Unit 23

The Horizontal Branch

23.1 Quick tour of non-hydrogen nuclear reactions

- After H burning, we have He burning through the general triple alpha process
- There are, however, no stable elements with $A = 5$ or $A = 8$ (lithium is 7 and berrylium is 9).
- So it's rather tricky for helium to burn (it can't just interact with hydrogen or with itself).
- There is however an isotope of berrylium present from its formation from 2 helium nuclei

$$^{4}\mathrm{He} + ^{4}\mathrm{He} \longrightarrow ^{8}\mathrm{Be} \tag{23.1}$$

$$^{8}\mathrm{Be} + ^{4}\mathrm{He} \longrightarrow ^{12}\mathrm{C} + \gamma. \tag{23.2}$$

- The ^{8}Be ground state energy is about 100keV higher than the ground state of 2 He nuclei, so it wants to decay into that, to find the lowest ground state.
- Its lifetime is only about 10^{-16}s.
- Since ^{8}Be decays so quickly, the third helium must arrive in a short amount of time.
- But this is orders of magnitude longer than a scattering event.
- Additionally, at high temperatures the $\alpha + \alpha$ reactions increase rapidly.
- The key is that a nucleus of carbon is produced before the berrylium decay.
- Energy release is about 7.3MeV, or about 0.6MeV per nucleon, which is about an order of magnitude smaller than CNO H burning.
- This all takes place in the $T = 1 - 2 \times 10^{8}$K range, and the reactions can be written

$$\varepsilon \approx \varepsilon_0 Y^3 \rho^2 T^{\nu}, \tag{23.3}$$

  where $\nu = -3 + 4.4/T_9$.

- So at $T = 10^{8}$, $\nu \approx 40$!
- As density increases, this reaction is favored due to the quadratic dependence in the rate.

- After a supply of carbon is produced, there are successive α particle captures to produce some "alpha elements"

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{4}\,\mathrm{He} &\longrightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + {}^{4}\,\mathrm{He} &\longrightarrow {}^{20}\mathrm{Ne} + \gamma \\
{}^{20}\mathrm{Ne} + {}^{4}\,\mathrm{He} &\longrightarrow {}^{24}\mathrm{Mg} + \gamma \\
{}^{24}\mathrm{Mg} + {}^{4}\,\mathrm{He} &\longrightarrow {}^{28}\mathrm{Si} + \gamma
\end{aligned}
$$

- The conversion of helium and carbon into oxygen is extremely important, as the C/O ratio is critical for understanding carbon-oxygen white dwarfs and their cooling times.
- And when the amount of He begins to be reduced in the core, this reaction competes with the main 3α reaction, and affects the He-burning lifetime overall.
- In 7Mb-2095 or so, the "abundance" and "burn" panels show this.
- The nuclear cross section is not that precisely known, however, due to a resonance and a very small value at low energies, making it difficult to measure.
- Note that the isotopes with an atomic weight in multiples of 4 are known as the *alpha* elements.

23.2 The horizontal branch properties

- Stars with $M \leq 2.3 M_\odot$ develop degenerate He core, go through helium flash.
- Stars with $2.3 \leq M/M_\odot \leq 9$ just start burning He, but will NOT ignite carbon, later (see Figure **??**).
- For most stars, He is now burning in the core (non-degenerately) and there is still an H-burning shell.
- When this is happening "quietly," the star is on the zero-age horizontal branch (ZAHB).
- The core is convective due to the large luminosity associated with He burning (Fig. **??**).
- Models predict a horizontal distribution on the HR diagram of these stars.
- The efficiency of the H-burning shell is modulated by the mass of the overlying envelope.
- The more massive, the hotter the burning.
- The effective temperature of these stars depends on mass of the envelope.
- The more massive envelope, the cooler (from inertia).
- Stars can fall into the "Red Clump" on the horizontal branch, which have large envelope masses.
- Less-massive enveloped stars are bluer.
- Also, the horizontal branch is not exactly horizontal, as more massive stars are slightly brighter.
- The luminosity is fixed mostly by the mass of the He core, and then by the mass of its envelope.
- Since the He core mass is almost constant for low-mass stars, the horizontal branch luminosity is an important distance indicator.
- Where cluster stars fall here can be a tricky problem, as metallicity and mass loss play a role in all of this.
- For increased He content, the blue part of the ZAHB (lower mass stars) becomes fainter and the red part brighter.

