Figure 5.9: How the base of the convection zone and the mass of the He core change with time for a $1M_\odot$ model. This illustrates how the first dredge up occurs.

November 14 . . . .

Helium flash

- So the temperature of the burning shell is increasing up the RGB, and when it reaches 10^8K, the *helium flash* occurs.

- It coincides when the He-core mass is about 0.5 $M_\odot$, mostly independent of the total stellar mass.

- In a more massive star (which would be non-degenerate matter), the release of energy by nucelar burning would cause an increase in pressure and an expansion of material (core), and then cooling and an equilibrium would be restored, all rather smoothly.

- In the degenerate case, however, the gas pressure is basically independent of temperature (recall the EOS), and the high temperature causes no immediate reaction at the core.

- Instead the nuclear energy generation increases $\to$ higher temperatures $\to$ increased energy generation, . . .

- This is called a thermal runaway.

- The local luminosity in the core increases to about 100 billion $L_\odot$ in a few hours!

- See Figure 5.10.

- The does not make it to the surface, however, but is absorbed by the overlying layers, which expand just outside the H-burning shell.

- Convection also sets in which spreads out the energy production over more mass layers.

- Eventually, the temperature gets so high that degeneracy is "lifted" at the point where the flash occurs (density is roughly constant). Recall Equation (2.65):

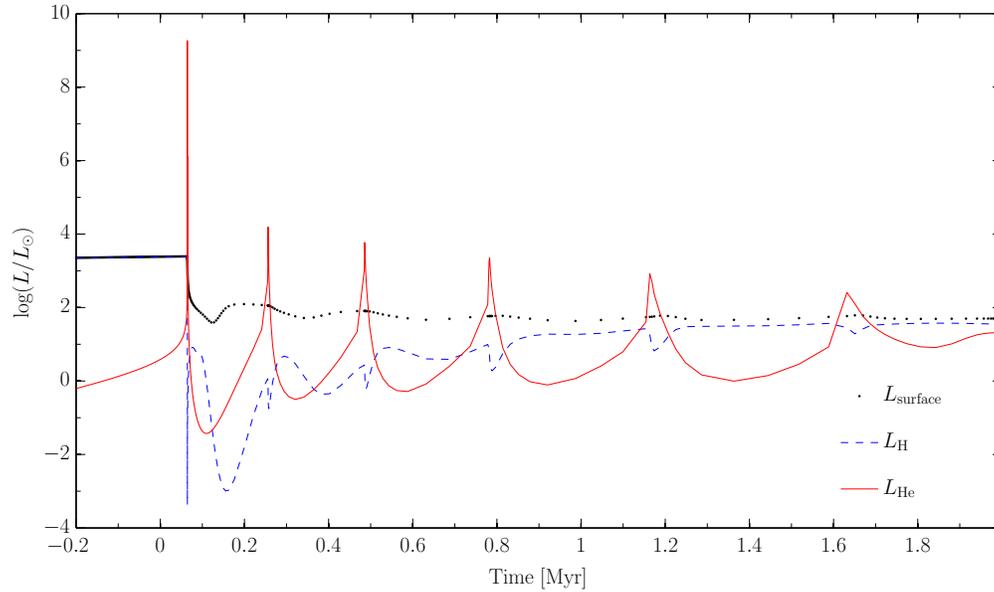$$\frac{\rho}{\mu_e} > 2.4 \times 10^{-8} T^{3/2}.$$

Figure 5.10: Helium flash for a $1M_\odot$ model. Time has been shifted to approximately the start of the flash, which corresponded to about 12 billion years. Note the decrease in the surface luminosity due to the expansion of the He core and cooling of H-burning shell.

- Interior to this first outer layer explosion, some smaller flashes may take place which eventually removes the degeneracy everywhere.

- After this, the core expands (envelope contracts!) and cools, and an equilibrium of helium burning in the core proceeds.

- The dynamical time scale of the star, because it is so large, is of the order of months.

- So the He flash in the core is not visible at the surface. The whole process takes on the order of one million years.

- See Figure 5.10.

- It is now on the *helium burning main sequence*, or better, the *horizontal branch*.

- The future evolution from now on follows roughly what a higher-mass star will be.

5.2.3   RGB properties

Here we discuss the main RGB features on various physical and chemical parameters.

RGB location

- The main determinator of the RGB location is the size of the convective envelope.

- With decreasing mass, the RGB is cooler.

- An increase in He content reduces the opacity, causing a shrinking of the convective envelope, and thus a hotter RGB.

- An increase in metallicity produces a deeper convection zone (higher opacity, cooler temps) and a cooler RGB.
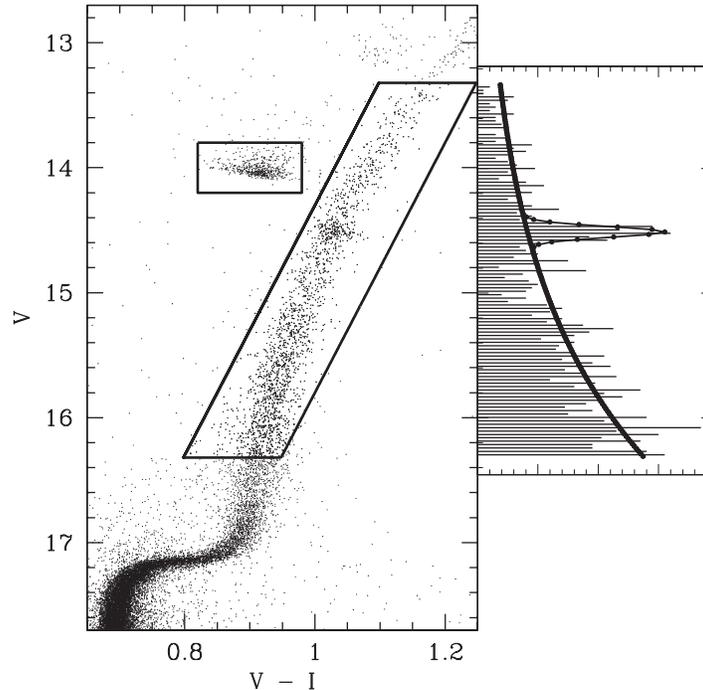
Figure 5.11: Left panel: the colormagnitude diagram of HST data for the globular cluster 47 Tuc. The RGB (including the RGBB) and the HB are all contained within their respective colormagnitude selection boxes. Right panel: magnitude distribution of RG stars. The RGBB stands out as a prominent and significant peak at $V = 14.51$, with a normalization of (122 ± 14) stars. From Nataf et al. [2011], where they show the lifetime of the RGBB is different for different He amounts in the cluster stars.

