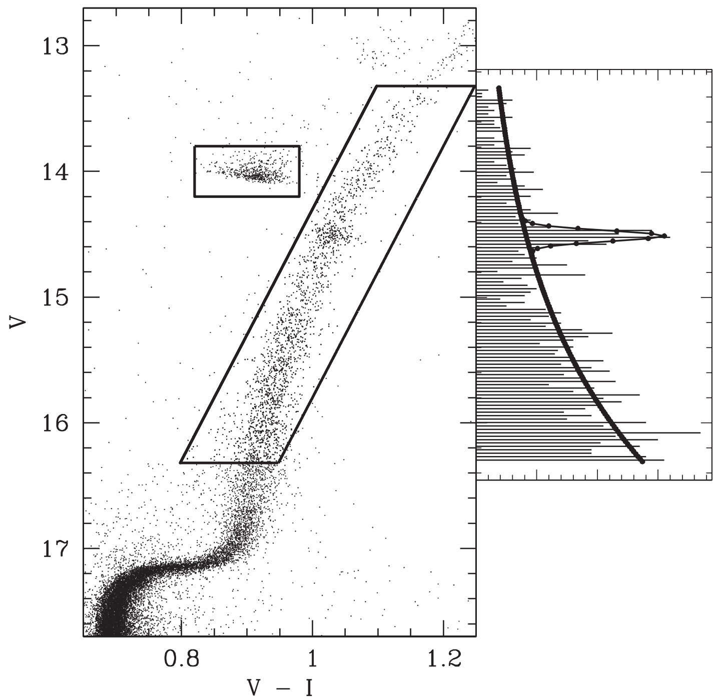

Figure 5.10: Left panel: the colormagnitude diagram of HST data for the globular cluster 47 Tuc. The RGB (including the RGBB) and the HB are all contained within their respective colormagnitude selection boxes. Right panel: magnitude distribution of RG stars. The RGBB stands out as a prominent and significant 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.

November 10 . . . .

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.
- 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 5.10 and the associated article.

RGB tip

- The luminosity at the tip of the RGB occurs when He is ignited.
- 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 5.11.
- 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.

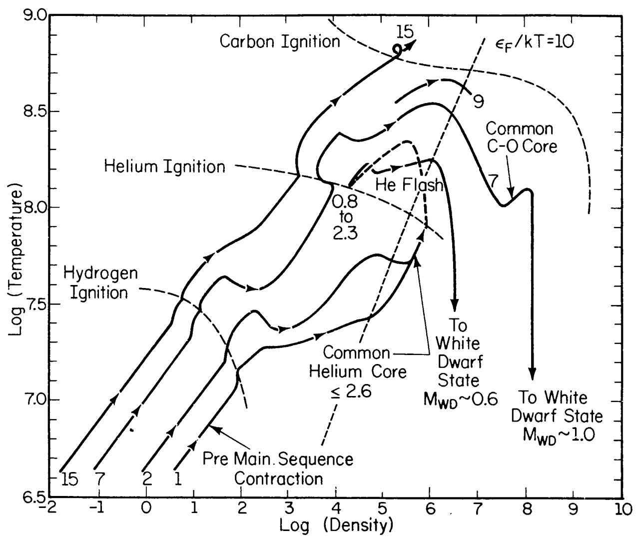

Figure 5.11: Tracks in the density-temperature plane for 4 different mass models. Density is in $\mathrm{g\,cm^{-3}}$. To the right of the diagonal dashed line is the degeneracy regime. From Iben [1985].

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

$$
\begin{aligned}
{}^4\mathrm{He} + {}^4\mathrm{He} &\longrightarrow {}^8\mathrm{Be} && (5.9)\\
{}^8\mathrm{Be} + {}^4\mathrm{He} &\longrightarrow {}^{12}\mathrm{C} + \gamma. && (5.10)
\end{aligned}
$$

- 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

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

- 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.
- 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 Fig. 5.11).
- 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. 5.4).
- 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.