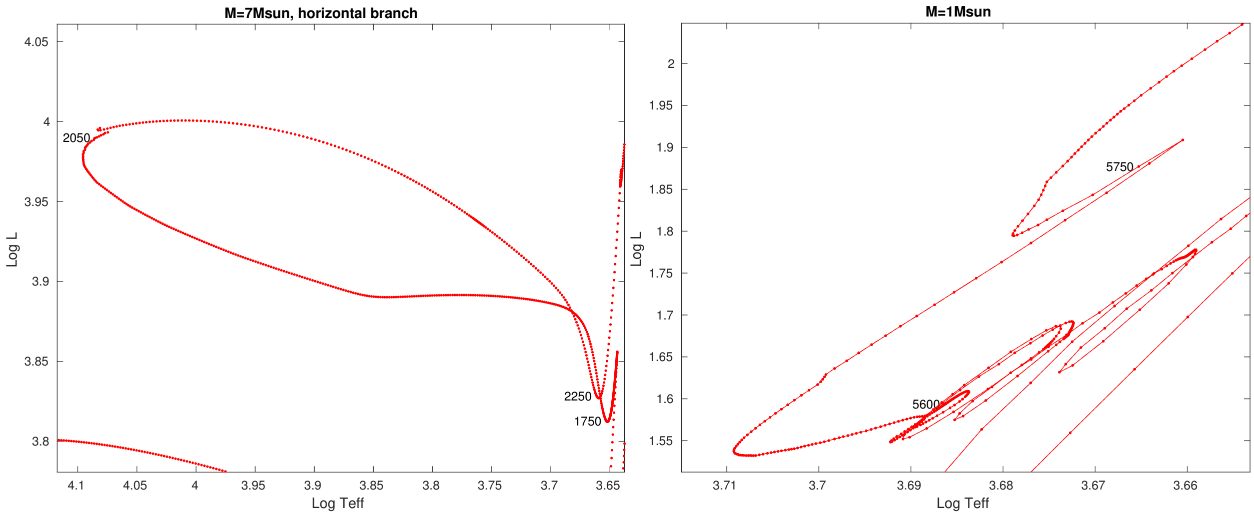

Figure 23.1: Zoom in on the horizontal branch for the 7 $M_\odot$ models (left) and 1 $M_\odot$ models (right). The model numbers are annotated.

- An increase in metals makes the ZAHB fainter and cooler, due to the lower core He mass at the flash and the increased opacity.
- Any process(es) leading to mass loss along the RGB, delaying the He flash, will lead to a hotter and brighter ZAHB.

23.3 Horizontal branch evolution

23.3.1 High-mass stars

The $7M_\odot$ star is on the horizontal branch in models 1750 to 2250, approximately. See Figure 23.1 for a zoom of the horizontal branch.

There are a few defining characteristics of the horizontal branch that need to be pointed out:

1. The (convective) core is burning He and a shell is burning H. Central He burning lasts about $1-2\times10^7$ yr.
2. The surface convection zone from the RGB is gone (see "kippenhahn" panel)
3. The high-mass star goes through a striking loop:
   - The star first goes blueward until model 2050, then redward on the H-R diagram.
   - In the blueward direction, the H-burning shell maintains an even level of efficiency and the He-burning core increases.
   - More than half of the luminosity still comes from shell burning.
   - As He burning briefly gets stronger, the core is expanding and the envelope shrinking.
   - At model 2050, the He in the core is $Y \leq 0.5$, and $L_{3\alpha} \approx 20\%$ of the total luminosity.
   - When the core starts to decrease in luminosity as He is running low, the star moves redward.
   - Figure 23.2 depicts these features.
4. The number of loops, and how far "blue" they go, depends on stellar mass.

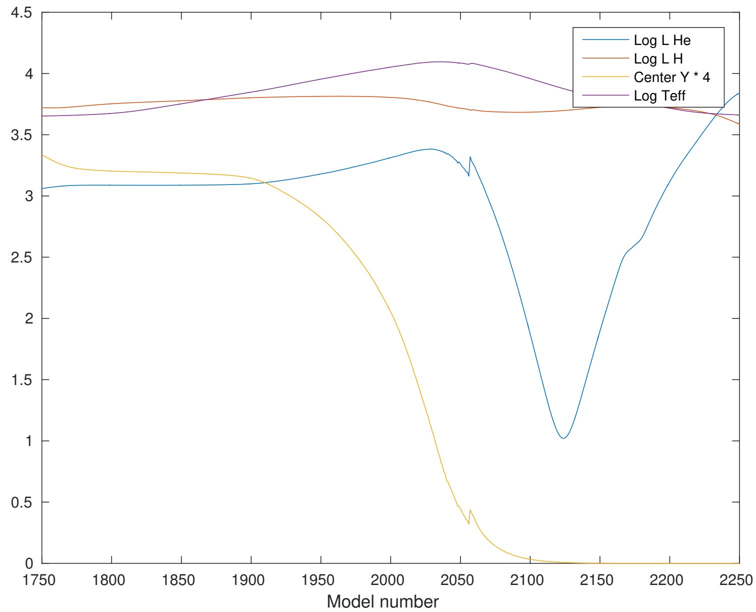

Figure 23.2: The luminosities, effective temperature, and core He content in the massive star along the horizontal branch. The He mass fraction has been multiplied by 4 to scale it near the other quantities.

