G).

- The mass of the CO core increases.
- The contracting releases gravitational energy and some gets converted to thermal energy and it reignites He.
- The core is too cold for C or O to burn (neutrinos are cooling it!).
- Now at point G there are 2 shells! (or point 11 in Fig. 5.3)
- The core is contracting and heating up, and the space in between shells expands, and the outer part of the star contracts, moving to higher $T_{\rm eff}$. (G-H) or (11-12)
- This is the shell-burning law in triple!
- Figure 5.12 shows the interior state for a $5M_\odot$ model at about point 12.
- The luminosity is interesting and notable: The luminosity at the innermost region is from gravitational contraction of the core.
- Between the 2 shells, the luminosity is decreasing slightly as that region expands (does work against gravity).
- In the outer part above the H shell, the envelope is also contracting, releasing gravitational energy.
- Remember that $\mathrm{d}L/\mathrm{d}r = 0$ unless energy is being generated, so here we'd really have to account for $\varepsilon_{\rm nuc} + \varepsilon_{\rm grav}$.
- Does C now burn?
- For stars lower than about $10M_\odot$, the carbon-oxygen core is degenerate.
- Thus, the contracting core does not heat up the gas and the high internal temperatures needed to ignite the core are not reached.
- This is clear from Fig. 5.11. Look at the $7M_\odot$ case.
- As the star reaches point H (or point 12) from G, the shell-burning law has the core contracting (increasing in mass), the inner shell expanding, and the outer envelope contracting and increasing in effective temperature.
- But now the region between the two shell-burning sources has expanded sufficiently so that the temperature in the outer H-burning shell drops and extinguishes.
- This is thought to occur in the range of $3-5M_\odot$ stars.
- Now there are only 2 distinct regions: the contracting core, and the now expanding envelope with He burning in between (shell-burning law).
- The star heads back to the right (toward K).
- The luminosity begins to increase as the CO core mass increases and contracts, and the star heads up the Hayashi track yet again.
- This is the Asymptotic Giant Branch (AGB).
- Since the outer shell burning ceased, the the luminosity drops a little and the star cools.
- A convective surface region develops and extends deeply, and "dredges up" processed material (at point K).
- It reaches down to the regions where the H shell had been burning for a while.
- Low-mass stars don't typically have a second dredge up since their H shell burning continues strongly.

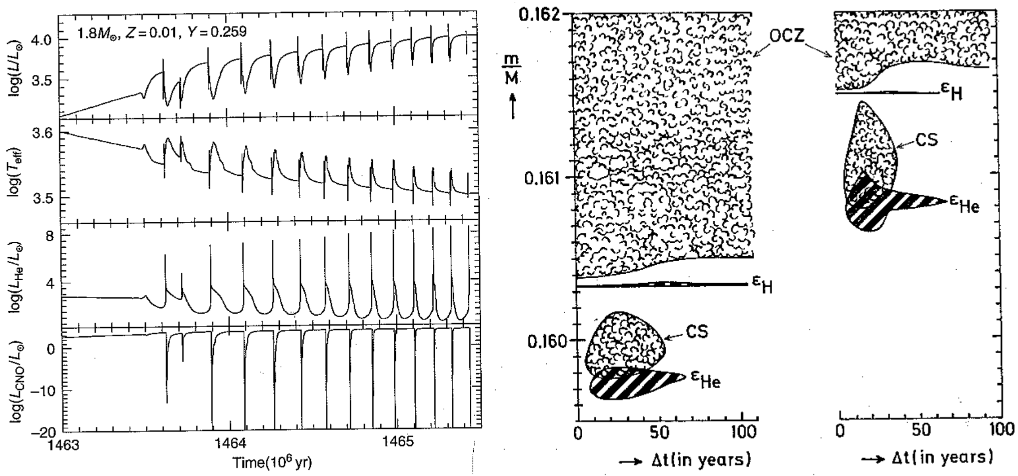

Figure 5.14: Thermal pulses. The left is for a $1.8M_\odot$ model showing many pulses with time. The right is for a $5M_\odot$ model

- This dredge up brings a lot of material to the surface and reduces the mass size of the H-exhausted region.
- This is one reason why very massive white dwarfs are not formed.
- An upper limit for carbon ignition in the core is about $8M_\odot$.
- The next phases are rather complex for stars below this limit .

5.3.6 Thermal pulses

- One sees that the growing He-burning shell approaches the bottom of the H-rich envelope.
- The He burning dies down a bit when it hits this region, contracts rapidly, and a H-shell reignites.
  1. As H burns, the He ashes fall onto the former shell burning region, and are compressed and heated.
  2. When the mass reaches about $10^{-3}M_\odot$ for a CO core mass of about $0.8M_\odot$, He ignites again.
  3. A runaway occurs, in that this ignition heats the overlying shell burning region and causes it to burn even more violently (note the temp. dependence of nuclear reactions).
  4. See Equation (5.12).
  5. The luminosity of the He burning reaches very high values, and this causes the layers above it to expand.
  6. The H-burning shell turns off.
  7. Because of the high luminosity, a convection zone develops.
  8. Eventually the convection helps expand the region, and the He burning drops strongly and cools.
  9. The convection zone disappears as the luminosity decreases.
  10. He burning continues, using up the He that the H-burning region produced before the flash.
  11. As this source reaches the new discontinuity, a new H-burning region is created as before.
  12. The He ash falls onto the He layer and the whole process happens again, now at a higher position.
- The thermal runaway is unusual because of the geometry.

- It can be shown using an ideal gas EOS (not much degeneracy here) that

$$\frac{\mathrm{d}\rho}{\rho}\left(4\frac{s}{r}-\alpha\right)=\beta\frac{\mathrm{d}T}{T}, \tag{5.12}$$

  where s is the thickness of the shell located at r, and the constants are positive.

- Stable burning usually causes a decrease in temperature when expansion occurs (lower ρ), but for a small enough shell s, the expansion can cause a *increase* in temperature.
- The timescale between pulses can be approximated roughly by

$$\log\tau \approx 3+4.5(1-M_{\mathrm{c}}/M_{\odot}). \tag{5.13}$$

- For a core mass of $0.5M_{\odot}$, this gives about 10^5 years; but drops to about 10 years for near-critical mass stars.
- Some stars can go through hundreds of pulses before the H shell gets depleted.
- In high-mass stars, these cannot be observed because they are buried within the massive envelope.
- In low-mass AGB stars, the effects of the pulses can be seen chemically.
  - In the pulses when H burning is turned off, the surface convection zone moves inward, and a third dredge up can occur.
  - This can bring up carbon and heavy s elements (Sr, Y, Zr, Ba, La, Ce, Pr, Nd). Carbon-rich stars can be "produced."
  - Stars below about $1.5M_{\odot}$ will likely not go through a third dredge up, as their envelope mass isn't large enough.
  - For more massive stars, large amounts of lithium can be produced (from berrylium 7) and brought to the surface.