- An increase in the convective efficiency, such as an increase in the mixing length, the RGB shifts to hotter effective temperatures.

- If the mixing length parameter is set to zero, the RGB disappears and expands until it falls apart.

RGB bump luminosity

- This phenomenon depends most strongly on the location of the H-abundance discontinuity after the first dredge up.

- The bump luminosity decreases as this location moves deeper into the star, as it will encounter it at earlier times.

- A decrease in He, or increase in metals, pushes this location deeper, and reduces the bump luminosity.

- More efficient convection, decreases the mass extent of the outer convection zone and the bump occurs at higher luminosity.

- Another prediction of stellar evolution theory is that the *lifetime* of the RGBB is decreased as the He content increases.

- Empirical support for this is alluded to in Figure 5.11 and the associated article.

RGB tip

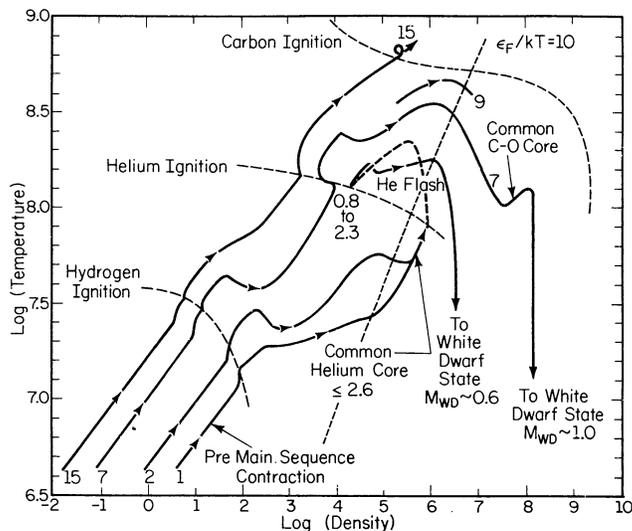- The luminosity at the tip of the RGB occurs when He is ignited.

Figure 5.12: Tracks in the density-temperature plane for 4 different mass models. Density is in $\mathrm{g\,cm^{-3}}$. To the right of the diagonal dashed line is the degeneracy regime. From Iben [1985].

- This typically happens at a well defined He core mass.

- For stars less massive than about $1.8M_\odot$, the mass of the He core at the flash does not depend on the overall mass that much, and they all develop about the same amount of electron degeneracy in the core.

- So the luminosity at the flash is about the same for these stars (all things otherwise being equal).

- For higher masses (about less than $3M_\odot$), the mass of the core is smaller and degeneracy is at lower levels, so the luminosity is reduced at the tip (ignition occurs earlier).

- For higher masses still, the luminosity starts to increase again as a result of the mass of the He core increasing again.

- An increasing He content increases interior temperatures and decreases electron degeneracy leading to lower He core mass and a lower tip luminosity.

- An increasing metallicity also helps lower the He core mass, because shell H burning is more efficient.

- This heats the He core faster; however, the luminosity is higher with increasing metals since L is strongly affected by the H-burning shell.

- Convection changes do not affect the tip luminosity since these don't really change the mass of the He core.

5.2.4   Summary

- See Figure 5.12.

- Stars of mass larger than those here ignite carbon before electrons become degenerate.

- Stars less than about 2 solar masses have electron-degenerate cores before helium is ignited.

- The helium core flash then lifts the degeneracy, allowing helium burning to take place.

5.3   Helium burning

5.3.1   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
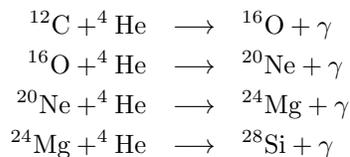
$$^4\text{He} +^4\text{He} \quad \longrightarrow \quad ^8\text{Be} \tag{5.9}$$
$$^8\text{Be} +^4\text{He} \quad \longrightarrow \quad ^{12}\text{C} + \gamma. \tag{5.10}$$

- 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

$$\varepsilon \approx \varepsilon_0 Y^3 \rho^2 T^\nu, \tag{5.11}$$

  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 captures

$$^{12}\text{C} +^4\text{He} \quad \longrightarrow \quad ^{16}\text{O} + \gamma$$
$$^{16}\text{O} +^4\text{He} \quad \longrightarrow \quad ^{20}\text{Ne} + \gamma$$
$$^{20}\text{Ne} +^4\text{He} \quad \longrightarrow \quad ^{24}\text{Mg} + \gamma$$
$$^{24}\text{Mg} +^4\text{He} \quad \longrightarrow \quad ^{28}\text{Si} + \gamma$$

- 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.

- 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.

5.3.2   Horizontal Branch

- 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 5.12).

- 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. 5.5).

- Models predict a horizontal distribution on the HR diagram of these stars.

5.3.3   Location of the ZAHB

- 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.

- 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.