- 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 on nuclear burning timescales.
- See Figure 23.3.

5. Also note the *Instability Strip* crosses the horizontal branch, where stars pulsate in long periods (RR Lyrae stars, Cepheids, more later).

23.3.2 Low-mass stars

The 1 $M_\odot$ star is on the horizontal branch in models 5600-5750. See Figure 23.1. There isn't too much more to add beyond the high-mass discussion:

1. There is no significant blue loop for lower-mass stars.
2. The He-core burning produces a carbon-oxygen core in about a 30/70 ratio when He is fully depleted. Figure 23.4 shows this.
3. This core is degenerate, as the "temperature-density" panel shows around 1Ma-5795.

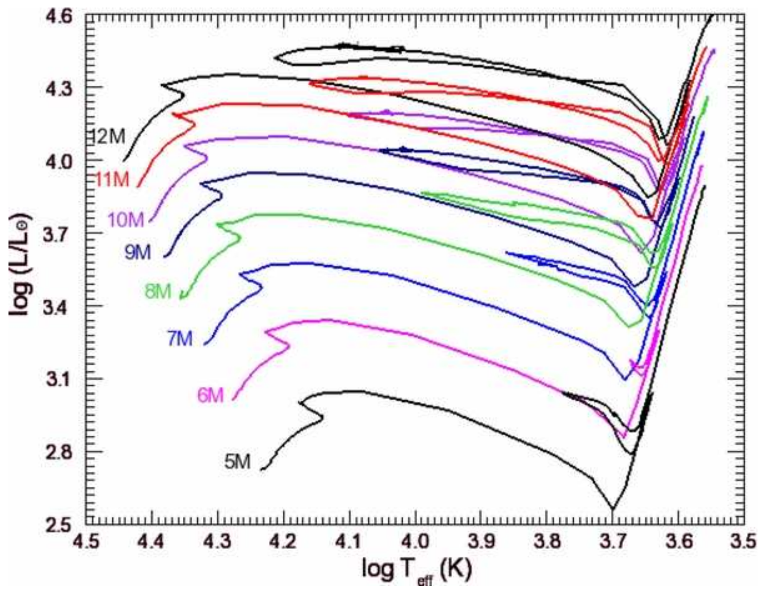

Figure 23.3: Evolutionary tracks for intermediate-mass stars and higher, showing the extent of the blue loops.

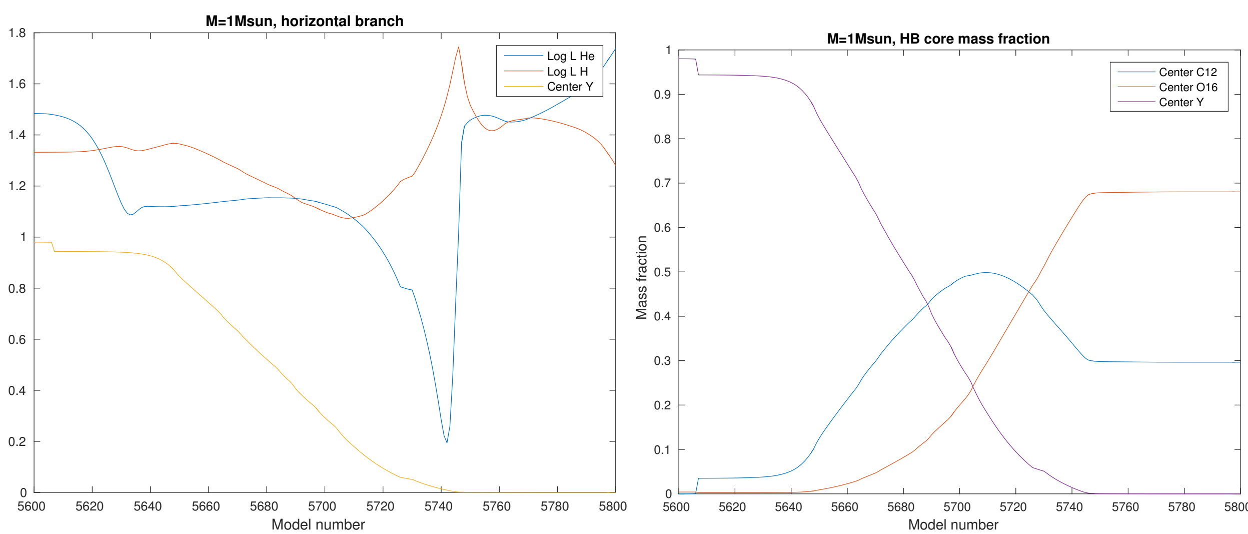

Figure 23.4: Horizontal branch properties for the $1\ M_{\odot}$ star.